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Efficacy of Advanced Seepage Mitigation Techniques in Earth Dams: A Case Study of Shahid Yaghoubi and Maloo Dams

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Abstract

Effective seepage management is crucial for the structural integrity and operational safety of earth dams. This paper presents a detailed evaluation of seepage control strategies implemented at the Shahid Yaghoubi and Maloo dams in Khorasan Razavi province, Iran. Our study utilizes hydrological and structural data to assess the impact of specific interventions. For this purpose, numerical analysis methods and commercial GeoStudio software have been used. At the Shahid Yaghoubi dam, the application of a geomembrane on the upstream face resulted in a 15% reduction in seepage flow, while the addition of a cut-off wall downstream of the dam core led to a 35% decrease in seepage. Despite these improvements, the critical hydraulic gradient in the downstream drain remained unchanged, underscoring the complexity of seepage dynamics within dam structures. Similarly, at the Maloo dam, the installation of a geomembrane and the modification of the cut-off wall height beneath the dam core achieved reductions in seepage of 6% and 25%, respectively. These results highlight the importance of tailored, site-specific adaptations in effectively managing seepage. This research provides significant insights into the optimization of seepage control measures, contributing to the development of more durable and safer earth dam structures.

Keywords: Earth Dam Safety, Seepage Control, Hydraulic Engineering, Geomembrane Application, Cut-Off Wall Optimization.

1. Introduction

Water management is an important issue in arid and semi-arid areas (Nassery et al., 2017; Koohbanani et al., 2018; Mirani Moghadam et al., 2021). Earth dams are crucial for water storage and supply across various regions, but their integrity is often compromised by seepage, the flow of water through the dam's body or foundation (Mortazavi and Soleimani, 2015; Ahadiyan et al., 2022). Understanding the dynamics of seepage is vital for effective dam safety management. Innovative studies help refine our understanding and mitigation strategies for seepage. For instance, Ahadiyan et al. (2022) focused on the effects of soil properties and the rip-rap on the breaching process and the failure mechanism of the levee. Their results indicated the crucial role of the riprap coverage and the soil properties in the breaching of the protective levees. Using the Finite Element Method, Haghdoost et al. (2023) analyzied the effects of penetration depth, distance from the beginning of the crest width, and inclination angle of the internal cutoff wall on the design parameters in an embankment dam.

Seepage within earth dams occurs under both steady and transient flow conditions (Reddi, 2003). The steady-state flow, often established a few years post-dewatering, is described by the governing equation (Das, 2019):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = 0 \tag{1}$$

In Eq. (1), h is a function of the piezometric head, expressed in terms of x and y. Also, k_x and k_y are soil permeability coefficients in horizontal and vertical directions. It should be noted that steady state flow will be established in the body or foundation of the dam when the reservoir (headwater) level is more or less constant. These conditions usually occur after a few years of the dam dewatering (Aboelela, 2016). In contrast to the steady-state flow, the water's height at any point changes with time in transient flow. When an earth dam is completely drained, the water's height in the core increases. This process continues until the core's water level reaches the free water line (phreatic line). This line shows the free surface of the water and represents the process of water level drop in the core (De Wrachien, 2009).

Note that usually, due to the discharge of the dam reservoir, the water level in the reservoir will rise and fall. In this case, the water level in the core will change slightly due to these changes (Aboelela 2016). In most cases, these changes are ignored because the dam's core is very impermeable. In contrast, transient flow conditions, characterized by varying water levels in the dam core, are governed by (Das 2019):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = c \frac{\partial h}{\partial t} \tag{2}$$

In Eq. (2), the expression $\partial h/\partial t$ on the right side of the equation indicates that the piezometric head will change with time, and the flow will be transient. In the past, different methods were introduced to solve the Laplace equation (Das, 2019). These methods include physical modeling, preparation of a similar electrical model or similar thermal model, and flow net drawing method. In recent years, the mentioned methods have become obsolete with computer software development, and the numerical analysis method has replaced them (Haghdoost et al., 2023, 2024; Memarian et al., 2023; Asadi and Khazaei, 2014; Chen et al., 2008).

In recent decades, finite element and finite difference methods have played a crucial role in advancing dam seepage studies, refining dam engineering strategies and others issues of river engineering (e.g. Krahn, 2004; Soleimanbeigi and Jafarzadeh, 2005; Aufleger et al., 2005; Pakbaz et al., 2009; Barati et al., 2012; Tajnesaie et al., 2020). Early foundational insights from Johansson (1997) and innovative monitoring techniques by Côté et al. (2007) set the stage for further developments. Fu and Sheng (2009) and Chen et al. (2008) tackled complex seepage issues with robust numerical solutions, enhancing the accuracy of drainage system characterizations. Building on this, Liu and Chiew (2014) studied the impact of injection on bedload transport in seepage contexts. Continuing this evolution, Siacara, Beck, and Futai (2020), Siacara et al. (2021) and Siacara et al. (2022) introduced a series of studies from 2020 to 2022 that integrated seepage analysis with dam safety assessments using advanced computational tools. These contributions significantly enhance the precision and reliability of seepage and safety evaluations in dam engineering.

Building on foundational studies, this research addresses critical gaps in the application of seepage control strategies, focusing particularly on the Shahid Yaghoubi and Maloo dams. Although previous researches, including the work of Chen et al. (2008), have effectively implemented techniques such as cut-off walls and permeability modifications, these strategies have not been specifically tailored to the unique conditions of these dams. The majority of these studies have relied on oversimplifying the complex interactions and seepage behaviors specific to individual dam structures.

In response to these limitations, this study aims to advance the field by employing both historical data analysis and cutting-edge computational modeling. By leveraging detailed data from 2021, this research will elucidate current seepage issues at the Shahid Yaghoubi and Maloo dams and evaluate the effectiveness of various seepage mitigation strategies within this specific context. This approach is inspired by the methodologies developed by Siacara et al. (2021) and Fu and Sheng (2009), which emphasize the importance of tailored, site-specific modeling in understanding and managing seepage. The expected outcomes include refined seepage models and the development of customized mitigation strategies that are both economically viable and technically effective. This novel contribution will significantly enhance the sustainable management and operational safety of earth dams, promoting greater resilience against seepage-related challenges.

Consequently, this research introduces several innovations, including: modeling the seepage problem in two constructed earthen dams through detailed numerical simulations and examining the technical and economic aspects of current solutions to optimize seepage performance based on real data.

2. Methodology

This study employs the GeoStudio 2012 software, specifically utilizing the SEEP/W module (Krahn, 2004), to analyze seepage through the body and foundation of two earth dams, Shahid Yaghoubi and Maloo. In the SEEP/W simulation, materials are assigned with the permeability coefficients in Tables 1 and 2, and the model undergoes meshing to divide it into smaller elements. Fine meshing is used in the core, filter, and drain sections for improved accuracy. Conditions are selected along with the desired lines from the dam body and its upstream and downstream for allocation. Finally, sections are drawn to calculate the discharge, with the program determining outlet discharge by calculating the water speed through the section and its area.

The methodology adopted for this analysis involved an initial validation phase for each dam. For the Shahid Yaghoubi dam, verification was conducted using actual seepage data recorded by onsite operators, while for the Maloo dam, piezometric data was utilized. Following validation, the study compared the seepage levels from the body and foundation of each dam under different scenarios: one with a geomembrane layer applied to the dam body and another with a cut-off wall installed beneath the clay core (Kiyani et al., 2024).

Based on these comparisons, the study proposes the most effective seepage mitigation solutions tailored to each dam's specific conditions. The subsequent sections of this paper will detail the results and effectiveness of these seepage reduction strategies, drawing on comprehensive instrumentation, measurements, and observations collected from the two case studies.

Table 1. Permeability coefficients of Shahid Yaghoubi dam materials

Part	Hydraulic permeability (m/s)
Core	4.59×10^{-8}
Drain	8.79×10^{-3}
Shell	9.82×10^{-5}
Filter	8.77×10^{-5}
Foundation	7.88×10^{-5}

Table 2. Permeability coefficients of Maloo dam materials

Part	Hydraulic permeability (m/s)
Core	1.12×10^{-7}
Drain	9.88×10^{-3}
Shell	9.97×10^{-4}
Filter	5.24×10^{-4}
Foundation	8.91×10^{-5}
Cut-off wall	10^{-8}

3. Analysis of Shahid Yaghoubi dam

The Shahid Yaghoubi Dam, a rockfill structure with a clayey core, has been operational since 1997. This dam is strategically located in the Khorasan Razavi province, near Torbat Heydarieh city. Figure 1 illustrates the dam's location and its access routes.

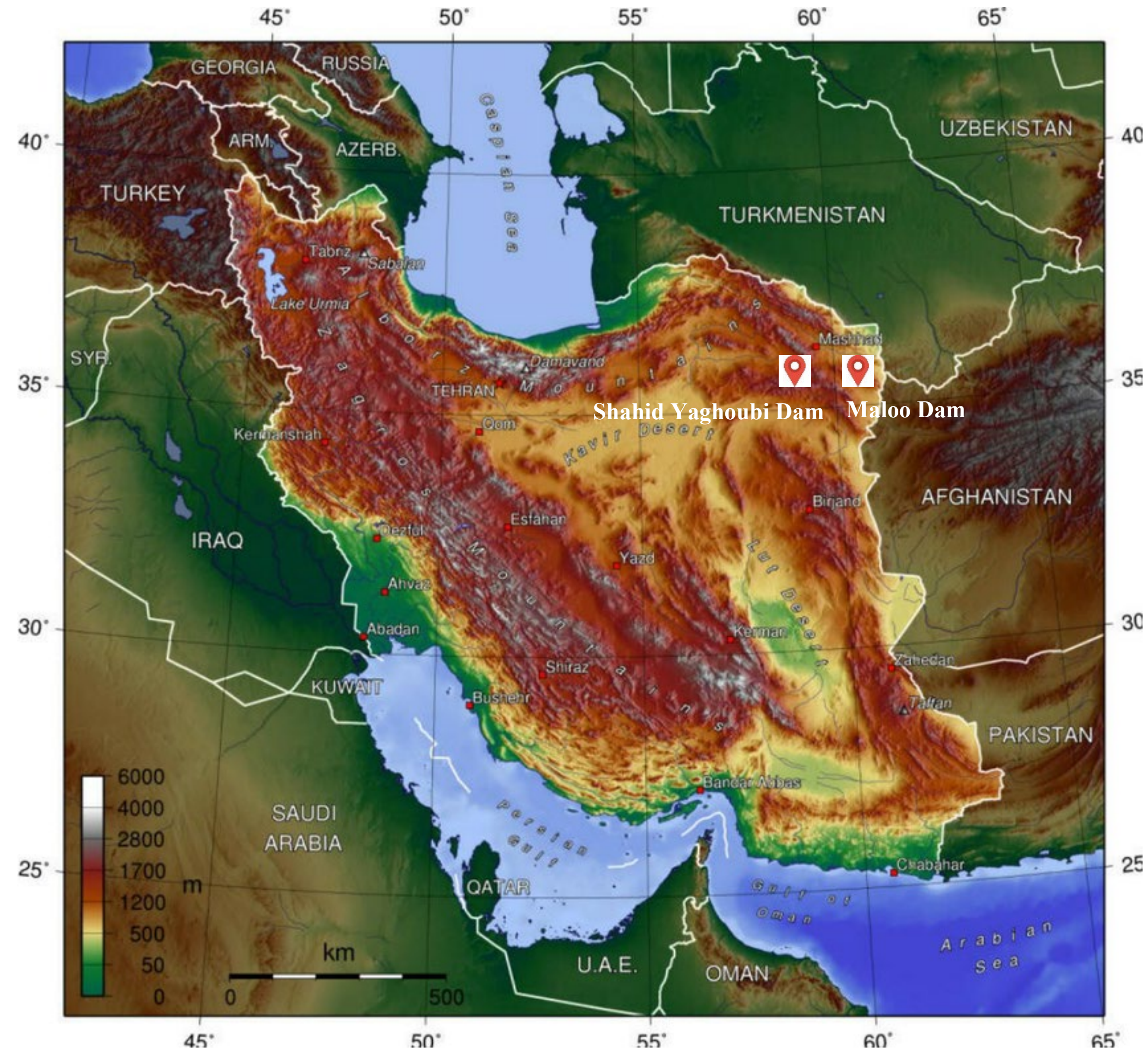

Fig. 1 The location of Shahid Yaghoubi and Maloo dams

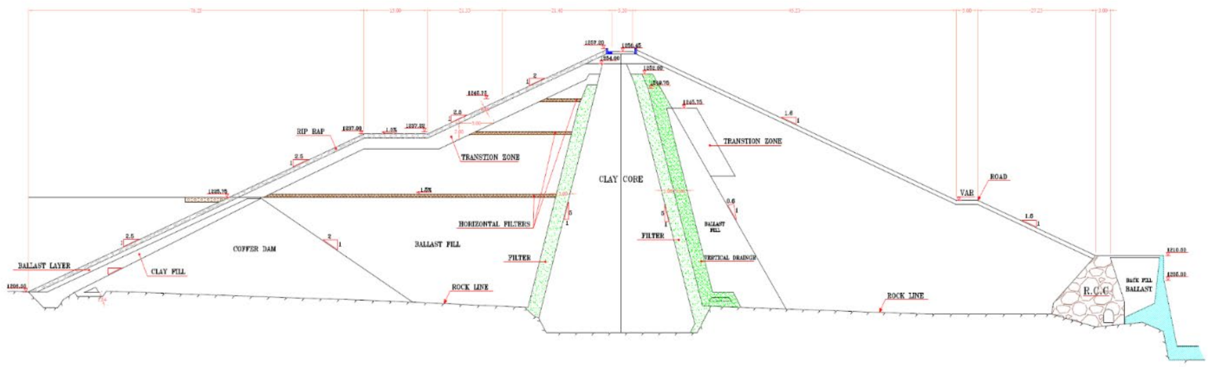

Fig. 2 Section of Shahid Yaghoubi dam.

The dam’s crest is positioned at 1256.45 meters above sea level along the dam's axis, as depicted in the as-built maps. The clayey core, extending with a slope of 5:1 (horizontal to vertical) on both the upstream and downstream sides, is asymmetrically located towards the upstream side relative to the dam axis. Figure 2 displays the sectional view of the dam based on these maps.

The reservoir of the Shahid Yaghoubi Dam holds a normal volume of 72 million cubic meters, with a dead storage volume of 27 million cubic meters. The dam's average annual yield is approximately 44 million cubic meters. Constructed primarily from sandstone and sandy shale, the dam incorporates a drainage gallery at its base, which is fed by four drainage paths. However, discrepancies have been noted in one of these pathways where seepage significantly exceeds that of the others.

Despite the presence of a downstream drainage gallery, none of the four channels leading into this gallery are equipped with spillways for discharge measurement. Although the gallery configuration would support the installation of such spillways, no measures have been implemented to date. Currently, discharge measurements are conducted via a rudimentary method that records the time required to fill a specific volume container, highlighting the need for a more precise and standardized measurement technique. The documentation and instrumentation system of the Shahid Yaghoubi Dam also exhibit several deficiencies, particularly with the calibration of piezometric pressure measuring tools, underscoring the need for comprehensive system upgrades and standardization to enhance operational accuracy and reliability.

3.1. Dam seepage modeling and analysis

Based on the sectional view presented in Figure 2, the cross-section of the Shahid Yaghoubi Dam has been meticulously modeled using GeoStudio software, as depicted in Figure 3. This modeling facilitated numerous iterative analyses using the SEEP/W module, aligning with the conditions on April 30, 2021, when the reservoir's water level was recorded at 1234.64 meters. The permeability parameters of the dam body materials, as outlined in Table 1, were configured with uniform coefficients in both horizontal and vertical orientations to ensure consistency in the simulation.

To accurately calibrate the model, seepage analyses were executed in both steady-state mode, corresponding to the highest water level observed in 2021, and in transient mode to reflect daily fluctuations in the reservoir's water levels. The outcomes from the transient analysis

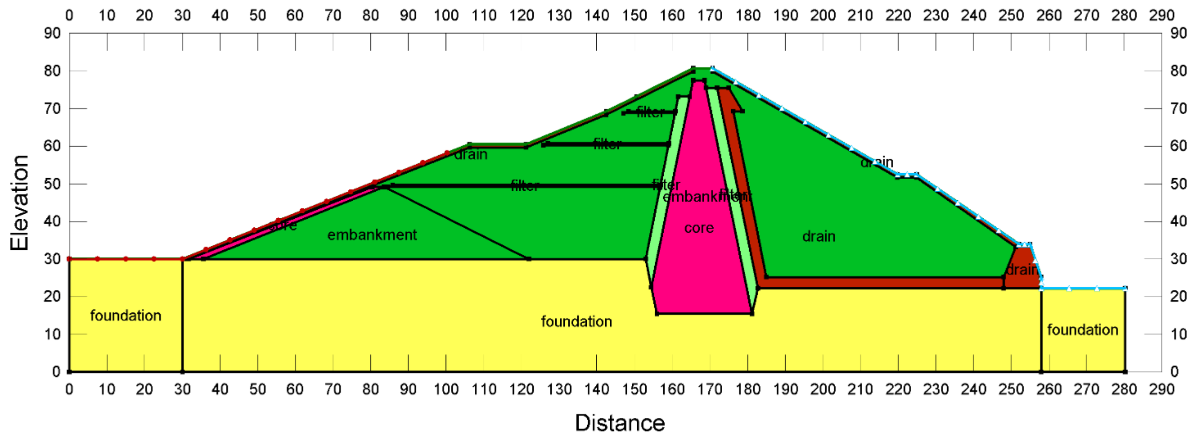

Fig. 3 Shahid Yaghoubi dam model in GeoStudio software.

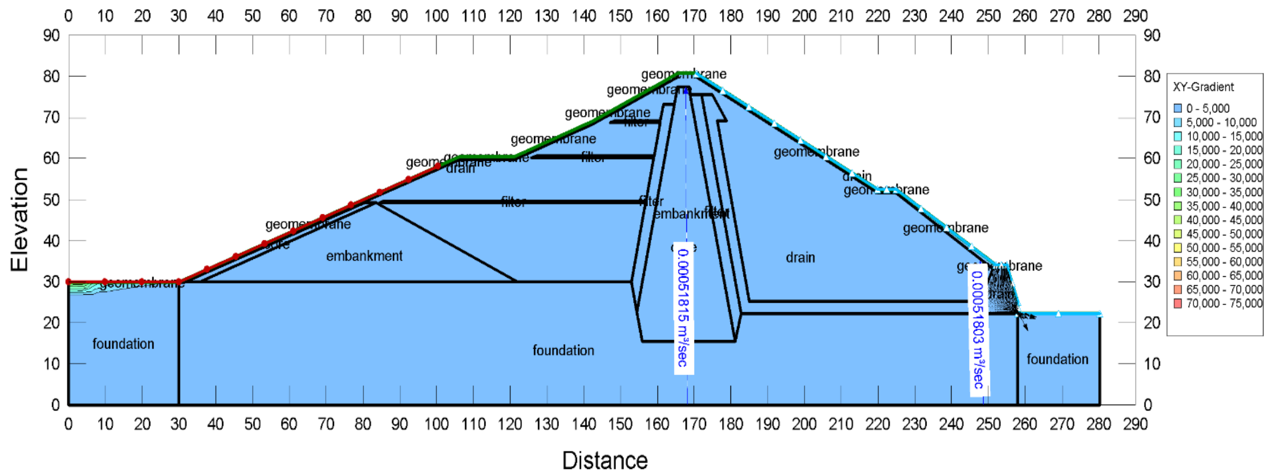

Fig. 4 Hydraulic gradient lines and discharge rate of the Shahid Yaghoubi dam with geomembrane layer.

revealed a seepage discharge rate of 0.46 liters per second. When compared to the actual recorded seepage rate of 0.41 liters per second during the same period, this result demonstrates minimal discrepancy, underscoring the model's high level of accuracy and reliability in simulating real-world conditions. This level of precision is crucial for validating the effectiveness of the modeling approach and for further refining the predictive capabilities of the seepage analysis methodology.

3.2. Suggested solutions for the first case study

In this section, two proposed methods to reduce the seepage of the dam have been examined. First, the use of a geomembrane layer for the surface of the dam upstream is modeled. In the second solution, a cut-off wall is used under the core. For this purpose, the wall has been modeled under the dam's core in three places, and its effect on reducing seepage was discussed.

Geomembrane modeling is being conducted in GeoStudio software to investigate the seepage of the Shahid Yaghoubi dam. The geomembrane has a thickness of 3 mm and a permeability coefficient of 5.0×10^{-13}m/s. Seepage analysis was performed with a geomembrane layer for the maximum water level in 2021 (Fig. 4). This figure indicates that the use of a geomembrane eliminates any critical areas of hydraulic gradient within the dam. Furthermore, this method resolves the drainage problem that occurs without a geomembrane in place. Additionally, the seepage amount is reduced by 15% compared to the scenario without a geomembrane.

Because of tensile properties, geomembranes enable projects that may not be achievable with other systems. This is largely due to their ability to accommodate deformations that could surpass the strength of a water barrier, as well as their capacity to withstand differential movements between the flexible dam body and the rigid structures that help ensure watertight joints between the dam and the concrete components. To implement geomembrane sheets, the number and size of the sheets are determined based on the land's area, dimensions, and shape. Next, the sheets are spread on the ground and bonded together using specialized machines. It is crucial to compact the sheets precisely to avoid cracks or gaps. Finally, the edges of the sheets must be securely glued or fastened with clamps to prevent water infiltration beneath them.

In dams with clay cores, the construction of the dam body and the core is interconnected, meaning that weather conditions, disruptions in placing filter materials, or issues with the compaction of the core can impact the overall construction timeline. In contrast, the installation of a geomembrane system is largely unaffected by weather and can be coordinated with the construction and operational schedule of the dam. The geomembrane can be added either after the dam is completed or during the ongoing construction of the upper part while the lower section is finished. If floods occur during construction, the waterproofed lower section of the dam will serve as a barrier against flooding, enhancing the safety of the project.

The second solution to control the seepage is to build a cut-off wall under the dam core. For this goal, a wall with a thickness of 1 meter and a height of 13.5 meters is designed. It is noted that the bedrock level under the dam core has yet to be discovered. Also, the permeability coefficient of the wall is selected as 10^{-9} m/s. Separate analyzes are performed by placing the cut-off wall at the core's middle, upstream, and downstream parts to find the optimal location of the wall.

Based on Fig. 5, the seepage flow rate in the first scenario, where the cut-off wall is positioned in the middle of the core, measures 0.4 liters per second. Consequently, compared to comparable conditions in terms of reservoir water level but without the wall, this solution can decrease seepage by 33%.

The seepage flow rate is marginally lower in the case where the cut-off wall is located in the middle part of the core (Fig. 6). The critical area of the hydraulic gradient has been formed in the downstream drain. Lastly, in the third scenario where the cut-off wall is positioned in the downstream part of the core, the seepage flow rate is lower than the other two cases (Fig. 7). In this instance, seepage is reduced by 35% compared to the same time and reservoir water level for the dam without the cut-off wall. It is important to note that implementing the cut-off wall is more complex than the geomembrane layer for this dam. However, Cut-off walls serve as an effective option for minimizing seepage in embankment dams and their foundations. These walls can be built using various techniques that eliminate the need for foundation dewatering and significantly lessen the excavation compared to traditional rolled earthfill cutoffs. Additionally, cut-off walls can frequently be installed in confined work areas.

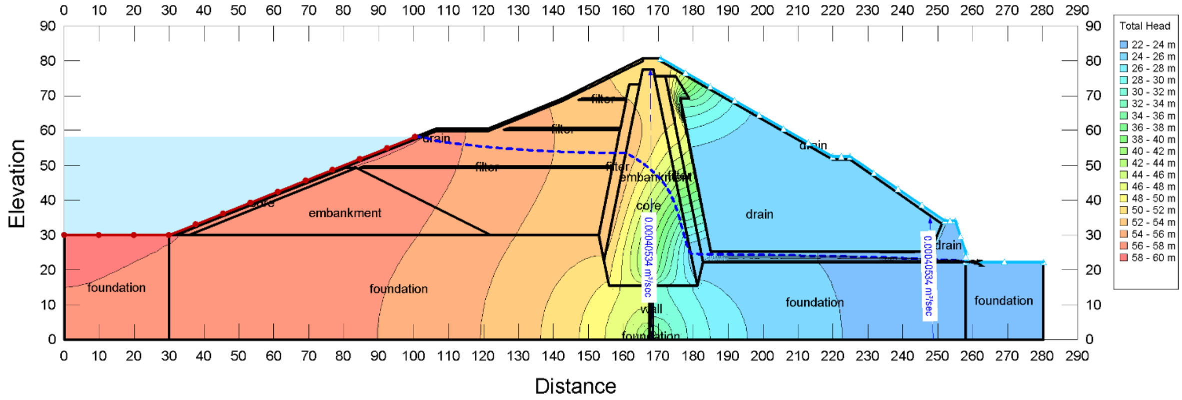

Fig. 5 The results of the cut-off wall modeling in the middle section under the core of the Shahid Yaghoubi dam.

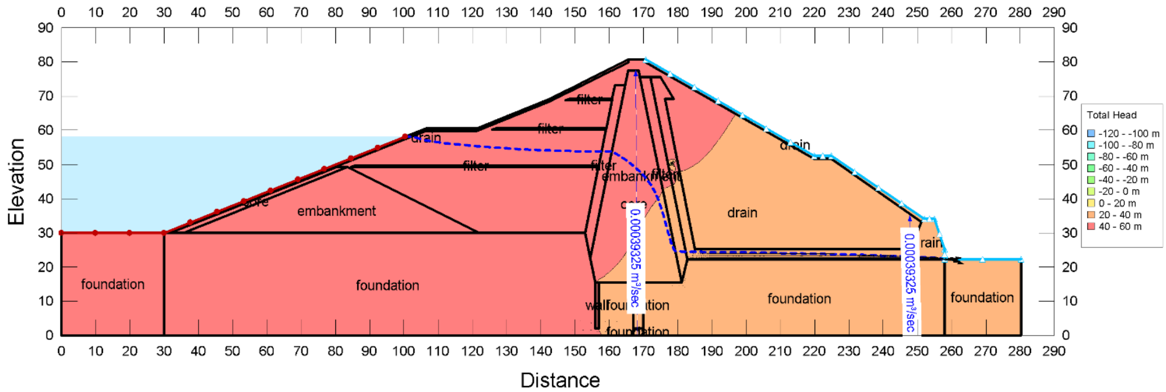

Fig. 6 The results of the cut-off wall modeling in the upstream under the core of the Shahid Yaghoubi dam.

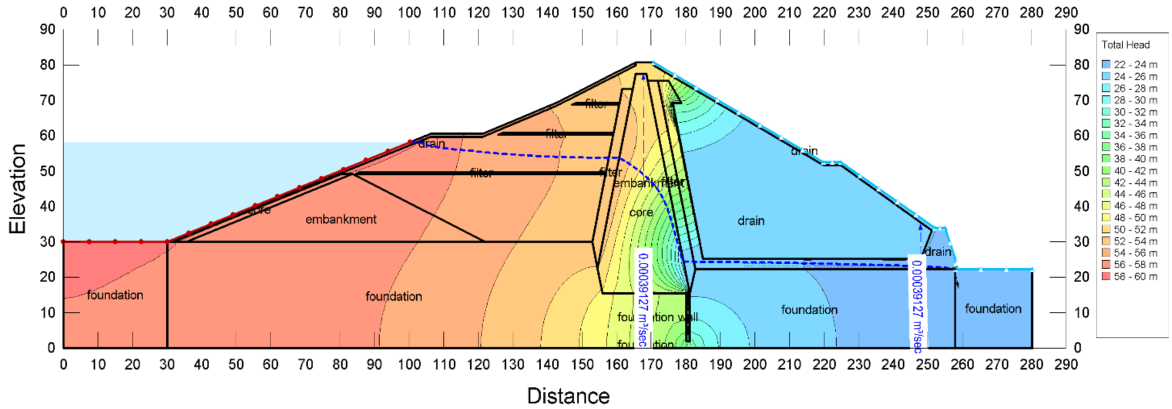

Fig. 7 The results of the cut-off wall modeling in the downstream under the core of the Shahid Yaghoubi dam.

4. Analysis of Maloo dam

The second case study is the Maloo earth dam, built near Torbat Jam city. This dam is located at a distance of 215 kilometers from Mashhad city. Maloo dam is an earth dam with a clayey core. The dam's height from the river bed is 21 meters, the width of the dam crest is 9 meters, and the length of its crest is 356 meters. The volume of the dam's reservoir is equal to 3 million cubic meters, and the maximum height of the reservoir is 19.43 meters.

The instrumentation of the Maloo dam is installed in four sections to check and control the dam's behavior. In the year 2021, only piezometric pressure measurement data were available. Casagrande piezometers are installed at different dam points, and their information is collected mechanically. The name of this tool is according to SP x-y, where x is the section number, and y is the instrument number in the desired section. Sections 3-3 of the dam's instrumentation section, where most piezometers are installed, were used to analyze the seepage. The installation level of instrumentation in sections 3-3 is shown in Fig. 8.

According to the information that has been gathered, it has been observed that the piezometers remained without water for the majority of the months throughout the year 2021. Out of the four standing pipe piezometers that were installed in sections 3-3, only the piezometer SP 3-6 had water present during the final two months of the year. In order to analyze seepage, this specific section is being modeled using the SEEP/W software, as depicted in Fig. 9.

Since the only data is related to piezometer SP 3-6, recursive analysis is conducted with this control data. For this purpose, steady state analysis is performed at the maximum level of the dam reservoir, which is in February 2021. The reservoir level is 852.5 meters from the free water level, and the corresponding water height in the piezometer SP 3-6, according to the model coordinates, is 13.67 meters. By performing recursive analysis to reach this piezometric pressure value, the permeability values of the dam materials were obtained according to Table 2.

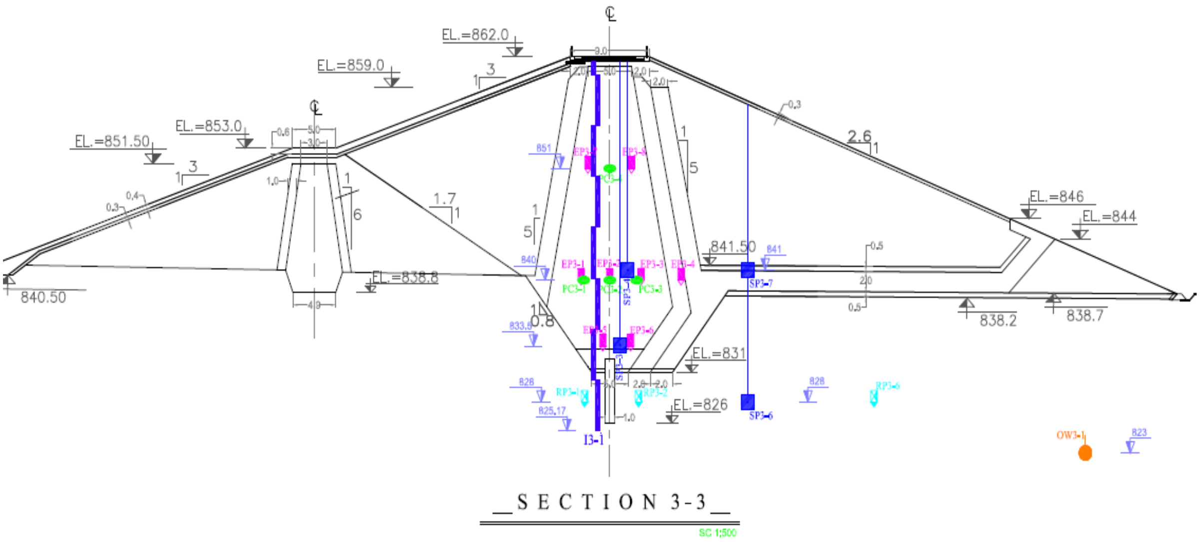

Fig. 8 Placement of instrumentation in the transverse section 3-3 of Maloo dam.

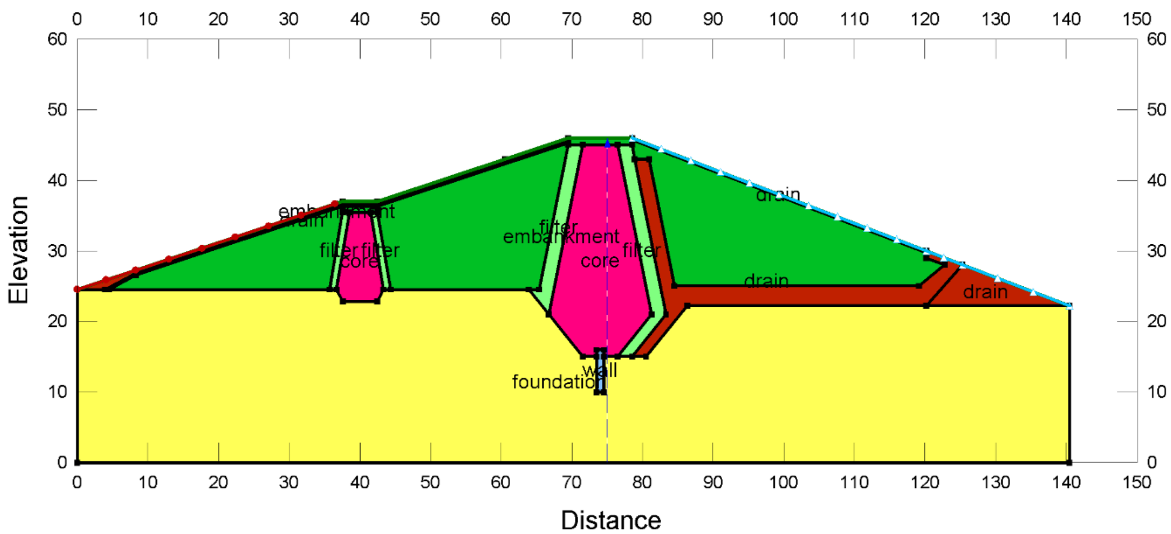

Fig. 9 Maloo dam model in GeoStudio software.

Fig. 10 shows the piezometric pressure of the control point, which is slightly different from the actual value and indicates the correctness of the model. In the conditions of the maximum reservoir level in 2021, the phreatic line and the seepage flow of the Maloo dam were obtained according to Fig. 11. As can be noticed, the seepage flow rate, in this case, is equal to 0.36 lit/s.

In the following, the suggested methods to reduce the Maloo dam's seepage are expressed according to the analysis outputs. In the first solution, the seepage analysis of the dam was done by applying a geomembrane layer to its body. Since a cut-off wall was implemented during the construction of this dam, it is called a combined system. As the second method, to reduce the total seepage, the height of the existing cut-off wall was increased, and the results were compared.
SEEP/W software assigns the geomembrane layer to the dam's surface upstream. The hydraulic permeability and thickness of this layer are selected as 5.0×10^{-13} m/s and 3 mm, respectively. The seepage analysis was done when the reservoir level was maximum to compare with the results of the dam without cover. The result of hydraulic gradient lines and seepage flow rate of the dam with the geomembrane layer is shown in Fig. 12. Therefore, using the geomembrane layer leads to removing critical areas of hydraulic gradient compared to the case without it. The seepage flow rate is also associated with a decrease of 6%, which seems reasonable considering the low level of the reservoir in 2021. Implementing the geomembrane layer when the dam reservoir is dry, is also recommended. Since it was implemented a cut-off wall below the dam's core, by increasing the height of this wall, the amount of seepage can be checked. For this purpose, 4 meters are added to the height of the 6-meter wall under the core, and the permeability coefficient of the wall is chosen as 10^{-8} m/s according to Table 2.
The total seepage flow rate is obtained by performing steady state analysis for the maximum reservoir level in 2021, according to Fig. 13. Therefore, this solution reduces the seepage rate by 0.27 lit/s. In other words, this method can reduce seepage by 25% compared to the dam's current condition. At the same time, the critical areas of the hydraulic gradient are similar to the initial state. According to the reservoir level data of the 2021 Maloo dam, which did not go beyond the upstream berm, the implementation of the cover for the entire upstream level is conservative.

5. Summary and Conclusions

Dams are important because they provide water for domestic, industry and irrigation purposes, especially in rivers with large floods (Shahheydari et al., 2015; Hosseini et al., 2016; Foroudi and Barati, 2022). Water flow within the body and foundation is a critical concern in earth dam engineering, with stability and safety paramount throughout all stages of construction and operation. Inappropriate design and management of water seepage, driven by hydrostatic forces, have led to significant damage in many earth dams.

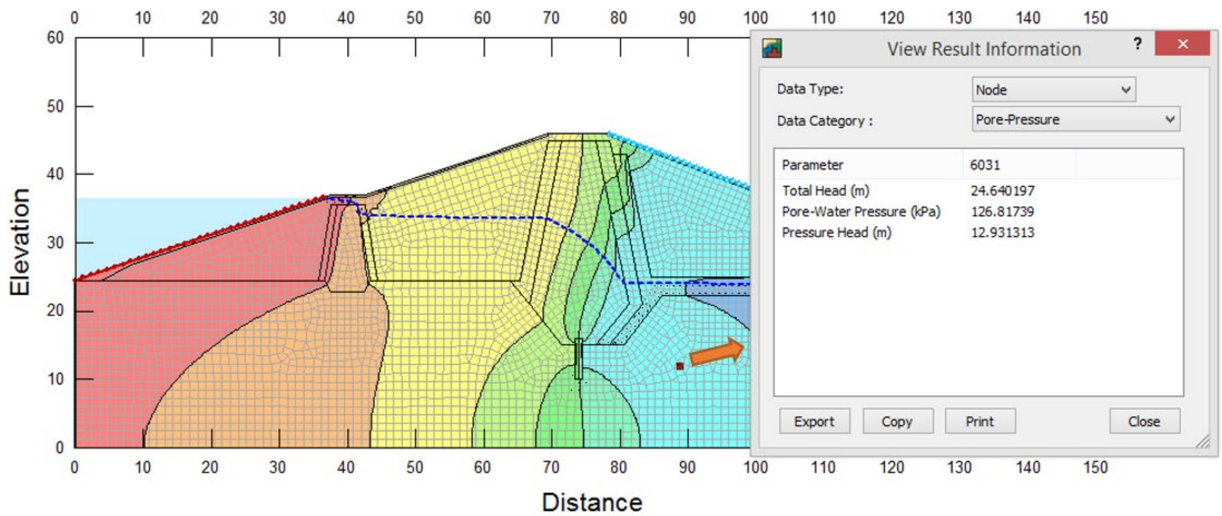

Fig. 10 Result of SP 3-6 piezometric pressure in Maloo dam.

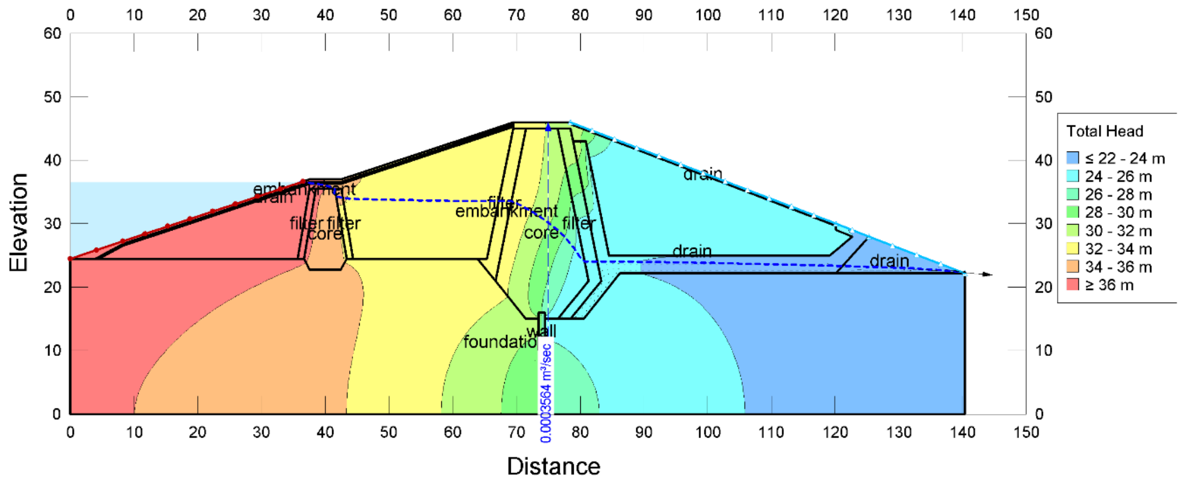

Fig. 11 Equipotential lines, phreatic line, and discharge rate of Maloo Dam in steady state condition.

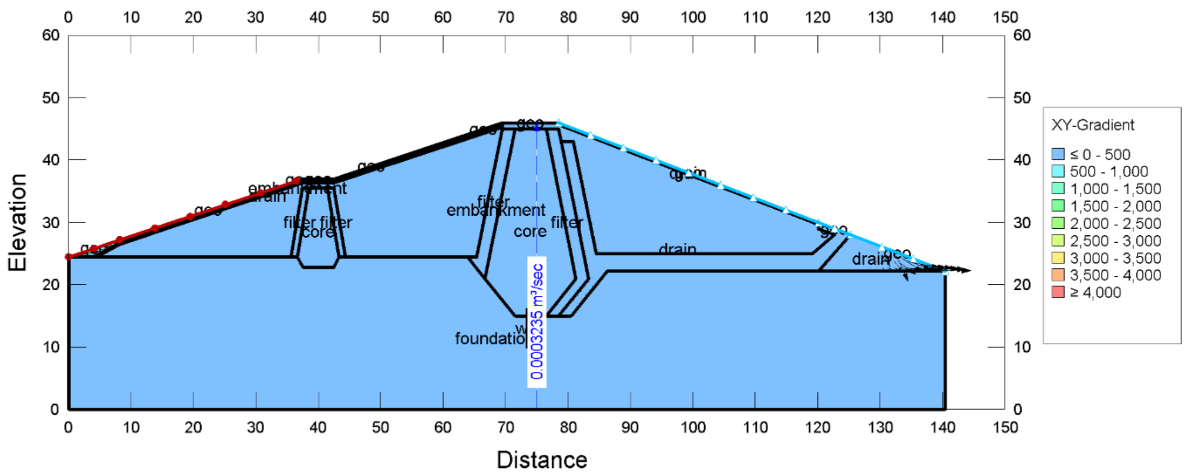

Fig. 12 The discharge rate and hydraulic gradient lines of Maloo dam with geomembrane layer.

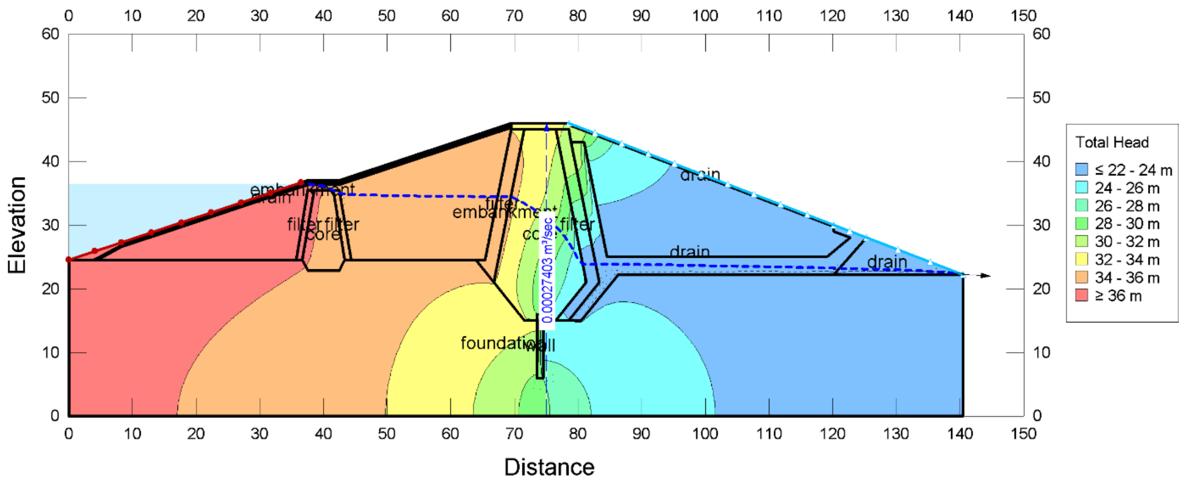

Fig. 13 Change of discharge rate with increasing the height of the cut-off wall under the Maloo dam core.

This research critically evaluates seepage management strategies, focusing on the Shahid Yaghoubi and Maloo dams, to assess their impact on dam safety and performance. Our analysis reveals both the benefits and limitations of advanced seepage control methods, highlighting their crucial role in maintaining dam integrity.

For the Shahid Yaghoubi dam, the implementation of a geomembrane on the upstream surface led to a 15% reduction in seepage rates, confirming its effectiveness in enhancing hydraulic performance. Additionally, introducing a cut-off wall downstream of the dam core achieved a 35% reduction in seepage. However, this measure did not significantly alter the critical hydraulic gradient at the downstream drain, illustrating the complexity of hydraulic interactions within earth dam structures. This underscores the importance of precise engineering and strategic placement of seepage control measures.

At the Maloo dam, applying a geomembrane eliminated critical hydraulic gradient areas, reducing seepage by 6%. A more significant result was observed by altering the height of the cut-off wall below the dam core, which led to a 25% decrease in overall seepage flow. This finding highlights the substantial impact of structural modifications on seepage control and emphasizes the need for tailored approaches based on specific dam characteristics and environmental conditions.

These cases underscore the nuanced nature of seepage mitigation, necessitating ongoing monitoring and adaptive management to optimize seepage control effectively. The study also reinforces the critical role of precise instrumentation and reliable data in assessing and refining dam safety measures.

Overall, this research enriches the engineering community's understanding of effective seepage management techniques and lays the groundwork for future advancements in earth dam design and maintenance strategies.

6. Notation

The following symbols are used in this paper:

c = constant;

h = function of the water height;

k_x = hydraulic permeability in the horizontal direction (m/s);

k_y = hydraulic permeability in the vertical direction (m/s);

t = time (sec);

x = horizontal direction;

y = vertical direction;

$\partial h/\partial t$ = change of water height with time;

$\partial^2 h/\partial x^2$ =Second partial derivative of water height in the x direction; and

$\partial^2 h/\partial y^2$ = Second partial derivative of water height in the y direction.

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