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Different configurations for cutoff walls in the design of Qeysaraq earth-fill dam: A finite element approach

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ABSTRACT

Dams are critical infrastructures for water resource management, flood control, and the provision of agricultural and drinking water. Among dam types, earth-fill dams are widely used due to their relatively low construction costs, adaptability to diverse geological conditions, and practicality in resource-limited settings. A major challenge for earth-fill dams is controlling seepage and internal erosion, which threaten safety and durability. Cutoff walls can enhance hydraulic performance by reducing seepage flow and hydraulic gradients. This study examines the effects of cutoff-wall depth (9, 12, 15, 18, 20 m) and thickness (1, 1.5, 2, 2.2, 2.5 m) on seepage flow, hydraulic gradient, and uplift pressure, based on specifications of an earth-fill dam in East Azerbaijan, Iran, using the finite element analysis. Numerical simulations quantify the influence of variations in depth and thickness on key hydraulic responses. The results indicate that increasing depth up to 15 m reduces seepage by 53.4%, while increasing thickness up to 2 m reduces seepage by 33.7%. Optimized cutoff wall dimensions (depth = 15 m, thickness = 2 m) achieve a 51.2% reduction in hydraulic gradient and a 22.3% reduction in uplift pressure. An economic analysis shows that optimization can reduce excavation costs by 53%. Additionally, raising the reservoir water height behind the dam from 24.5 m to 31 m increases seepage flow by up to 27%, highlighting the influence of head on seepage. The results demonstrate that selecting a cutoff-wall depth of 15 m and thickness of 2 m provides substantial seepage and hydraulic-performance benefits while offering significant cost savings.

Keywords: Earth-fill dam, Seepage; Hydraulic gradient, Uplift pressure, Cutoff wall, Finite element method, Economic analysis

1. Introduction

Dams are vital structures in water resource management, serving fundamental roles in flood control, irrigation, drinking water supply, and energy generation. Among the various types of dams, earthen dams are widely constructed due to their relatively low cost, adaptability to diverse geological conditions, and ease of implementation. Despite these advantages, one of the primary challenges in the design and operation of earthen dams is seepage through the dam body and foundation (Salmasi et al., 2025). Uncontrolled seepage can increase pore water pressure, trigger internal erosion, reduce structural stability, and, in severe cases, lead to dam failure. Consequently, seepage control is a critical consideration in the safe and sustainable operation of earthen dams, particularly those founded on alluvial deposits (Liu et al., 2023; Zhang et al., 2024). Several methods have been developed to manage seepage in earthen dams, with cutoff walls being among the most effective. These walls, typically constructed of plastic concrete, soil–cement mortar, or steel sheet piles, act as vertical barriers within the dam foundation. By increasing the seepage path length and reducing hydraulic energy, cutoff walls decrease seepage discharge and exit hydraulic gradients, thereby enhancing dam stability (Moharrami et al., 2014; Beiranvand and Komasi, 2021). Numerical simulation provides a powerful tool for analyzing the performance of cutoff walls under varying design conditions. Parameters such as cutoff wall depth and thickness can be systematically evaluated to determine their influence on seepage, hydraulic gradients, and uplift forces. Excessive water seepage from the foundation and body of the dam causes water loss from the reservoir and the dam lake. High hydraulic gradient, especially at the exit of the dam (dam toe), can cause internal erosion (piping) and movement and migration of soil particles, and in the worst case, lead to emptying under the dam and complete collapse of the dam. High uplift force can disrupt the balance between vertical forces and compromise the dam's stability. The insights gained from such simulations support the optimization of cutoff wall design, ensuring both hydraulic efficiency and economic feasibility (Sharifi et al., 2018). Given the importance of seepage control in maintaining dam safety and preventing adverse consequences, studies of this type are highly valuable. They not only contribute to improved understanding of hydraulic behavior but also inform the development of more effective sealing systems for earthen dams. Ultimately, optimized seepage control measures enhance dam performance, ensure sustainable water resource management, and strengthen the resilience of hydraulic structures against natural and anthropogenic challenges (Nourani et al., 2023; Pourghani et al., 2025).

A numerical comparison of cutoff wall performance in relation to the hydraulic characteristics of dam foundations remains a key topic in water engineering. Numerous studies have investigated the role of cutoff walls in seepage reduction and hydraulic performance improvement, and their importance in modern dam engineering practice. Previous studies have highlighted the importance of cutoff walls in improving dam safety and hydraulic performance. Nourani et al. (2025) demonstrated that increasing the seepage path length by constructing a cutoff wall beneath a dam enhances overall stability. Suzuki et al. (2005) conducted experimental and numerical investigations showing that greater wall thickness significantly reduces seepage flow and minimizes reaction forces. Lee et al. (2010) used advanced numerical simulations to confirm that cutoff walls effectively prevent water movement under dams, thereby improving structural stability. Morris and Wang (2012) further analyzed wall thickness effects, concluding that cutoff walls substantially reduce seepage discharge. Sharifi and Moghaddam (2018) compared wall performance under varying hydraulic conditions,

emphasizing that proper design choices can greatly improve hydraulic efficiency. Garcia et al. (2019) examined the influence of climate change, finding that fluctuations in climate can alter dam hydraulic behavior and affect sealing system performance. Wang et al. (2020) applied numerical modeling to evaluate multiple parameters, showing that increased wall depth reduces seepage and enhances stability. Finally, Kim et al. (2021) combined experimental and numerical approaches, concluding that integrated cutoff wall methods can optimize hydraulic performance and improve dam safety.
Plastic concrete cutoff walls are one of the most common and effective methods for controlling seepage in earthen and rockfill dams. These walls are constructed as vertical barriers in the dam foundation, lengthening the groundwater flow path and reducing hydraulic energy, thereby reducing seepage flow, hydraulic gradient, and uplift force (Salmasi and Abraham, 2025).

Plastic concrete cutoff walls under dams are usually installed by deep trench excavation and simultaneous filling with plastic concrete. This method is especially applicable to earth fill and rockfill dams and allows the construction of walls with a depth of more than 100 meters. Steps for implementing a plastic concrete cutoff wall are as follows (Salmasi et al., 2020):

1. Deep trench excavation with bentonite support: First, a vertical trench is dug in the dam foundation, which usually continues to the impermeable layer (bedrock or dense clay). To prevent the walls from collapsing, bentonite slurry is used, which creates lateral pressure and maintains the stability of the trench. Excavation is carried out with a special excavator, a Hydromill, or a Trench Cutter wall drilling machine, which are capable of drilling to great depths (up to 100 meters).

2. Quality control and cleaning of the trench floor after reaching the desired depth: The trench floor is cleaned with special equipment to ensure proper bonding of the plastic concrete with the impermeable layer.

3. Pouring the plastic concrete simultaneously with the exit of bentonite plastic concrete with specific rheological properties (high fluidity, slow setting, medium compressive strength, very low permeability) is prepared and poured into the trench from above or injected from below. Simultaneously with the entry of the plastic concrete, the bentonite slurry is gradually removed until complete replacement is achieved.

4. Curing and quality control of the plastic concrete: Sampling of the plastic concrete is carried out for compressive strength, permeability, and yield strength tests. In some projects, limited reinforcement or geotextiles are used to control cracking or increase durability.

The main objective of this study is to investigate the hydraulic performance of cutoff walls in earth-fill dams using the finite element numerical modeling. Specifically, the effects of wall depth and thickness on seepage discharge, hydraulic gradient, and uplift force are analyzed. Unlike most previous studies, which focused solely on hydraulic aspects, this research introduces an economic dimension by evaluating implementation costs under different design scenarios. The novelty of this work lies in its dual consideration of hydraulic efficiency and economic feasibility, providing a more comprehensive framework for dam design. By integrating technical and financial perspectives, the study offers practical guidance for decision-makers seeking to optimize seepage control systems while ensuring cost-effective and sustainable dam construction.

2. Material and Methods

Numerical modeling was performed using Seep/w software to assess the effectiveness of the cutoff wall in reducing seepage and controlling pore water pressure in the Qeysaraq earthen dam. The software is based on the finite element method (FEM) and incorporates the hydrogeological and geotechnical conditions of the study area. Field data and laboratory results, including soil hydraulic conductivity, were utilized in model development.

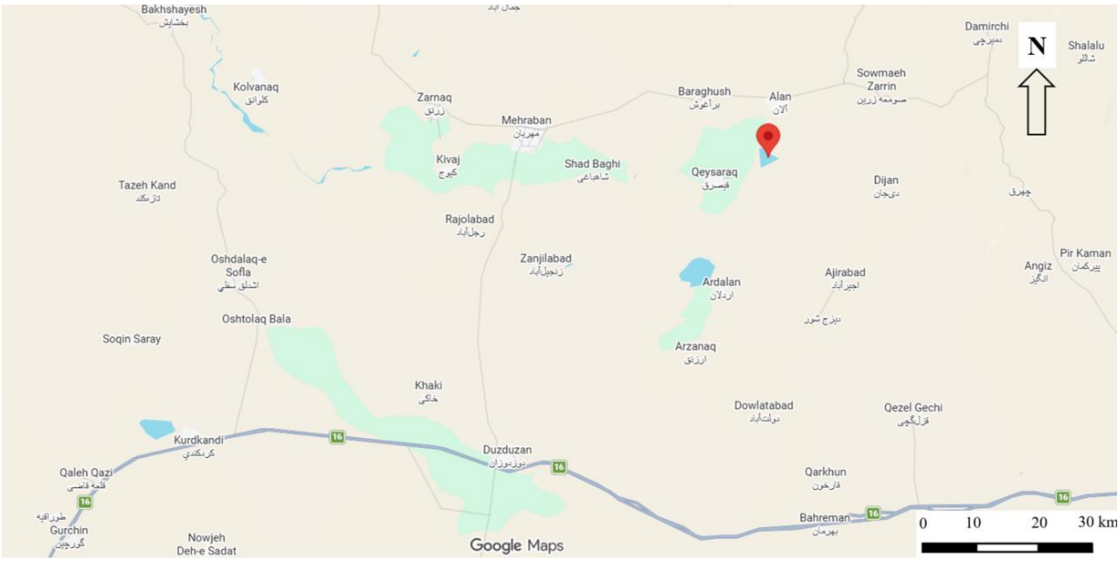
Seepage analysis was conducted under saturated, isotropic, and two-dimensional soil conditions. In the valley section of the dam, several cross-sections can be assumed; therefore, the largest cross-section of the dam—representing the critical state in terms of seepage discharge—was selected for numerical simulation. Boundary conditions consistent with actual site conditions were applied to ensure realistic modeling.

2.1. Geometric and Permeability Characteristics

The Geysaraq earthen dam is located in East Azerbaijan Province (Iran), upstream of the village of Qaisarq, approximately 61 km northeast of Bostanabad and 10.3 km east of Mehraban. Figure (1a) illustrates the geographical location of the dam, while Figure (1b) presents a satellite image showing the reservoir, dam structure, and surrounding agricultural lands. These images provide essential information for evaluating topography, land use, and water resource distribution, thereby supporting hydraulic behavior analysis.

Figure 2 depicts the longitudinal geological profile along the dam axis. The geometric specifications and permeability characteristics of the Geysaraq Dam are summarized in Tables 1 and 2. Permeability parameters were determined through standard laboratory tests, as described in the following section.

(a): Geographical location of the Geysaraq Dam in Iran.



(b): Map of communication roads and villages near the dam.

Figure 1. (a): Geographical location of the Geysarag Dam in Iran; (b): Map of communication roads and villages near the dam.

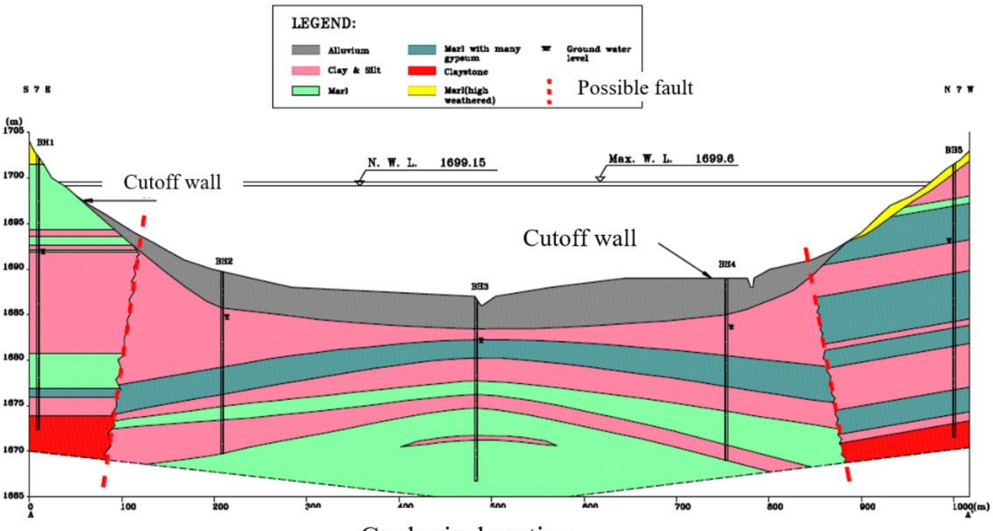


Figure 2. Longitudinal geological profile along the dam axis.

Table 1. Geometric characteristics of the Geysaraq Dam

Parameter	Value
Dam height	16 m
Crest length	988 m
Crest width	6 m
Upstream slope (V: H)	1:3
Downstream slope (V: H)	1:3
Crest elevation	1701 m above sea level

Table 2. Hydraulic conductivity of foundation and dam body materials

Material name	Hydraulic conductivity value (m/s)
Clay core	10^{-9}
Fine filter	10^{-3}
Coarse filter and drainage	10^{-2}
Shell	10^{-5}
Surface alluvial layer	10^{-6}
Silt and clay layer	10^{-7}
Cut-off wall	10^{-8}

2.2. Boundary Conditions and Modeling Approach

Boundary conditions included the upstream reservoir water level, downstream water level, and bedrock depth. Numerical models were developed for multiple scenarios, with emphasis on variations in the depth and thickness of the cutoff wall. These models enabled comparison of seepage control methods and provided a basis for optimizing the design of the seepage control system in earth dams. In Figure 3, the boundary conditions defined for numerical simulation and meshing of the dam body and its foundation are presented.

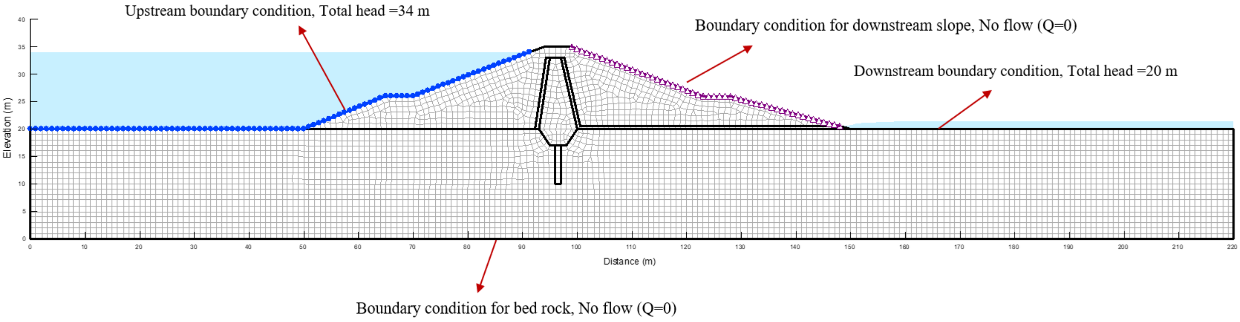


Figure 3. Boundary conditions and meshing of the dam.

2.3. Model Parameters and Variables

The effects of dam wall depth, wall thickness, and hydraulic conductivity of the alluvial foundation layers on seepage rate and pore water pressure were investigated. Table 3 summarizes the numerical model specifications. Five cases were considered for cutoff wall depth and five for cutoff wall thickness, resulting in a total of 25 numerical simulations. To evaluate implementation costs, excavation, material transport, and construction expenses were analyzed.

Table 3. Characteristics of model variables

Variable row	Order of change
Cutoff wall depth (m)	9, 12, 15, 18, and 20
Cutoff wall thickness (m)	1, 1.5, 2, 2.2, and 2.5
Total number of simulations	25 cases

2.4. Plastic Concrete Cutoff Wall

The dam cutoff wall was constructed using plastic concrete, composed of water, aggregate, cement, and bentonite (Table 4). This material was selected due to its adequate strength and ductility, allowing deformation compatible with surrounding soil conditions without rupture. Plastic concrete cutoff walls are particularly suitable when hydraulic gradients and dam heights are high, as they require materials with resistance to erosion and long-term durability. Such cutoff walls also exhibit high deformation capacity, enabling them to withstand strains imposed by foundation loading and hydraulic conditions without cracking.

Table 4. Plastic concrete mix design

Gravel (kg/m³)	Cement (kg/m³)	Bentonite (kg/m³)	Water (L/m³)
1500	150	40	420

2.5. Validation of Numerical Modeling

To validate the numerical model, simulation results were compared with data from piezometers installed in the Geysaraq Dam.

The relative error (RE) and root mean square error (RMSE) are calculated using the following equations.

$$RE\% = \frac{\sum_{i=1}^{N}(E_i - O_i)}{\sum_{i=1}^{N} O_i} \times 100 \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{n}} \quad (2)$$

where O_i represents the observed data, E_i is the numerical simulation data and n is the number of data. Calibration was achieved by adjusting hydraulic conductivity in selected zones by approximately 15%, resulting in acceptable agreement between simulated pore water pressures and piezometer readings. Figure 4 compares the simulated water head with measurements from piezometer SP_1. The average relative error was 6.5%, which is considered reasonable and confirms the reliability of the modeling approach. In addition, the root mean square error (RMSE) was 0.036 m.

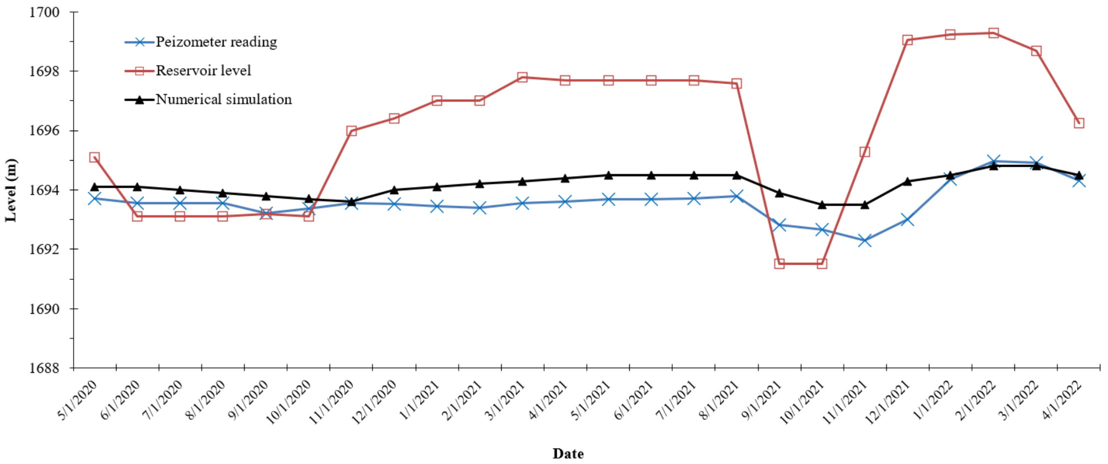


Figure 4. Comparison of total head obtained from numerical analysis with measured values in piezometer SP_1.

3. Results and Discussions

3.1. Equipotential Lines and Seepage Behavior

The dam body and its foundation are modeled in two cases. (i): dam without a cutoff wall and (ii): dam with a cutoff wall. The case (ii) alone includes 25 separate modes (Table 3).

Figures 5-8 show equipotential curves, the phreatic line, and seepage discharge under a 14 m upstream water head. The phreatic line represents the boundary between saturated and unsaturated soil, corresponding to points where pore water pressure equals atmospheric pressure. As observed in these figures, equipotential lines are concentrated within the clay core, significantly reducing water energy due to its low hydraulic conductivity relative to other dam materials. A similar concentration of equipotential lines is evident around the vertical cutoff wall, effectively reducing seepage through the dam body and foundation.

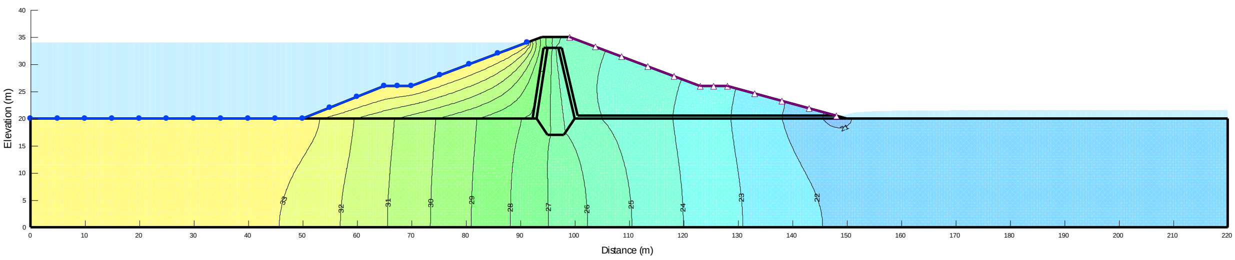


Figure 5. Cross-section of the dam showing equipotential lines without a cutoff wall.

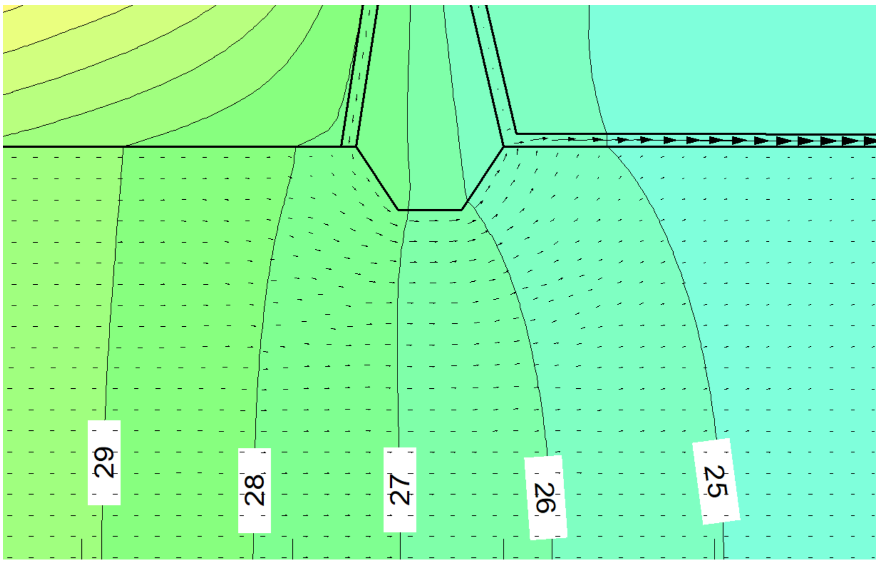


Figure 6. Water flow bypassing the clay trench under the dam clay core, showing (enlarged) velocity vectors

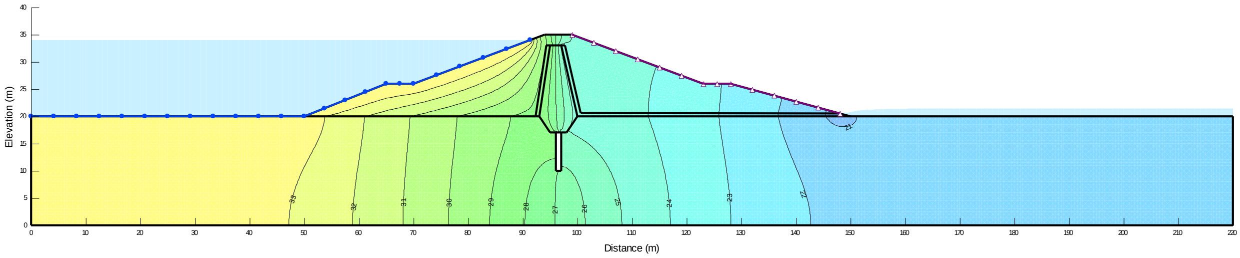


Figure 7. Cross-section of the dam showing equipotential lines including a cutoff wall (depth = 6 m and thickness = 1 m)

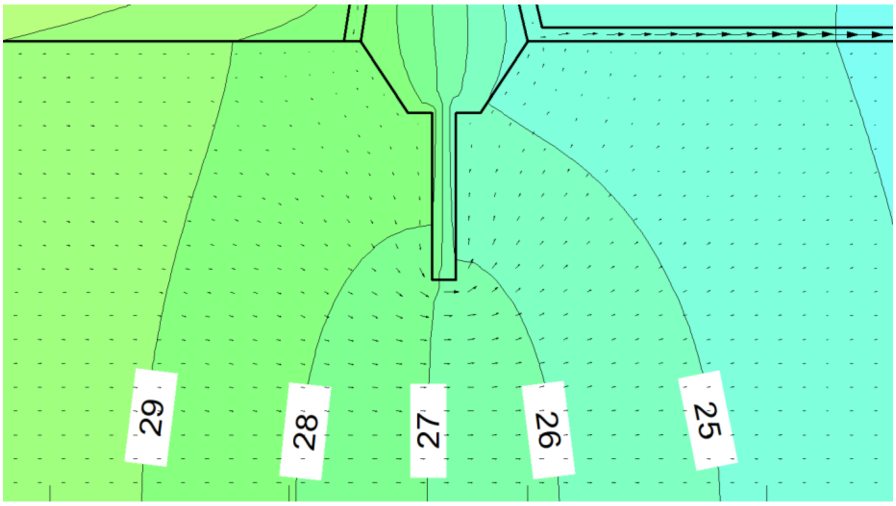


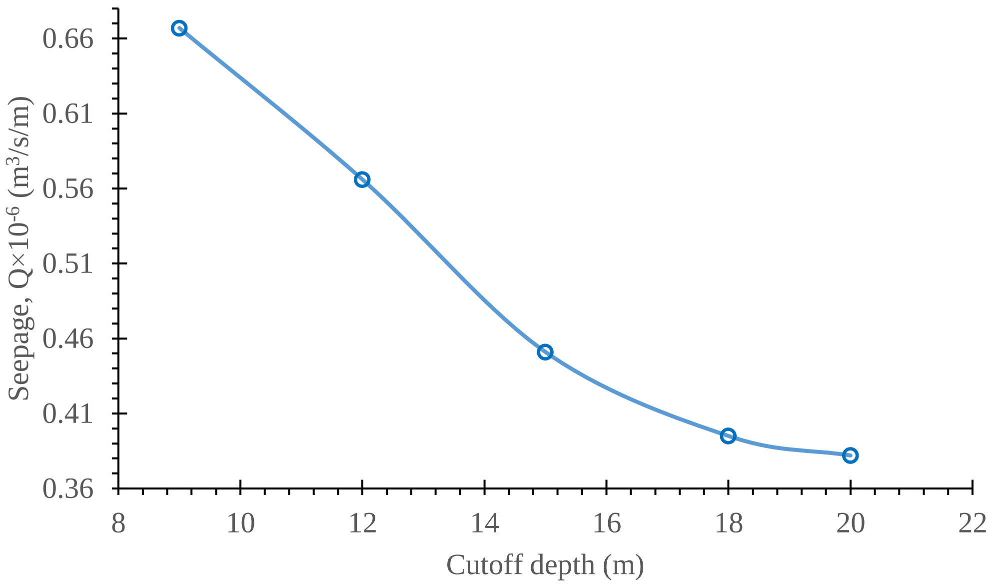
Figure 8. Water flow bypassing the dam cutoff wall under the clay core of the dam, showing (enlarged) velocity vectors (cutoff wall depth = 6 m and thickness = 1 m)

3.2. Seepage Analysis

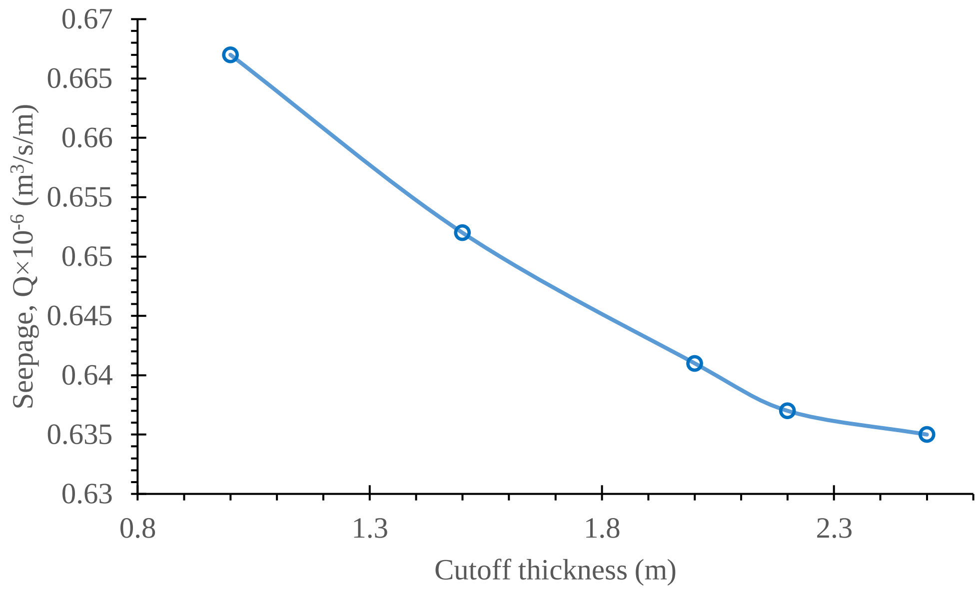
Figure 9 illustrates the influence of cutoff wall depth and thickness on seepage flow rate. Numerical modeling results demonstrated that wall depth exerts a more pronounced effect than cutoff wall thickness in reducing seepage. Increasing the cutoff depth from 9 m to 15 m resulted in a 53.4% reduction in seepage, whereas increasing the thickness from 1.5 m to 2 m produced only a 33.7% reduction. Depths greater than 15 m did not yield significant additional reductions, and seepage flow remained nearly constant. These findings suggest that a wall depth of 15 m represents an optimal design value, improving hydraulic performance while avoiding unnecessary construction costs.

With respect to the hydraulic gradient, a 15 m cutoff wall depth reduced the exit hydraulic gradient by 51.2%, whereas increasing the thickness to 2 m achieved only a 22.3% reduction. Furthermore, analysis of the uplift force indicated that increasing the wall depth to 15 m resulted in a 44.4% increase, whereas increasing the thickness to 2 m resulted in only a 3.8% increase. These values highlight the limited impact of the cutoff wall thickness compared to depth. Importantly, the observed changes do not negatively affect dam stability, as uplift forces are primarily controlled by the weight of the dam body.

The results of this study emphasize the importance of depth optimization in plastic concrete cutoff walls for earth dams. While increasing the cutoff wall thickness provides some improvement, depth is the dominant factor in controlling seepage and hydraulic gradients. Designing cutoff walls with an optimal depth of approximately 15 m can achieve significant hydraulic benefits without incurring unnecessary construction costs. These findings contribute to practical dam engineering by offering a reproducible framework for balancing hydraulic efficiency, structural stability, and economic feasibility. More broadly, the methodology applied here -numerical modeling validated against piezometer data- demonstrates a reliable approach for evaluating seepage control systems in similar earthen dam projects worldwide.



(a) Variation of seepage versus cutoff wall depth.



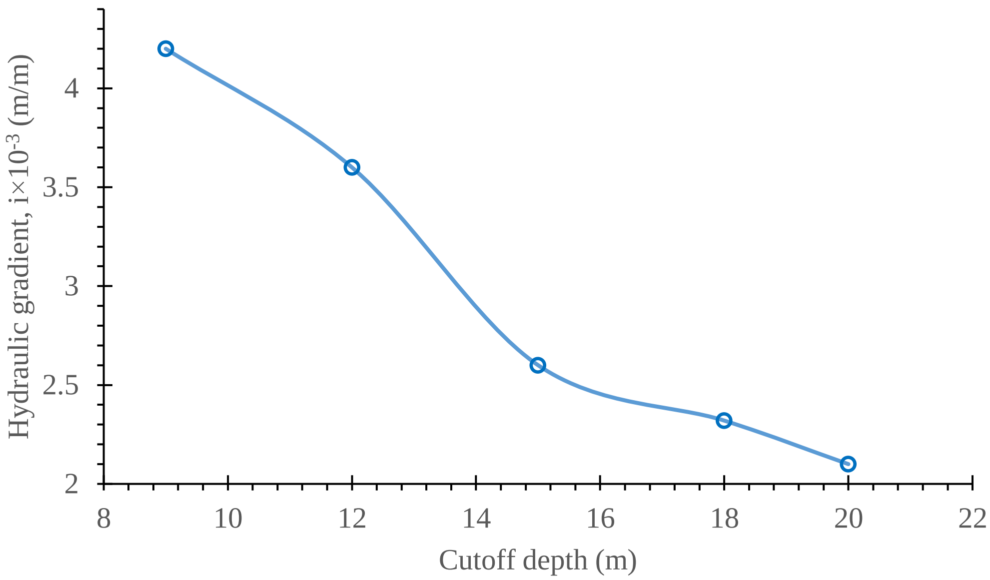
(b) Variation of seepage versus cutoff wall thickness.

Figure 9. (a) Effect of cutoff wall depth on seepage discharge; (b) Effect of cutoff wall thickness on seepage discharge.

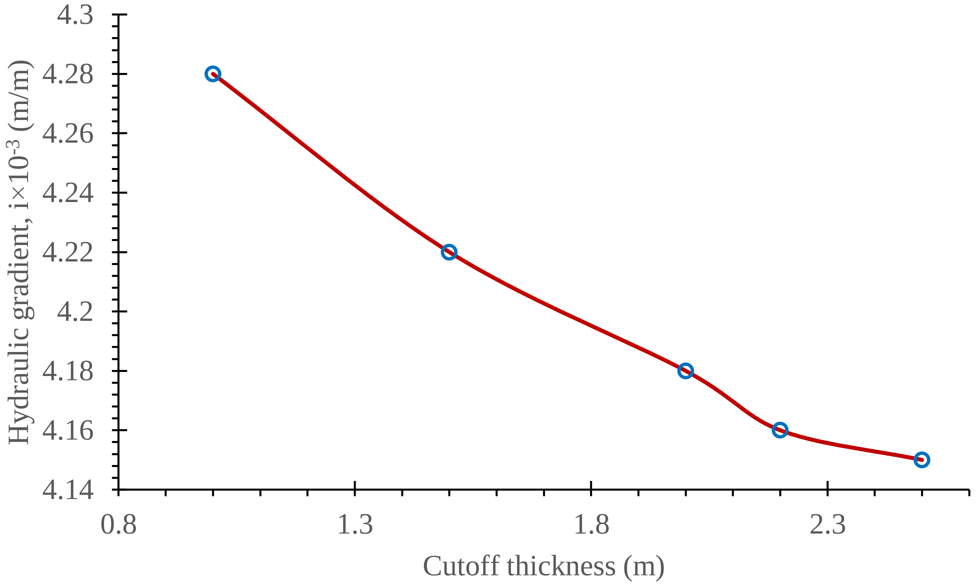
3.3. Hydraulic Gradient Analysis

Figure 10 presents the effect of cutoff wall depth and thickness on the exit hydraulic gradient. Hydraulic gradient (i) is defined as the ratio of the hydraulic head difference between two points to the flow path distance between them, a dimensionless parameter. When evaluated at the downstream toe of a dam, it is termed the exit hydraulic gradient and denoted by i_e.

Previous studies indicate that an exit hydraulic gradient greater than one can initiate the migration of sand particles, a progressive phenomenon that may extend from downstream to upstream and, in severe cases, lead to dam failure (Salmasi and Abraham, 2026; Karimzadeh et al., 2025). As shown in Figure 10 (a), increasing the cutoff wall depth to 15 m resulted in a 51.2% reduction in hydraulic gradient. Depths greater than 15 m did not produce significant additional reductions. Similarly, Figure 10 (b) demonstrates that increasing the cutoff wall thickness to 2m reduced the hydraulic gradient by 33.7%, with no noticeable improvement beyond this value.



(a) Variation of hydraulic gradient versus cutoff wall depth



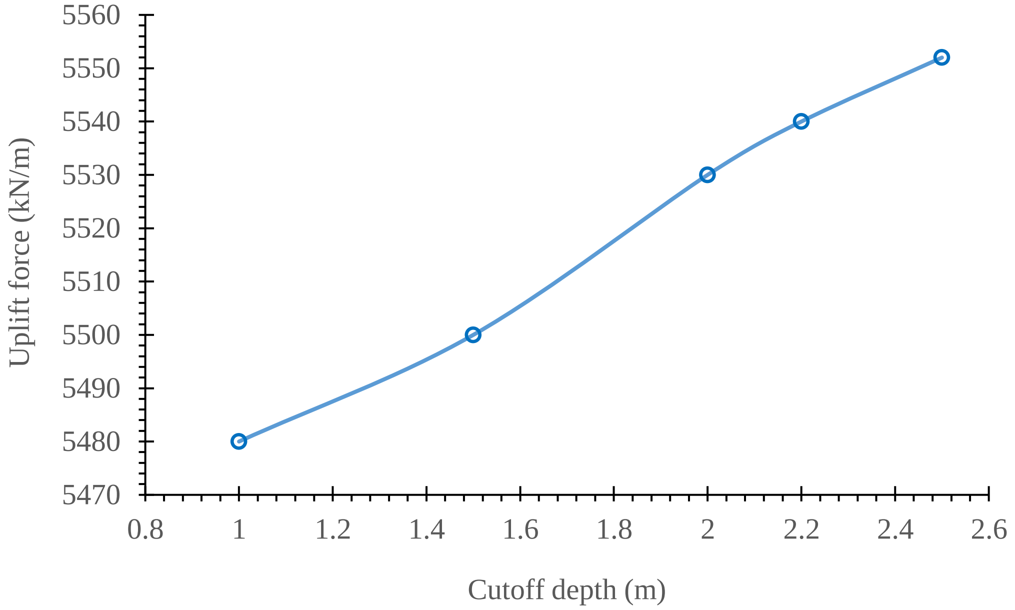
(b) Variation of hydraulic gradient versus cutoff wall thickness

Figure 10. (a) Effect of cutoff wall depth on hydraulic gradient; (b) Effect of cutoff wall thickness on hydraulic gradient.

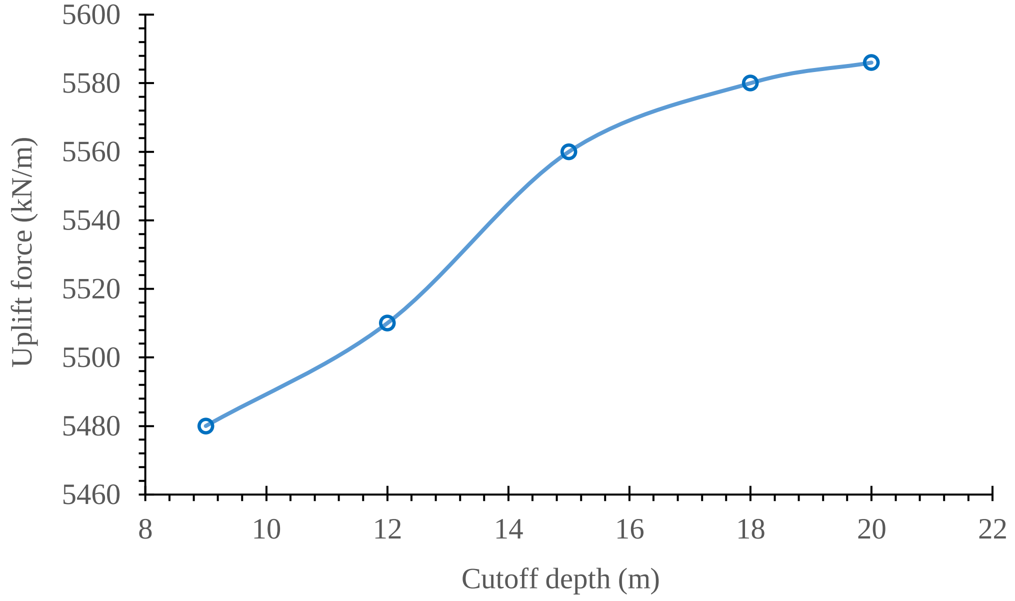
3.4. Uplift Force Analysis

Figure 11 illustrates the influence of the dam cutoff wall's depth and thickness on the uplift force. Uplift force is the upward force acting on a hydraulic structure due to pore water pressure in the foundation soil. This force reduces effective stress and may compromise stability (e.g., by promoting sliding or overturning). Its magnitude is derived from the pore water pressure distribution (PWPD) beneath the dam base, and the total uplift force is obtained by integrating this distribution over the base area.

As shown in Figure 11 (a), increasing the cutoff wall depth to 15 m decreased uplift force by 51.2%, with negligible changes beyond this depth. Figure 11 (b), indicates that increasing the cutoff wall thickness to 2 m reduced uplift force by 33.7%, with no significant improvement at greater thicknesses.



(a) Variation of uplift force versus cutoff wall depth



(b) Variation of uplift force versus cutoff wall thickness

Figure 11. (a) Variations in uplift force with dam depth; (b) Variations in uplift force with dam thickness.

Further analysis confirmed that increasing the cut wall depth from 16 m to 20 m and thickness from 2 m to 2.5 m had no significant effect on seepage, uplift force, or hydraulic gradient. This finding highlights that excessive increases in dam dimensions do not enhance hydraulic performance but instead raise construction costs.

3.5. Economic Optimization and Implementation Costs

A cost analysis demonstrated that properly selecting cutoff wall dimensions substantially reduces overall project expenses. Implementation costs include excavation, material transport, and placement of plastic concrete. Optimizing the cutoff wall depth and thickness improved hydraulic performance and reduced costs.

Figure 12 presents a bar chart of construction costs. Increasing the cutoff wall depth to 15 m reduced seepage flow by 53%, thereby lowering excavation and concrete placement costs. Increasing the cutoff wall thickness to 2 m reduced costs by 33%.

For example, excavation to a depth of 7 m with material transport over 500 m was estimated at 1.19×10^7 rials/m³. With a section length of 93 m, width of 1.5 m, and thickness of 1.5 m, the total excavation volume was 14.71 m³, yielding a cost of approximately 8.76×10^8 rials. The clay core, with a volume of 135.71 m³, was implemented at a unit price of 1.10×10^7 rials/m³, resulting in a total cost of 7.85×10^9 rials.

The final cost of constructing the cutoff wall was estimated at 8.53×10^9 rials, representing a significant reduction compared to conventional methods. This reduction was achieved through optimized geometric design, minimized excavation, and efficient material use.

The results demonstrate that optimizing the dam cutoff wall depth to 15 m and thickness to 2 m provides substantial hydraulic benefits while minimizing construction costs. Excessive increases in dimensions do not yield additional performance improvements and only raise expenses. Thus, careful adjustment of design parameters enhances both hydraulic efficiency and economic feasibility, contributing to the sustainable optimization of earth dam construction projects.

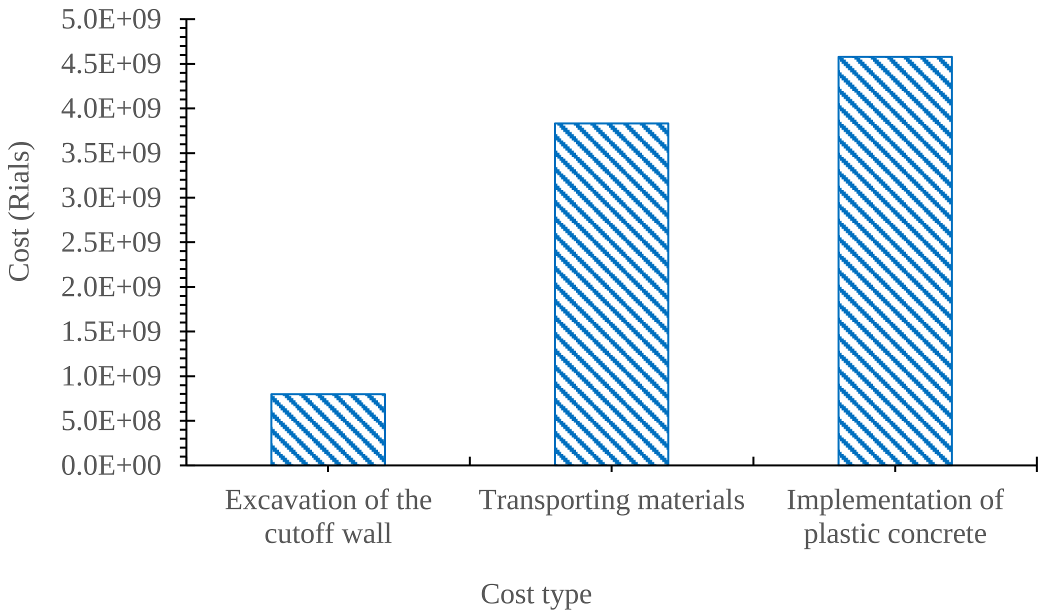


Figure 12. Bar chart of the estimated construction cost of the cutoff wall.

4. Conclusions

This study employed finite-element numerical modeling to investigate the effects of dam cutoff wall depth and thickness on seepage control, hydraulic gradient, and uplift force at the Geysaraq earthen dam. Results demonstrated that the cutoff wall depth has a greater influence than wall thickness. Specifically, a cutoff depth of 15 m reduced seepage discharge by 53.4%, whereas increasing the thickness to 2 m reduced seepage by only 7.3%. Increasing depth to 15 m or thickness to 2 m produced no significant improvement, confirming optimal values of 15 m depth and 2 m thickness. The 15 m cutoff wall depth reduced the outlet hydraulic gradient by 51.2%, while increasing the thickness to 2 m reduced it by 22.3%. Uplift force analysis showed a 4.4% increase with depth and a 3.8% increase with thickness, both of which had limited impact on dam stability, as the weight of the dam body and slopes primarily governs stability. From an economic perspective, optimization of cutoff wall dimensions resulted in a 53% reduction in excavation costs, a 33% reduction in additional costs, and overall savings of approximately 4.5×10^{10} rials. Water height analysis further indicated that increasing the dam height from 24.4 m to 31 m resulted in a 27% increase in seepage discharge, underscoring the importance of a balanced design. The 2025 price list confirmed that optimized drilling and plastic concrete implementation significantly reduced costs compared to conventional methods. In summary, excessive increases in cutoff wall depth and thickness do not improve hydraulic performance and only raise construction costs. Conversely, adopting the optimal values of 15 m depth and 2 m thickness enhances seepage control, improves hydraulic efficiency, reduces costs, and increases overall project productivity.

This study employed two-dimensional numerical modeling. Although the river valley geometry is irregular—suggesting that three-dimensional modeling could refine and extend results for future investigations—the current analysis assumed isotropic (homogeneous) soil properties. In practice, earth dams are constructed in layers (typically 5–7 cm thick), compacted to high density, which generally results in higher horizontal hydraulic conductivity than vertical conductivity ($k_x > k_z$). Therefore, future studies should consider anisotropic (non-isotropic) soil modeling. Nevertheless, uncertainty remains in accurately determining hydraulic conductivity due to the complex behavior of soil and its temporal seepage characteristics. Other recommended improvements include modeling unsaturated soil conditions, where hydraulic conductivity is not constant but varies with soil moisture content and matric suction.

Author Declarations

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code Availability: No custom computer code or software was developed specifically for this study.

Author Contributions

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Consent to Participate: Not applicable.

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Author Contributions: Farzin Salmasi conceived and designed the study, developed the methodology, and prepared the original draft of the manuscript. **John Abraham** performed the formal analysis and conducted the investigation. All authors contributed to reviewing and editing the manuscript and approved the final version for publication. **John Abraham** supervised the research and provided overall guidance throughout the study.

References

Beiranvand, B., Komasi, M. (2021). An Investigation on performance of the cut off wall and numerical analysis of seepage and pore water pressure of Eyvashan earth dam. Iran J Sci Technol Trans Civ Eng 45, 1723–1736 (2021). https://doi.org/10.1007/s40996-021-00613-y

Garcia A, López M, Ortega J. (2019). Climate variability impacts on dam sealing system performance: A multi-decadal analysis. Hydrol Process., 33(21):2795–2811.

Karimzadeh P, Salmasi F, Nourani B, Abraham J, (2025). Utilizing Gene Expression Programming Strategies for Estimating Relative Uplift Pressure Head at Key-Points Beneath Straight Horizontal Aprons, ISH Journal of Hydraulic Engineering, https://doi.org/10.1080/09715010.2025.2452574.

Kim H, Choi D, Jung S. (2021). Integrated experimental–numerical approach to optimize cutoff wall systems for dam foundations. Int J Numer Anal Meth Geomech. 45(12):1570–1592.

Lee, S., Cho, W., & Kim, H. (2010). The Effect of Cutoff Walls on Pressure Distribution in Dam Foundations. Journal of Soil Mechanics and Foundations Division, ASCE, 136(5), 589-596.

Liu D, Lin T, Gao J, (2023). Study on the influence of water level on earth dam reinforced by cutoff wall: A case study in Wujing Reservoir. Water. 15(1):140. https://doi.org/10.3390/w15010140.

Moharrami A, Moradi G, Hajialilue Bonab M, Katebi J, (2014). Performance of Cutoff Walls Under Hydraulic Structures Against Uplift Pressure and Piping Phenomenon, Geotechnical and Geological Engineering, 33(1):95-103, https://doi.org/10.1007/s10706-014-9827-7

Morris, H. J., & Wang, H. (2012). Impact of Cutoff Wall Thickness on Hydraulic Parameters of Dam Foundations. Journal of Geotechnical and Geoenvironmental Engineering, 138(5), 589-596.

Nourani, B., Salmasi, F. & Abraham, J. (2025). Investigating Seepage and Stability of Unsaturated Embankment Dams Under Transient Conditions. Transportation Infrastructure Geotechnology. 12(17), 1-27 (2024). https://doi.org/10.1007/s40515-024-00459-7

Nourani B, Salmasi F, Ghorbani MA, (2023). Development of a new hybrid technique for estimating of relative uplift force in gravity dams based on whale optimization algorithm, Journal of Hydraulic Structures, 9(1):43-62, https://doi.org/10.22055/jhs.2023.41889.1230

Pourghani S, Salmasi F, Nourani B, Abraham J, (2025). Investigation of effect capillary fringe in seepage characteristics of only saturated and unsaturated-saturated materials used in earthen dams, ISH Journal of Hydraulic Engineering, https://doi.org/10.1080/09715010.2025.2467654

Salmasi F, Nourani B, Abraham J, (2025). Effect of Unsaturated Soil on Seepage and Stability of Earthen Dam in Steady-State Conditions, Case Study (Doiraj Dam), Indian Geotechnical Journal, https://doi.org/10.1007/s40098-025-01208-4

Salmasi F, Abraham J, (2025). Pore-water pressure and seepage through earth dams (numerical case study: Doiraj Dam), ISH Journal of Hydraulic Engineering, https://doi.org/10.1080/09715010.2025.2467685

Salmasi F, Abraham J, (2026). Numerical simulation of water infiltration into soil and investigation of slope stability using the effect of different rainfall intensities, Modeling Earth Systems and Environment, 12:101, https://doi.org/10.1007/s40808-026-02745-4

Salmasi F, Norouzi R, Abraham J, Nourani B, Samadi S (2020). Effect of inclined clay core on embankment dam seepage and stability through LEM and FEM, Geotechnical and Geological Engineering, 38(S2), https://doi.org/10.1007/s10706-020-01455-7

Sharifi, S., & Moghaddam, M. (2018). Comparative Study of Cutoff Wall Performance under Various Hydraulic Conditions. Dams and Reservoirs, 28(2), 123-135.

Sharifi M, Hosseini S, Rahimi A. (2018). Comparative performance of dam cutoff walls under varying hydraulic conditions. Water Resources Management., 32(14):4679–4694.

Suzuki T, Yamamoto K, Saito M. (2005). Experimental and numerical evaluation of cutoff wall thickness on foundation hydraulics. Canadian Geotechnical Journal, 42(9):1524–1536.

Wang P, Zhao R, Sun W. (2020). Multi-parameter finite element assessment of cutoff wall depth effects on seepage and stability. Soil Dyn Earthq Eng., 137:106303.

Wang, Y., & Zhang, L. (2020). Numerical Analysis of Parameters Affecting Cutoff Wall Performance. Journal of Hydraulic Engineering, 146(2), 04019073.

Zhang W, Chen C, Xue B, (2024). Performance of plastic concrete cutoff walls under reservoir impoundment: Displacement and stress evaluation. J Hydraul Eng. 2024;150(6):04024025.