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OPTIMIZATION OF DRAINAGE SYSTEM GEOMETRY IN EARTH-FILL DAMS A NUMERICAL ANALYSIS OF SEEPAGE BEHAVIOR IN THE IRANIAN SAHAND DAM

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ABSTRACT

This study investigates seepage behavior for the Sahand Dam, which is an earth-fill embankment situated in northwestern Iran, using SEEP/W finite element analysis software. This research compares the effectiveness of various drainage configurations for maintaining seepage control and affecting pore water pressure distribution. The dam geometry was modeled with a mesh interval of 1.1 meters, together with material parameters and boundary conditions, in order to simulate steady-state seepage conditions. Tests were conducted to contrast without and with toe drainage conditions for discharge rates across different cross-sections and reservoir levels. The result shows a decrease in seepage discharge by 4% per meter of fall in reservoir level for both cases, the imposition of toe drains curiously raising the discharge rate by 1.5% due to longer hydraulic paths. The research also analyzed the impact of horizontal and vertical drain lengths, and concluded that 50 meters long horizontal drains were most economical despite having slightly greater discharge rates. Vertical drain performance was a function of height, with considerable control of seepage only when installed at maximum reservoir elevation. Horizontal drain thickness analysis also failed to demonstrate significant correlation with discharge rates with respect to configurations tested (0.5-1.5 meters), though 1-meter thickness was found to be most economical. Results of this are most indicative in terms of optimizing the drainage system design of earth-fill dams with respect to seepage behavior and that of the drainage structure.

Keywords: Earth-fill dam seepage, SEEP/W finite element analysis, Drainage system optimization, Pore water pressure distribution, Hydraulic conductivity modelling.

INTRODUCTION

Earth dams are critical types of infrastructure that are employed for storing water, controlling floods, and for intending irrigation purposes (Ayari et al., 2016; Bekhira et al., 2019; Aroua, 2020; Benslimane et al., 2020; Abd Rahman et al., 2023; Zegait and Pizzo, 2023; Baudhanwala et al., 2023; Remini, 2023; Ben Said et al., 2024). One of the most complex problems in the construction and management of earth dams is dealing with seepage (Toumi and Remini, 2006; Benfetta et al., 2016; 2017a; 2017b, Hariri Asli and Nazari, 2021), which can weaken the strength and safety of the dam. Seepage happens as a result of water passing through the dam's porous structures which causes some of the following issues: internal erosion, piping, and slope failure. Proper risk management of seepage is very important to the durability and safety of earth structures such as earth dams (Chabokpour, 2025; Chabokpour and Minaei, 2024). Through its extensive application in environmental and geotechnical engineering, the SEEP/W tool has proven to be successful. Its functions related to the simulation of groundwater and seepage makes it an important tool for models of seepage through dams, canals, foundation earthworks, and for other structures. These could be: levees which are critical in protecting flood-prone areas, and understanding seepage through these structures is essential for ensuring their long-term stability and effectiveness, foggaras which protect populations from the effects of floods (Remini, 2018; Remini, 2020a; 2020b; 2020c; 2020d), reservoirs for preventing and managing effects of floods whose integrity relies on accurate modeling of groundwater seepage to prevent water loss and maintain proper water storage levels (Hountondji et al., 2019; Hafnaoui et al., 2022; Mezenner et al., 2022; Gassi and Saoudi, 2023; Verma et al., 2023; Trivedi and Suryanarayana, 2023; Mehta et al., 2023; Shaikh et al., 2024), tunnels, especially those used for transportation or utilities, require careful monitoring of seepage to prevent structural damage and ensure water does not undermine their foundations, culverts, which allow water to flow under roads or railways, are designed to withstand seepage and prevent erosion, ensuring the stability of the surrounding infrastructure, embankments, which are used to control water flow and prevent flooding, must be designed with careful consideration of seepage to avoid erosion and maintain their effectiveness.

Gholami et al. (2012) studied seepage behaviors in the clay core of Karkheh Dam to advance knowledge about optimal dam engineering approaches. Ghorbani et al. (2013) studied Qazvin and Isfahan channel seepage through SEEP/W along with evolutionary polynomial regression for analysis. The research confirmed SEEP/W represents a powerful application for environmental hydraulic modeling. Using Khasa-Chai Dam as the subject Zedan et al. (2017) explored core seepage and soil permeability to enhance safety designs for dams. The Hub Dam in Pakistan received thorough investigation from

Arshad and Babar's (2014) case study about seepage. A comprehensive evaluation of SEEP/W simulations based on field observations showed that the software effectively predicts earthen dam seepage behaviors. Deka (2017) demonstrated SEEP/W successfully reduces water loss in lined canals through unsaturated seepage modeling. SEEP/W successfully helps identify and minimize safety risks from seepage through dams and foundations according to Khazaei (2014). Ziagharib (2024) demonstrated the validity of numerical models applied to landfill cover systems through SEEP/W while showing the program's value for geotechnical and environmental engineering practices. Asadi and Khazaei (2014) demonstrated that seepage modeling serves as a critical tool for improving both the stability of dams and the optimization of water management practices (Bahir et al., 2015; Bouly et al., 2019; Jayasena et al., 2021; Kezzar and Souar, 2024). Dolatkhah et al. (2015) implemented the SEEP/W simulation tool to evaluate seepage from earthen canals at Moghan which resulted in better irrigation efficiency. Faraji Sorbaghi et al. (2014) showed how SEEP/W works together with FLAC for computing seepage inspections in rock-fill dams. The study demonstrated that SEEP/W exhibits high accuracy levels when used to solve demanding problems in situations where water levels change. SEEP/W modeling predicted unsaturated seepage behavior in a lined canal as validated by Deka's (2017) research. A case study by Jamel (2016), examined seepage through homogenous earth dams built without filter elements. With SEEP/W applications researchers obtained exact seepage rate calculations which advanced the understanding of how dams behave in terms of safety and operation. In another study, Zedan and Faris (2017) evaluated seepage through the Khasa-Chai Dam, leveraging SEEP/W to predict seepage volumes under varying conditions, leading to recommendations for safe hydraulic designs.

Jamel (2018) achieved seepage discharge analysis through earth dams by implementing SEEP/W with artificial neural networks. Statistical results showed exceptional conformity between theoretical outcomes generated by SEEP/W and real-world observations. As part of Saleh's research in 2018 the analysis tool SEEP/W effectively modeled seepage behavior under a concrete dam foundation. The water viscosity response analysis of seepage through altered soils gained focus in environmental studies through Aribudiman et al. (2019) who used SEEP/W to simulate dynamic soil-water interactions. The analysis conducted by Paiva et al. (2019) demonstrated SEEP/W capabilities for assessing sustainable water management through its model of containment curtain effects on groundwater flow. The results derived from Oh et al. (2020) use of SEEP/W demonstrate its ability to analyze clay deposit instability alongside SLOPE/W to measure changes in pore water pressures. Taleb et al. (2025) utilized SEEP/W to optimize the seepage control and dam stability in earth dams by conducting comparative drain simulations involving horizontal and pipe drain systems.

Alongside versatility SEEP/W demonstrates its ability to analyze different aspects of seepage. SEEP/W simulation of Gotvand-Olya Dam seepage conducted by Karbala (2014) delivered important information for performing stability evaluations on the dam. Using SEEP/W simulations Hassan et al. (2024) evaluated the influence of drain pipes on slope stability performance in zoned earth dams to enhance safety improvements. Scientists at Paiva et al. (2019) utilized SEEP/W modeling to explore how containment curtains affected subterranean water flow paths. Research outcomes from this study enabled the design of structures that would promote sustainable water containment methods. Nordin et al. (2021) applied SEEP/W software to study how drawdown conditions affect failed levees at the Kerian River flood mitigation project. SEEP/W demonstrates its application in developing disaster prevention measures according to this investigation. Through an examination of Hilla Canal regulator seepage Mahdi and AI-Hadidi (2023) demonstrated SEEP/W operating capacity for investigating foundation infrastructure exposure to seepage effects. SEEP/W underwent implementation by Alwan and Al-Adili (2022) to examine the movement of water through clayey soils thus validating this simulation method for soil-water studies. Recent investigations show SEEP/W delivers important benefits for landfill operations. Ziagharib (2024) created a model to examine moisture change processes in sulfide soil waste site cover designs for minimizing environmental threats and preventing oxidation events. SEEP/W modeling platforms helped researchers investigate soil-water behavior across multiple environmental conditions.

The infiltration barrier design with the application of SEEP/W for mining dams was analyzed by Martins and Prinz (2024). The modeling of geosynthetic covers performed by the research shows the materials selected have an effect on performance and thus, is a step in the direction of optimized dam design. Mohajeri Afsharimoghadam, and Barati (2024) developed and analyzed processes for mitigating seepage in earth dams with the aid of the SEEP/W module. Their work of analysis focused on Shahid Yaghoubi and Maloo dams. Their work proved the software's potential in finite element analysis of water flow in the dams and provided ways for innovative solutions for mitigation. With analyses, SEEP/W has been used for understanding the stability of slope during intense rainfall regions extensively. Yusof et al. (2025) analyses proved that antecedent rainfall simulated with SEEP/W greatly influences slope stability at Teluk Bahang, including the potential for risk mitigation strategies involving delay during certain periods of the rainfall.

Numerous studies have employed SEEP/W software to investigate seepage behavior in different earth dams and hydraulic structures which established its effectiveness in predicting sophisticated flow structures and soil pressures. The optimizing procedures for drainage system arrangements remain unclear despite numerous researched seepage control approaches while drain shape variables yield unexpected effects on seepage rates. Using numerical modeling this research investigates seepage behavior changes in the Sahand Dam based on drainage configuration analysis by studying drain dimension effects on seepage discharge rates to establish practical design recommendations for earth-fill dam drainage systems.

METHODOLOGY

Introduction to GeoStudio

GeoStudio suite software employs finite element method (FEM) principles, well developed in (Amara and Berreksi; 2018; Amara et al., 2019), to deliver an extended platform for complex geotechnical along with geoenvironmental analysis solutions. Through its features users can accomplish extensive simulations which incorporate stress-strain analysis as well as rapid drawdown seepage calculations and slope stability examinations and dynamic assessments and thermal distribution simulations. The suite comprises specialized modules tailored to specific engineering challenges: Seven analysis tools power the GeoStudio 2023 software suite which include SIGMA/W for stress-deformation analysis and SEEP/W for modeling groundwater seepage together with SLOPE/W for assessing slope stability and QUAKE/W for dynamic and seismic applications in addition to TEMP/W for thermal regime assessments and CTRAN/W for contaminant transport modeling as well as VADOSE/W for tracking unsaturated soil responses to environment conditions such as solar radiation

SEEP/W operates as the Finite Element Method (FEM)-powered analysis instrument inside GeoStudio 2023 to evaluate enhanced water seepage processes and fluid flows within porous structures (Chetti et al., 2010; Ikni et al., 2017; Govindarajan et al., 2020). SEEP/W allows researchers to view various hydraulic measurements using visual representations of phreatic surfaces and velocity vectors and flow lines together with equipotential contours (Paulo Monteiro and Costa Manuel, 2004). The software delivers exceptional performance when measuring flow rates throughout soil segments in earth dams while effectively generating results for saturated and unsaturated flow conditions. The system delivers efficient solution of unconfined problems by implementing specialized algorithms which enable precise simulation of saturated-unsaturated flow at steady-state and transient stages. SEEP/W offers transient seepage modeling capability along with reservoir infiltration analysis features as well as evaluation tools for pore water pressure analysis and modeling rainfall infiltration. Users receive both pictorial outputs including flow nets as well as velocity distributions pictures and hydraulic head gradient visualizations together with computed discharge rates from defined cross-sections from this program. The combination of SEEP/W's essential features establish this tool as a vital component for engineering practitioners who focus on geotechnical and hydrological applications especially in evaluating seepage control systems for dams alongside levees and landfills. The combination of saturated-unsaturated flow theory with FEM results in accurate prediction capabilities for complex groundwater responses across multiple environmental and operational scenarios.

Field study area, Sahand dam and its instrumentation system

The Sahand Dam is an earth-fill embankment structure with a clay core, constructed on the Qaranqu Chay River, a tributary of the Qezel Uzan River in northwestern Iran. The engineers built the dam as a vital component for managing local water resources because it controls water flow while supplying irrigation for Hashtroud's western agricultural plains. The 47-meter-tall dam rests on alluvial land and stores 165 million cubic meters of water at its normal operational levels which generates 99 million cubic meters per year for agricultural and municipal uses. The top stone framework stretches 450 meters long and measures 10 meters wide while the enclosed reservoir stretches 10 kilometers along its length and creates 10 square kilometers of water surface. The geographical position of this dam measures 37°25' N, 46°53' E through Gurchenloo historical village on Mount Sahand eastern slope within East Azarbaijan Province. The reservoir inundates lands spanning longitudes 46°45' E to 47°06' E and latitudes 37°19' N to 37°40' N, approximately 26 kilometers southwest of Hashtroud and 65 kilometers southeast of Tabriz. The dam is located in a valley composed of igneous and sedimentary rocks, necessitating rigorous engineering to address geological and hydrological challenges (Fig. 1).

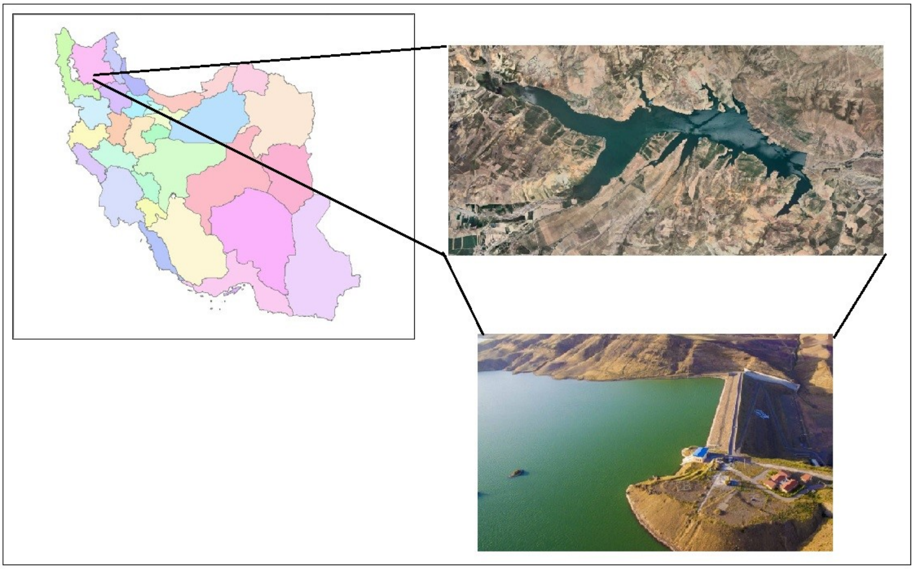

Figure 1: Geographical location of field study area (Sahand Dam)

To maintain the construction and operational safety standards of the dam, a unique system has been incorporated to keep track of its conditions. To help with this, the dam has embedded piezometers within its body and foundation, and also set inclinometers which continuously monitor the slopes for any possible deformations or instabilities. Once gathered, these measurements are useful for estimating the pore water pressures within the dam, as well as the leakage rates using the seepage measurement devices set on the downstream. Together with these, settlement gauges are used to monitor the vertical displacement which the embankment undergoes. The meteorological stations set next to the reservoir are key for monitoring the precipitation received within the area, as well as for estimating the evaporation rates. With the support of hydrological models, these data can be helpful for formulating a strategic plan. Aside from that, the monitoring network set can be helpful in analyzing the risk that comes along with sedimentation, seismic activity, and hydrological changes from season to season. The data from all the instruments set can be utilized and interpreted to make changes and adjustments to the maintenance plans of the dam, and ultimately the operation of the hydraulic system and environmental system.

Modeling the Sahand dam in GeoStudio software

Computational modeling starts with selecting precise input parameters which require logical assumptions and dependence calculations. The first critical step to model the Sahand Dam demands the establishment of structural geometry that includes slopes, crest measurements, and specifications about filter systems and drain elements. The material properties and their constitutive models are established after hydraulic boundary conditions have been determined. The initial simulation model maintains a steady-state flow system which requires precise boundary conditions at both the downstream dam axis and toe drain locations. A finite element mesh divided the structural dam shape in GeoStudio (Fig. 2). The simulation model used a 1.1 meter mesh to improve precision but sensitivity tests showed seepage results remained consistent across mesh sizes from 1 to 5 meters.

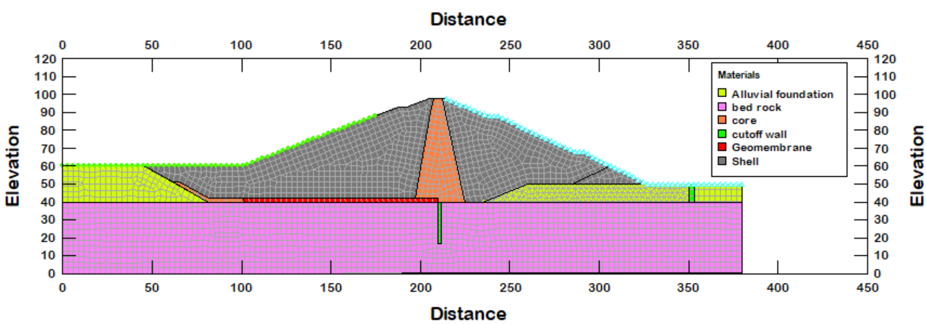

Figure 2: Geometric configuration of Sahand Dam in SEEP/W software including different parts

A summary of hydraulic conductivity values (Kx) for the dam materials appears in Table 1. Earthfill elements exhibit varying permeability measurements which highlight the anisotropy nature between embankment and foundation soil layers.

Table 1: Hydraulic conductivity of materials which is used in the Sahand dam

Material	Kx (m/s)
Shell	5×10^{-7}
Core and Blanket	1×10^{-8}
Alluvium	1×10^{-5}
Rock Foundation	5×10^{-7}
Geomembrane	1×10^{-10}

The upstream boundary of the model was assigned a fixed hydraulic head equivalent to the reservoir's operational water level to simulate steady-state seepage. At the downstream boundary, the water table was defined as a free surface in contact with the ground, reflecting natural drainage conditions. Additionally, a zero-pressure head boundary condition was applied to the toe drain region to represent its full drainage capacity, ensuring unimpeded discharge of seepage water. These boundary conditions collectively enabled the accurate simulation of pore water pressure distribution, flow pathways, and seepage rates through the dam structure under steady-state scenarios.

RESULTS AND DISCUSSION

Following the numerical modeling of the Sahand Dam using SEEP/W software, the seepage discharge rates at various elevations and pore water pressure distributions were analyzed for two scenarios: (1) without a toe drain and (2) with a toe drain. Simulation models assessed the modification of seepage discharge in the dam axis space through drainage installations at different drain depths and orientation configurations. This simulation aimed to evaluate operational performance results of the dam under these two conditions through seepage analysis and pore pressure evaluation.

The illustrations of Figs. 3 and 4 show the design format of the modeled dam reservoir and its phreatic surface height variations across different operational conditions. Minimal phreatic line variations occur inside the Sahand Dam which possesses a zoned embankment construction with low-permeability clay core material. Without a toe drain model shows an elevated phreatic surface which indicates higher water content inside the dam structure. The flow vectors in Fig. 4 (model with a toe drain) show significant direction change toward the drain which demonstrates the drain's effectiveness for lowering phreatic surface elevation and decreasing seepage-induced pore pressure.

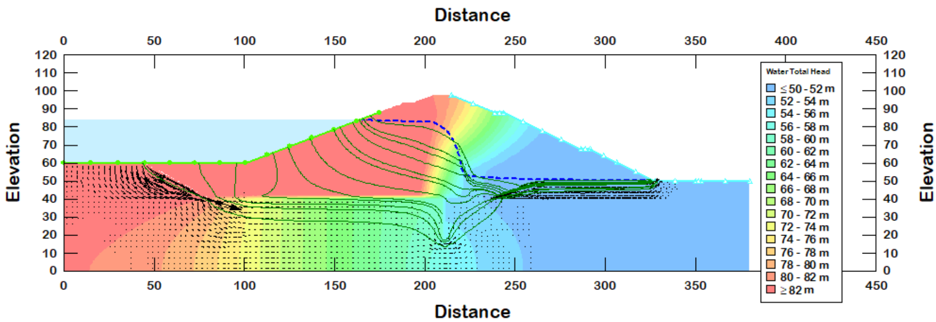

Figure 3: Results of the seepage analysis model without a drainage system

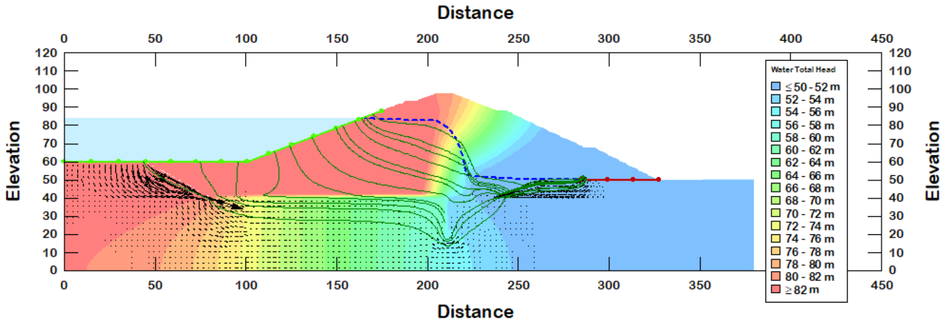

Figure 4: Results of the seepage analysis model with a drainage system

The toe drain reduced seepage discharge substantially through concentrated vector movements toward the drain channel. The performance of horizontal and vertical drains depended heavily on geometric parameters such as drain thickness. The research measured the link between drainage thickness dimensions and seepage flow rates then applied the findings for designing efficient drainage systems at affordable costs. The research demonstrates the crucial importance of drainage systems to reduce seepage hazards and secure long-term structural stability for earth-fill dams when subjected to operating forces.

Analysis of seepage discharge was performed for three predefined control sections (displayed in Fig. 5) throughout the dam structure under two operational conditions (both with and without a rock toe drain) at various elevation points; results tabulated in Tables 2 and 3. The testing produced a 4% decreased seepage rate for each meter drop in the reservoir sea level under both testing conditions. Results demonstrated a persistent 1.5% increase in discharge among rock toe drain installations above no-drain controls during observation periods despite reservoir elevation changes. Computational software restrictions produced slight differences in discharge values across equal elevation points but theoretical agreement was expected. Discharge reached its peak at the normal operating reservoir height of 1590 meters since the applied seepage principles controlled the drainage flow. Rock toe drains which are designed to address pore water pressure and seepage sometimes lead to increased discharge because they create longer flow paths which enhance permeability. Drainage engineering constructions for embankment dams produce complex interactions that shape seepage responses according to research findings.

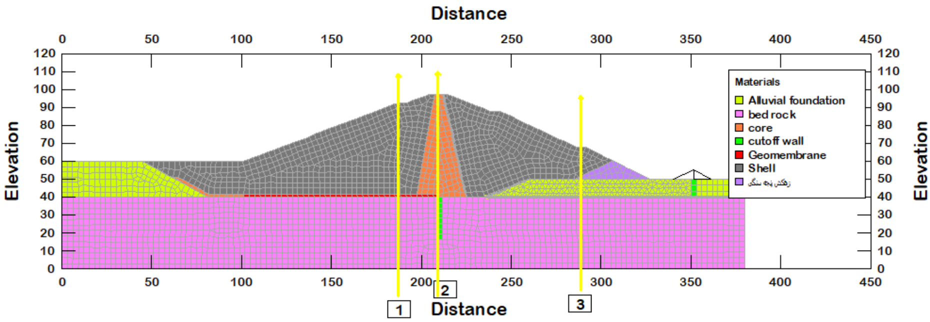

Figure 5: Location of selected cross sections for extraction of flow parameters

Table 2: Obtained discharge values from software analysis without toe drainage at different reservoir levels

No.	Reservoir Level (h, m)	Discharge at Section 1 ($\times 10^{-4}$)	Discharge at Section 2 ($\times 10^{-4}$)	Discharge at Section 3 ($\times 10^{-4}$)
1	1590	5.2240	5.1441	5.2240
2	1589	5.0473	4.9697	5.0473
3	1588	4.8725	4.7973	4.8725
4	1587	4.6996	4.6267	4.6996
5	1586	4.5286	4.4580	4.5286
6	1585	4.3591	4.4909	4.3591
7	1584	4.1914	4.1255	4.1914
8	1583	4.0251	3.9615	4.0251
9	1582	3.8606	3.7993	3.8606
10	1581	3.6974	3.6385	3.6974

Table 3: Obtained discharge values from software analysis with toe drainage at different reservoir levels

No.	Reservoir Level (h, m)	Discharge at Section 1 ($\times 10^{-4}$)	Discharge at Section 2 ($\times 10^{-4}$)	Discharge at Section 3 ($\times 10^{-4}$)
1	1590	5.3007	5.2196	5.3007
2	1589	5.1213	5.0426	5.1213
3	1588	4.9440	4.8677	4.9440
4	1587	4.7685	4.6945	4.7685
5	1586	4.5950	4.5235	4.5950
6	1585	4.4231	4.3539	4.4231
7	1584	4.2529	4.1860	4.2529
8	1583	4.0842	4.0197	4.0842
9	1582	3.9172	3.8551	3.9172
10	1581	3.7516	3.6918	3.7516

Quantitative analysis of pore water pressure at the critical section of the dam with and without toe drainage

Primary evaluation and monitoring methods for assessing pore water pressure inside the dam body occur through three control sections. The research demonstrates that the position of the phreatic line changes only marginally throughout the dam body between conditions with proper drainage systems and scenarios without drainage systems. When drainage exists the downstream section shows a significant trend toward the drainage paths through changes in both contour lines and flow patterns.

This report demonstrates the variations in pore water pressure throughout three separate sections with drainage and without drainage as illustrated in Figs. 6 and 7. The graphical representations base their measurements on 'y' to show the elevation heights recorded from the control section inside the dam body. Fig. 6 shows the distinct pore water pressure distributions that occur between the three sections when drainage measures are absent.

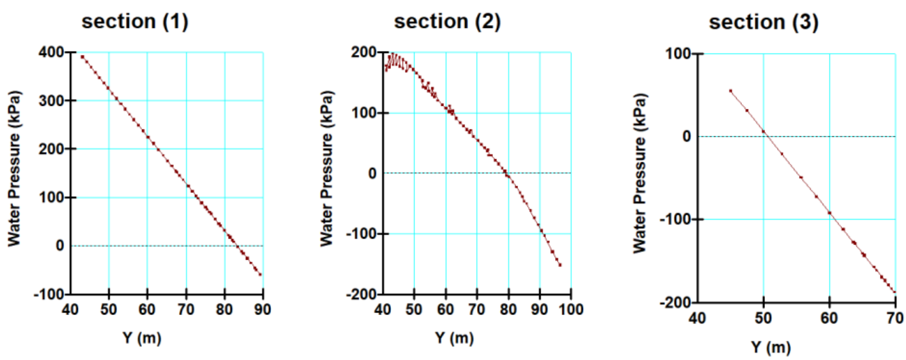

Figure 6: Distribution of pore water pressure across three distinct sections under no-drainage conditions

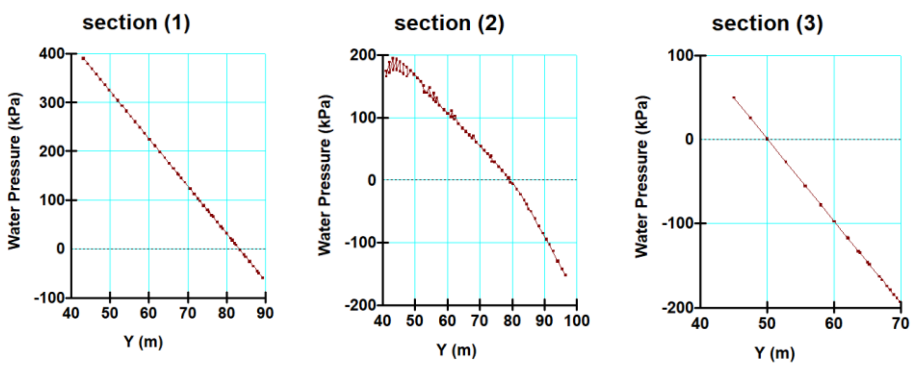

Figure 7: Distribution of pore water pressure across three selected sections under drainage conditions

The pore water pressure measurements show a linear distribution pattern existed when the control section contained soil with uniform characteristics. The direction of pore water pressure depends mostly on how permeable each soil zone becomes. Under the drainage conditions of Section Three researchers observed positive pore water pressure extending twenty meters from the surface to a depth of fifty meters where the control section maintains elevation below the drainage zone. Conversely, at higher elevations above the phreatic line (suction zone), the pore water pressure transitions to negative values.

Horizontal drain length analysis

The no-drain condition leads to the highest permeability rate of 5.2240×10^{-4} m³/sec found at the normal reservoir elevation of 1590 m. To further evaluate drain efficacy, the influence of horizontal drain length was investigated under three configurations: minimum (40 m), intermediate (50 m), and maximum (60 m). The minimum length functioned as the essential minimum to stop phreatic line intersection of the downstream slope while providing protection equal to the capillary rise height of the soil. Simulation tests of seepage discharge revealed minimal differences in seepage levels when using the shortest horizontal drain length of 40 meters versus keeping the site undrained. Extending drain length up to 50 m and 60 m intensified seepage discharge rates through the increased concentration of flow vectors and lowered elevation of the seepage line. The modified water flow path concentrates passage through maintained sections while boosting discharge capacity. When the drain length increased from 40 m to 60 m the overall seepage discharge grew by 0.3 m³/day. The 50 m drain proved to be the best choice because it provided both good drainage performance with the lowest cost. The results underscore a paradox: Vertical drains help reduce seepage but their extended length creates faster flowpaths and therefore stimulates enhanced water discharge. The findings stress how drain geometry optimization must combine economic goals with hydraulic control measures within heterogeneous embankment dams.

Vertical drain length analysis

Researchers methodically studied how drain height affects seepage flow and the movement of the phreatic line. Two configurations were evaluated: (1) a drain height below half of the water level elevation and (2) a drain height equivalent to the maximum reservoir elevation. Sample drains with a low installation height of 12 m showed no noticeable changes to discharge rates and phreatic line positions. The seepage risk reduction occurred exclusively when vertical drain height-maintained alignment with maximum reservoir elevation. An increase in vertical drain height from 12 m to 24 m in heterogeneous embankment dams permitted a shift in discharge levels by 0.4 m³/day due to improved flow connections between the core material and drainage network. The effect of horizontal drain thickness on downstream slope seepage dynamics was analyzed for three scenarios: 0.5 m, 1 m, and 1.5 m. The test results showed that no detectable relationship existed between drainage thickness and key operating parameters of flow vector distribution and discharge rate and saturation height reduction. The subject behavior was apparent because the drain acted as the major flow pathway and additional thickness operated at the same level as a narrow channel yet sparse thickness proved inefficient for capturing peripheral water movements. The combination of hydraulic performance evaluation with financial feasibility led to selecting a 1 m material thickness as the most economical yet efficient seepage control solution.

CONCLUSION

The comprehensive examination of seepage behavior in the Sahand Dam, conducted using the SEEP/W software, has provided several key findings that enhance our knowledge about the optimization of drainage systems in earth-fill dams. The research proves that drainage systems are critical for seepage control, but their application depends on thorough analysis of a series of geometric and hydraulic parameters in an effort to achieve maximum efficiency. The apparent paradox in drainage system and seepage rate interaction, as manifest in the 1.5% rise in discharge rates following the toe drain installation, belies expectations of drainage system design. The investigation of horizontal drain configurations discovered that intermediate lengths (50 meters) provide the optimum economic solution if not the greatest minimization of seepage. The finding highlights the need to harmonize engineering performance with economic considerations in dam construction. Vertical drain height investigation proved that efficiency is mostly realized where drain height is equal to maximum reservoir elevation, with drains of smaller height having little effects on seepage control. This information is useful in guiding future rehabilitation and dam design operations. Analysis of variations in drain thickness (0.5-1.5 meters) indicated that above 1 meter thickness, further thickness causes diminishing returns in seepage control and the presence of an optimal thickness from a practical standpoint. The patterns of pore water pressures distribution in various sections of dams documented in this study hold important information for monitoring and maintenance of stability of dams, especially in heterogeneous embankment dams. These results are of particular relevance to the operation and design of earth-fill dams, with drainage system optimization attempting a balance between efficiency in seepage control and cost of construction. Future study is suggested that examines the long-term behavior of such drainage configurations over different operating regimes and the influence of climate change on seepage characteristics. In addition, development of more sophisticated numerical models that account for transient flow conditions can greatly enhance our understanding of seepage dynamics in complex dam structures. This comprehensive study investigates the complex dynamics of erosion in rockfill structures such as gabion baskets and rip-rap. Utilizing advanced computational fluid dynamics (CFD) simulations, the research elucidates the multifaceted factors influencing erosion initiation and progression, both upstream and downstream of these structures. The study emphasizes the critical roles of granulometry in both the rockfill material and the erodible bed, as well as the characteristics of flow passing through and over the structure. Through detailed analysis of velocity distributions, hydrostatic pressure patterns, scour depth evolution, and turbulent kinetic energy, the research provides insights into the formation of high-velocity zones, pressure gradients, and turbulence-induced erosion. The simulations reveal the gradual development of scour holes, particularly downstream of the structures, and the impact of flow characteristics on bed morphology changes over time. By examining various scenarios with different rockfill sizes and water depths, the study demonstrates how these parameters influence flow patterns and erosion rates. This research not only enhances our understanding of the hydraulic and geomorphological processes at play but also offers valuable guidance for the design, optimization, and maintenance of rockfill structures in riverine environments. The findings underscore the importance of considering both the structural properties of the rockfill and the dynamic nature of the surrounding flow in ensuring the long-term stability and effectiveness of these erosion mitigation measures.

Declaration of competing interest

The authors declare that they have no know competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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