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Assessment of the Impact of Foundation Seepage on the Structural Design and Architectural Stability of the Bakhtiari Dam Using Finite Difference Modeling

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Abstract

The Bakhtiari Dam, as one of the tallest concrete arch dams under construction in the Middle East, possesses significant geotechnical and structural importance. Given the complex geological setting of the region, foundation seepage has emerged as one of the major challenges in evaluating the safety and stability of the dam. If left uncontrolled, seepage can lead to increased pore water pressure, reduced stability, differential settlements, and even structural failure over time. Therefore, accurate identification and analysis of the hydraulic and structural behavior induced by seepage are essential during both the design and operational phases.

This study aims to assess the impact of foundation seepage on the architectural stability and structural design of the Bakhtiari Dam using numerical modeling based on the Finite Difference Method (FDM) to simulate the coupled hydraulic–mechanical behavior of the structure. Initially, a 3D numerical model of the dam and its foundation was developed using regional geological and geotechnical data. Subsequently, hydrostatic loads and various permeability conditions were applied to analyze seepage paths, pore pressures, and the resulting stresses in the foundation and dam body.

The results indicate that foundation seepage can alter the stress–strain distribution in the dam body, increase horizontal displacements at the crest, and reduce structural safety in specific zones. Key findings include the identification of high-risk seepage zones, the effectiveness of drainage systems in controlling pore pressure, and the recognition of design weaknesses at the foundation–abutment interface. Accordingly, solutions such as deep grout curtain enhancement, reinforcement of the dam body with special materials, and the implementation of real-time monitoring systems are proposed.

The innovation of this research lies in the integrated use of numerical modeling, architectural–structural approaches, and seepage risk analysis within a unified framework tailored for high arch dams. The outcomes of this study can serve as a scientific and practical reference for enhancing the safety of similar dams located in highly permeable regions.

Keywords: Foundation seepage, Bakhtiari dam, Architectural stability, Structural design, Finite difference modeling.

1 | Introduction

Dams are vital infrastructures for water supply, energy production, and flood control, playing a strategic role in the sustainable development of various regions. The Bakhtiari Dam, one of the tallest double-curvature

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concrete dams under construction in the Middle East, plays a significant role in the economic and environmental development of southwestern Iran. Due to its great height and the region's specific geological conditions, studying its hydraulic and geotechnical behavior is of special importance [1].

One of the most critical technical challenges in the design and operation of dams is water seepage from the foundation and the dam body, which can lead to reduced structural stability, abnormal settlements, particle erosion (Piping), and even long-term failure of the structure. In such situations, numerical methods such as the Finite Difference Method (FDM) offer powerful tools for analyzing the hydraulic and structural behavior of dams [2].

Given the large scale of the Bakhtiari Dam project and its environmental and economic sensitivity, accurately assessing the impact of seepage through the dam foundation on its structural and architectural design is crucial. Improper analysis could result in increased maintenance costs, premature structural failure, or even environmental disasters. On the other hand, limited studies combining geotechnics, structural architecture, and numerical modeling have been conducted regarding the Bakhtiari Dam, indicating a research gap. Despite numerous hydraulic and geological studies, a comprehensive numerical analysis based on FDM addressing simultaneous seepage, structural stability, and architectural design has yet to be presented. Moreover, previous research often overlooked structural aesthetics and architectural design alongside geotechnical considerations.

The main goal of this study is to assess the impact of foundation seepage at Bakhtiari Dam on its structural stability and architectural design using the FDM [1]. This research aims to understand the relationship between subsurface hydraulic behavior (Seepage) and the structural-architectural response of the dam under both operational and critical conditions. Additionally, this study seeks to offer suggestions for improving structural design and enhancing dam safety based on precise simulations. The key questions addressed are:

I. What is the effect of seepage on the structural stability and architectural design of the dam?

II. Can the FDM accurately predict seepage behavior and its impact on structural design?

The findings of this research include pore water pressure mapping, seepage path identification, and design or modification recommendations for the dam's architecture in the face of seepage. Furthermore, combining architectural and structural engineering perspectives in evaluating stability and proposing a new framework for risk assessment in the design of high arch dams represents one of the innovations of this research.

2 | Research Background

In dam design, seepage from the dam foundation and its effects on the stability of the structure and abutments are of great importance. In addition to engineering aspects, this phenomenon can profoundly impact the architectural design around and within the dam. For example, water seepage can cause material erosion, wall damage, and changes in architectural spaces [3]. Therefore, it is necessary to perform predictive analyses to manage such challenges during the design phase.

The Bakhtiari Dam, designed to generate hydroelectric energy and create a stable engineering environment, is located in a region with unique geological features, which must be considered in the design of related structures and architectural spaces.

The Bakhtiari Dam site, intended for power generation through the construction of a hydropower plant downstream of the Bakhtiari River, is approximately 5 km upstream from the confluence of the Bakhtiari and Sezar rivers and about 50 km upstream from the Dez Reservoir Dam. The Bakhtiari River's watershed area at the dam site is approximately 6,503 km^2.

Originating from southern Aligudarz County, the Bakhtiari River flows southward, receiving numerous tributaries until it joins the Sezar River. The Sezar River drains surface water from the northern and western regions, while the Bakhtiari River handles the eastern and southern parts of the Dez River basin. These two rivers merge at a place called Do Ab, located between the Tang-e 5 and Tele Zang railway stations on the Tehran–Ahvaz railway line, forming the Dez River.

The rate of water seepage from the dam foundation and abutments is a major design concern, directly related to the natural permeability of the ground. Failure to properly analyze and evaluate this can pose serious challenges to the project. Seepage through dam foundations is significant both in terms of water loss and the technical problems arising from hydraulic gradients and uplift pressures, which affect dam stability [4].

Changes in the groundwater flow network and increased hydraulic head in the abutments and foundation after reservoir impoundment are among the adverse consequences of dam construction. To prevent negative outcomes like increased uplift pressure, stability hazards, foundation erosion, hydraulic failure, and reservoir water loss, several mitigation methods are adopted, one being the construction of grout curtains. The effectiveness of a grout curtain in reducing seepage discharge from the dam foundation can be evaluated by developing a model of the foundation.

2.1 | Dam Location and Main Access Routes

The Bakhtiari Dam, currently in the design phase, is a 325-meter-high double-curvature concrete dam intended for hydroelectric energy production on the Bakhtiari River in southwestern Iran. It is located approximately 70 kilometers northeast of Andimeshk and about 65 kilometers southwest of Doroud. The dam site lies in the lower Bakhtiari River area in Lorestan Province, in the southwestern part of Iran, along the southwestern slopes of the folded Zagros Mountains. It is situated at longitude 48°46'41"E and latitude 32°57'26"N, northeast of Tang-e Panj railway station (The eighth station between Andimeshk and Doroud) on the Tehran–Ahvaz railway, over the Bakhtiari River.

The dam site is approximately 50 km (Aerial distance) from the Dez Dam and about 3 km upstream of the confluence of the Bakhtiari and Sezar rivers [1].

2.2 | Geological Characteristics of the Bakhtiari Dam Site

The location of the Bakhtiari Dam and its reservoir lies within the folded Zagros tectonic-sedimentary basin. The Bakhtiari Dam reservoir, which is located in the folded Zagros sedimentary basin, is divided into several zones in terms of depositional conditions, including the Dezful Embayment, Coastal Fars, Interior Fars, and Lorestan. The site of the Bakhtiari Dam and reservoir is situated in the northwestern part of the folded Zagros, on the boundary between the Lorestan zone and the Dezful Embayment. The sequence of anticlines and synclines in the study area constitutes the main geomorphological structures [4].

The lithological sequence in the region generally comprises formations ranging from the Cretaceous to the Miocene, which—listed from oldest to youngest—include the Gurpi, Sarvak, Ilam, Gurpi, Amiran, Pabdeh, Taleh Zang, Kashkan, Asmari–Shahbazan, Gachsaran, Bakhtiari formations, and Quaternary deposits. The outcropping formations are mainly carbonate, and the absence of erodible formations has led to the dominance of high ridges and steep slopes as the prevailing morphological features of the area [5].

The Bakhtiari Dam site is located in a gorge approximately 1,150 meters long and 25 to 30 meters wide at its base, oriented nearly perpendicular to the axis of the Siah-Kuh anticline. The width of the gorge at the dam crest is about 340 meters. *Fig. 2* shows the geological map of the dam site area. The bedrock and the central part of the dam abutments consist of siliceous limestone and marl-siliceous limestone containing nodules of silicified limestone or chert, belonging to the second, third, and fourth units of the Sarvak Formation (SV2, SV3, and SV4). Due to the steep slopes at the dam site, there is no significant overburden. In the lower elevations of the central part of the Siah-Kuh anticline, the slopes are gentle, while at higher elevations, the slopes become steeper, with some areas even showing negative slopes.

Topographically, the right abutment has an apparently uniform slope averaging 70 degrees, while the left abutment has a variable slope ranging from nearly vertical to even negative inclinations [4].

The most important tectonic features of the Bakhtiari Dam site include the Siah-Kuh–Geryeh anticline, the axial plane of the Siah-Kuh anticline, fault F1, fault F3, fault F2, fault F4, a chevron fold zone (In the northeastern limb of the Siah-Kuh anticline), kink-band zones (In the core of the Siah-Kuh anticline in units SV2 and SV3), near-vertical structures, and joint sets. The relationship of fault F2 with other structures is not precisely known, but it appears that the formation of this fault is associated with a deformation phase that resulted in the folding of sediments into anticlines and synclines. The formation of kink-band zones in the core of the Siah-Kuh anticline is most likely related to the folding of weak zones during the formation of the Siah-Kuh anticline [1].

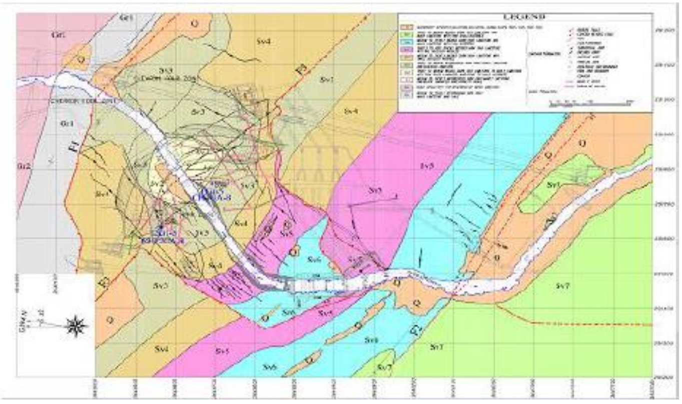

Fig. 1. Geological Map of the Bakhtiari Dam Site (Iran Water and Power Resources Development Company).

2.3 | Discontinuity Conditions at the Dam Site

In the rock mass forming the abutments of the Bakhtiari Dam and power plant site, four main discontinuity systems are observed, as described below:

Bedding planes: Generally consist of thin to thick limestone layers and marly limestone containing nodules or siliceous bands. The bedding planes typically dip at around 70 degrees, although in the hinge zones and middle elevations they appear relatively horizontal. The dip direction is 030 degrees on the upstream limb and 215 degrees on the downstream limb [5]. From a geotechnical perspective, the bedding planes exhibit openings of 0.1 to 1 mm, dominant spacing of 20 to 60 cm, planar shapes with slickensides, and infill materials of clay and calcite [6].

Main Joint Set J1: This joint set is generally divided into two groups:

I. Type A with a dip of approximately 70 degrees and a dip direction of 310 degrees.

II. Type B with a dip of approximately 40 degrees and the same dip direction of 310 degrees.

In terms of geotechnical properties, J1 joints have openings of 0.1 to 1 mm, dominant spacing of 6 to 60 cm, planar shapes ranging from rough to smooth, and calcite infill.

Joint Set J2: Also generally divided into two groups:

I. Type A with a dip of about 35 degrees.

II. Type B with a dip of about 75 degrees.

Both types have a dip direction of 125 degrees, and Type B joints are less frequent than Type A. From a geotechnical standpoint, J2 joints have openings of 0.1 to 1 mm, dominant spacing of 6 to 60 cm, planar shapes ranging from rough to smooth, and calcite infill.

Joint Set J3: This set occurs much less frequently than the others. It generally has a dip of 15 degrees and a dip direction of 045 degrees [6].

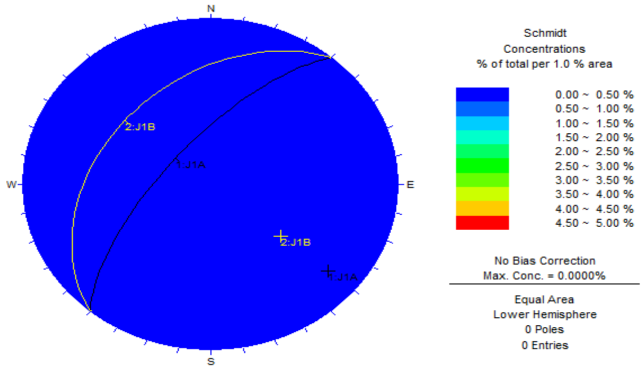

Fig. 2. Geometry of both types of joint set J1 displayed on stereonet.

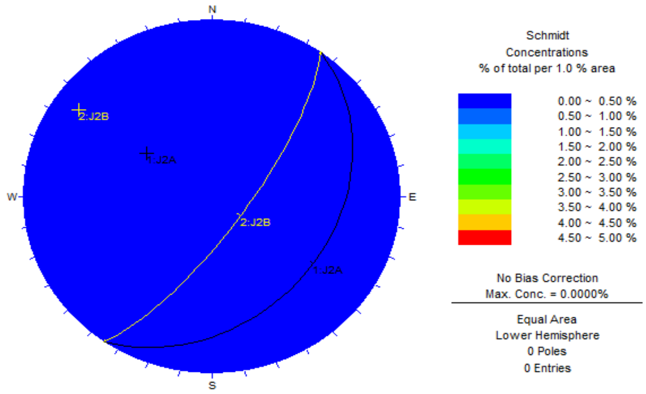

Fig. 3. Geometry of Both Types of Joint Set J2 Displayed on Stereonet.

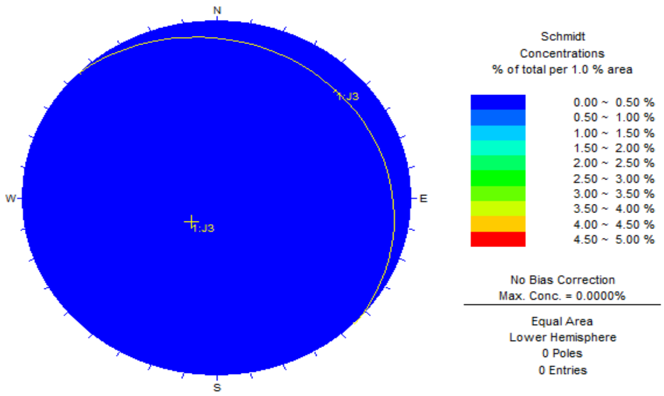

Fig. 4. Geometry of Joint Set J3 Displayed on Stereonet.

Table 1. Engineering geological characteristics of the joint sets at the Bakhtiari dam site.

Characteristics	Description	Join set J1	Join set J2	Join set J3
Dip	-	40 – 70	35 -75	15
Dip Direction	-	310	125	045
Aperture (mm)	0.1 - 1	90	95	95
	1 - 5	10	5	5

Table 1. Continued.

Characteristics	Description	Join set J1	Join set J2	Join set J3
Spacing (cm) (Percentage)	2 - 6	2.5	3	6
	6 - 20	48.5	52	25
	20 - 60	45	43.5	62.5
	60 - 200	4	1.5	6.5
	200 - 600	0	0	0
Infill Material (Percentage)	Clay	10	2	0
	Calcite	67.5	55	43
	Bitumen	1	0	0
	Iron Oxide	0	0	0
	Vuggy	21.5	43	57
Roughness (Percentage)	Wavy - Stepped	2	0	0
	Planar - Stepped	2	1	0
	Wavy - Smooth	1	1	0
	Planar - Smooth	47	54.5	72.5
	Wavy - Rough	0	0	0
	Planar - Rough	48	43.5	27.5

2.4 | Geographical Location and Its Impact on Architectural Design

The Bakhtiari Dam is located within a gorge, which necessitates that its architectural and structural design not only ensure safety and stability but also harmonize with the aesthetic characteristics of the surrounding environment [7]. Due to the dam's geographical position and its abutments, the architectural design of spaces such as control rooms, maintenance stations, and visitor areas presents specific challenges beyond purely technical considerations.

2.5 | Geological Features and Their Impact on Architectural Design

The region in which the Bakhtiari Dam is situated has distinctive geological features that must be considered in both architectural design and surrounding structural planning. The presence of various rock formations and diverse layering can significantly influence the selection of suitable construction materials for nearby buildings and structures. Moreover, structural analyses must be conducted to prevent negative effects such as water seepage and erosion [8].

2.6 | Seepage Analysis and Its Impact on Architectural Design

Seepage through the dam's foundation can weaken structural bases and damage architectural spaces such as tunnels, stations, and service areas. One engineering solution for this issue is the use of grout curtains to reduce seepage [9]. However, the key question is: How can these technical measures affect the architectural design of spaces? Specifically, spaces such as control rooms near the dam must be designed in a way that minimizes water seepage and enhances safety, thereby preventing potential damage and structural degradation.

2.7 | Architectural Methods for Managing Seepage and Enhancing Stability

In addition to engineering measures aimed at reducing water seepage, architectural design and the use of sustainable architectural techniques can help mitigate its negative impacts. For example, designing moisture-resistant spaces and using building materials that can withstand environmental pressure and changes will contribute to greater spatial durability and reduce maintenance and repair costs [10].

3 | Research Methodology and Findings

Based on the study level, modeling of the dam abutments was performed to analyze seepage using the two-dimensional software, GeoSlope. The model incorporated the orientation of geological layers and the permeability of each geological unit. The assumed permeability of the grout curtain for sensitivity analysis was 1.3E–7 m/s (Equivalent to one Lugeon) and 6.5E–7 m/s (Equivalent to five Lugeons).

The permeability values of each unit are presented in *Table 2*. The mesh elements used in the models were spaced at 2-meter intervals. The model dimensions were set at 600 meters in the upstream-downstream direction and 640 meters in height, ranging from elevation 200 to 840 meters.

To ensure a higher safety factor in analysis, two-dimensional vertical models were developed for elevations 800 and 650 on the left abutment, based on dye injection studies that identified preferred seepage paths, as well as for elevation 540 (The foundation section). Calculations for the right abutment (With better geological quality) were also included. However, this study focuses solely on seepage analysis at elevation 540 (Foundation section).

Table 2. Permeability in Different Units of the Sarvak Formation at the Bakhtiari Dam Site.

Unit	K (m/s)
SV1	3.1E-06
SV2	4.8E-05
SV3	1.9E-04
SV4	2.3E-04
SV5	4.2E-05

Using the finite element model developed for the Bakhtiari Dam site, seepage analyses were conducted under various conditions. To evaluate the effectiveness of the grout curtain, both models without a grout curtain and models incorporating a grout curtain were developed. In these models, the permeability quality of the grout curtain was assumed to be equivalent to 3 Lugeons.

To examine how seepage varies with increasing curtain depth, models with different curtain depths were designed, and the seepage volume beneath the foundation was calculated. The results are presented in *Table 3*.

According to the findings, the designed grout curtain with a depth of 90 meters and a permeability of 3 Lugeons reduces seepage by approximately 78%.

Table 3. Calculated seepage volumes for the grout curtain with three lugeon quality at various depths.

3 Lu: 3.9E-7	Length of Section (m)	Without Curtain (m^3/s)	Grouting Curtain Depth (m)		
			75	90	120
Section 540	170	1.9285	0.4545	0.3512	0.3367
Section 650	65	0.6292	0.1174	0.0975	0.0715
Section 800	330	0.2826	0.1746	0.1642	0.0447
Sum of the left Bank (m^3/s)		2.8403	0.7465	0.6128	0.4529
Total (m^3/s)		5.681	1.493	1.226	0.906

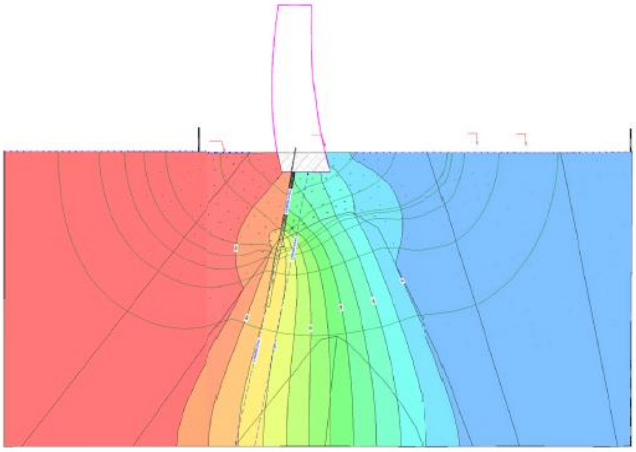

Fig. 5. Section 540 without grout curtain.

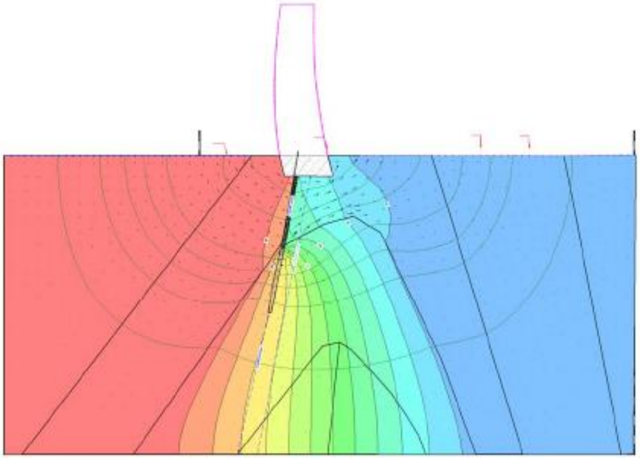

Fig. 6. Section 540 with an injection curtain to a depth of 90 meters and Lugeon class 3 quality.

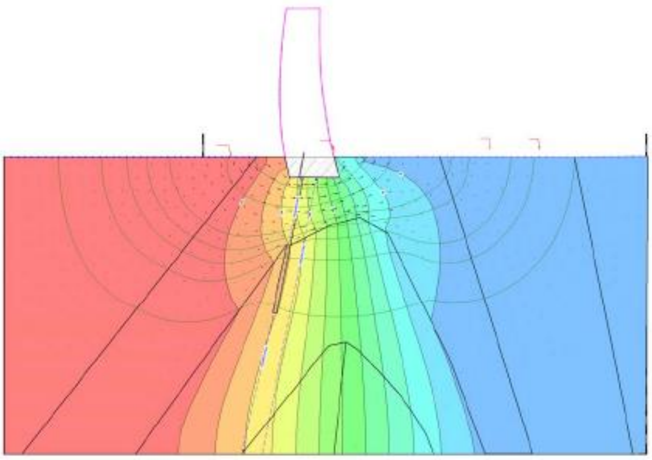

Fig. 7. Section 540 with an injection curtain to a depth of 75 meters and Lugeon class 3 quality

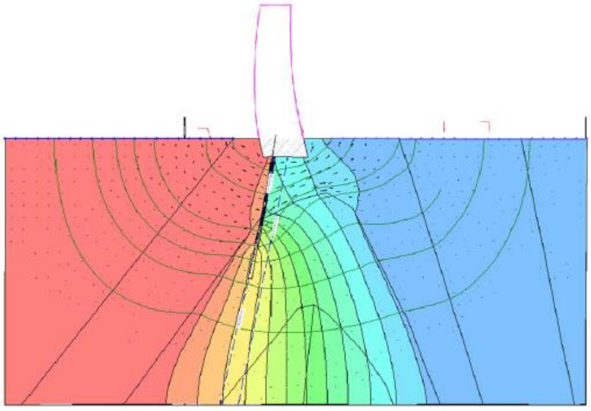

Fig. 8. Section 540 with an injection curtain to a depth of 120 meters and Lugeon class 3 quality.

Based on the seepage flow analysis conducted in SEEP/W software, the following results were obtained:

The quality of the grout curtain in terms of permeability has been considered within the range of 1 to 3 Lugeon units. All seepage calculations are based on achieving a sealing criterion of 3 Lugeon.

The grout curtain will be constructed in two rows with a spacing of approximately 1.2 meters.

The grout curtain reaches a very low-permeability zone at a depth of 75 meters below the foundation; however, due to the critical importance of the structure, the depth extends to 90 meters, reaching an elevation of 420 meters above sea level. Borehole depths in this area will reach 110 meters.

Without the grout curtain, the seepage from the abutments is calculated to be approximately 5.68 cubic meters per second. With the construction of the grout curtain, 78% of this seepage is controlled, thereby preventing the annual loss of around 140 million cubic meters of water.

4 | Recommendations

Based on the analysis and existing findings, the following recommendations can be made regarding the performance of the grout curtain:

Evaluation of the Grout Curtain Based on the Sealing Criterion (Lugeon)

Considering the final permeability range of 1 to 3 Lugeon, which is regarded as very suitable for large arch dams from an engineering perspective, it can be concluded that the grout curtain has acceptable quality performance. To further ensure long-term stability, it is recommended to:

I. Conduct periodic Lugeon tests (Post-Grouting Lugeon Tests) every 5 years.

II. Perform secondary grouting in areas with questionable performance to maintain uniform permeability.

Grout Curtain Depth and Its Impact on Seepage Reduction

Extending the grout curtain beyond the low-permeability zone at 75 meters to a depth of 90 meters (Elevation 420 m.a.s.l.) is a significant step in conservative design. Reaching 110-meter-deep boreholes also enables more accurate assessment of deep tectonics and variations in groundwater pressure. It is recommended to:

I. Use dynamic numerical modeling (Dynamic FDM or FEM) to simulate curtain behavior under seismic loading.

II. Utilize borehole data for probabilistic seepage modeling to predict performance under critical conditions.

Significant Seepage Reduction and Water Resource Conservation

According to the data, the initial seepage rate of about 5.68 m^3/s has been reduced by approximately 78% through the implementation of the grout curtain, preventing the annual loss of nearly 140 million m^3 of water. From economic, environmental, and operational perspectives, this is a considerable achievement. To further improve efficiency:

I. It is suggested to design a collection and redirection system for the recovered seepage water to downstream reservoirs or water recycling systems.

II. The successful outcomes of this project could serve as an implementation model for other arch dams in Iran.

The grout curtain at the Bakhtiari Dam, in terms of depth, density, sealing quality, and cost-environmental efficiency, is currently in an optimal state. However, to enhance long-term performance and mitigate potential risks due to seismic activity, new fractures, or gradual erosion, continuous monitoring, secondary injections, and periodic updates of numerical models should be part of ongoing operations.

5 | Conclusion

This study was conducted to investigate the role of foundation seepage in structural stability and architectural design of the Bakhtiari Dam, using numerical modeling via the FDM. The results of the simulations showed that seepage flow in the foundation—particularly through abutments and geological joints—can lead to increased pore water pressure, stress concentration, and localized displacement within the dam body. If neglected, this phenomenon could compromise the dam's operational stability over time, leading to differential settlement, cracking in critical zones, and potentially threatening structural integrity.

However, the design and implementation of a dual-row grout curtain with an effective depth of 90 meters and boreholes reaching 110 meters significantly reduced seepage by about 78%. This action prevented the annual loss of approximately 140 million cubic meters of water and improved the structural performance of the dam. Achieving permeability levels of 1 to 3 Lugeon at the dam foundation also reflects the high quality of grouting operations and adequacy of the sealing system.

To further enhance structural stability and optimize sealing performance, several recommendations were made, including reinforcing the grout curtain in high-risk areas, developing internal drainage systems, using variable-stiffness materials in stress-prone zones, and installing real-time monitoring systems. Additionally, redesigning structural joints between the dam body and abutments and applying geosynthetic and polymer-based sealing in critical areas were among the key findings.

Overall, this research demonstrates that combining numerical modeling with detailed geotechnical-structural analysis provides an effective tool for predicting dam behavior under seepage conditions and offers practical solutions for improving safety and extending the service life of high arch dams. The findings of this study can serve as a valuable reference for the design and maintenance of similar dams in geologically comparable regions of Iran.

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Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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