University of Baghdad
College of Engineering

JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 6 June 2025

Analysis of Seepage in the Foundation of Haditha Dam During the Last Decades

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ABSTRACT

Seepage under earthen dams is considered a major factor in their stability. Statistics showed that 40% of dam failures are caused by foundation seepage**.** In this study, the finite element method was used to calculate the amount of seepage under (Haditha Dam, located on the Euphrates River. A simulation model was created for each decade, and the seepage amount was calculated for three decades. The results showed a match in the values and that the amount of seepage between the first and second decades increased by (0.000022 m^3/s) or (7.62%). Seepage increased between the second and third decades by (0.000056 m^3/s) or (17.89%). This increase is considered small for three decades and does not affect the dam's stability. Therefore, with climate change and the decline in water supply sources, it is necessary to address this issue and find the best solution.

Keywords: Haditha Dam, Geo-studio, Model, Seepage analysis.

1. INTRODUCTION

Dams are one of the oldest and most efficient forms of structures that can be used for water storage purposes as well as for containing stored potential energy. These are used for domestic and industrial purposes. One of the most important factors taken into consideration when building earthen dams is the seepage of water through the dam body and its foundations, which is the gradual flow of water from the top of the dam to the dam course **(Ade et al., 2019).** Water seepage causes significant water loss, especially in arid regions, and may also compromise the stability of the earthen dam. Therefore, controlling water seepage from high-permeability dams is one of the most difficult challenges affecting the stability of the dam**(Abass and Najeeb, 2018).** The rate of seepage under the foundations of hydraulic structures is a very important problem in design and construction. The properties of the foundation material, as well as the dams, determine the extent of

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.06.04

Article received: 03/11/2024
Article revised: 17/03/2025
Article accepted: 27/03/2025
Article published: 01/06/2025

seepage through and under the dams **(Farooq et al., 2015).** Seepage becomes undesirable if it compromises the integrity of the dam by eroding the downstream dam as fine material erodes and moves out of the dam, depositing in the pipes that complete the earthen dam structure **(Jamel, 2018).** The foundation treatment constitutes a critical step in designing and developing safe structures. It can take various forms, types, and approaches. Aims are always directed toward minimizing seepage through the foundation channel to minimize water losses **(Adamo et al., 2018)**.

The flow of water seeping through a porous medium and under the foundation of an earthen dam can be determined mathematically using Laplace's equation **(Chouireb et al., 2023)**.

Because of Iraq's location on the northeastern edge, scientists have documented more than 80 major seismic events that occurred before 1900 AD, and this may be one of the reasons that affected the change in the composition of the dam foundation layers **(Khalaf and Al-Hadidi, 2023)**.

(Geo-Studio), a CAD-style software developed by Geo-Slope International solves seepage problems as well as groundwater problems in permeable soils using FEM. This software is used to calculate water seepage. The software calculates a variety of issues, including basic saturated steady-state problems, time-dependent saturation problems, as well as saturated/unsaturated problems **(Mohammed and Salih Ameen, 2024).**

To calculate the amount of seepage in the dam, the (Geo-Studio) program and the (SEEP/W) subprogram for 2018 were used. The Geo-Studio program uses the finite element method (FEM) as a basis for analyzing the seepage through the section of the earthen dam. **(Al-Nedawi and Al-Hadidi, 2020).** It is a general numerical modeling technique used to deal with highly nonlinear problems that depend on the size of the elements and the physical properties of the materials. The current (SEEP/W) model is suitable for geotechnical and other engineering projects, and the model can be used with confidence **(Jassam et al., 2020).** This is a general-purpose seepage analysis program that can handle both saturated and unsaturated flow conditions, enabling it to solve a variety of real-world problems similar to other seepage software packages **(Zedan et al., 2022).**

One mathematical way to calculate water flow is through Darcy's Law. Soil particles can be classified as either saturated or unsaturated. The formulation of Darcy's Law is as follows: **(Thieu et al., 2001)**

$$q = k^* i \quad (1)$$

Where: i = total head gradient
k= coefficient of permeability.

The seepage law for the heterogeneous predictive equation used for modeling is the Partial Differential Equation (PDE). This study incorporated Stability analysis into geo-studio software **(Malik and Karim, 2021)**.

(Darbandi et al., 2007) studied the analysis of the seepage behavior of the Oba Dam using the Finite Element Method (FEM). The chosen form for constructing both the dam bottom grid and the piezometric heads was the rectangular element grid, with the heads evaluated at the nodes. The coordinates of the water surface configuration of the seepage were also determined. The observations made in this case were then compared with those derived from the flow network approach. The method under consideration was found to be suitable for analysis in this context.

(Irzooki, 2016) studied three different cases of water flow effect in an earthen dam using Geo-Studio software. The study changed the geometrical properties such as dam slopes, height, drain length, and free boundaries. These simulation results indicate that the water flow rate increases with the height of the dam geometry and the water level in the reservoir. However, it has an inverse relationship with the top width and free boundary height. **(Kirra et al., 2015)** used finite element modeling through the (Geo-Studio) program to solve seepage problems in earthen dams, where Mandali Dam (Iraq) was chosen as a model for seepage analysis by simulating the adopted model under three operational situations, including end of construction before filling the reservoir, steady state seepage, and rapid reservoir withdrawal. The safety evaluation of Mandali Dam against combined seepage and slope stability proved to be positive in each operational situation. **(Hadi and Mohammed, 2024)** studied the verification analysis of the types of regular measurements with their recorded values for Haditha Dam, studied for their conformity with international standards for monitoring and control procedures, such as the International Commission on Large Dams (ICOLD) procedures, as well as other methods for safe and efficient operation of the dam. The results of the data analysis showed that the seepage rate through the dam body was within the permissible limits.

(Hashim and Al-Hadidi, 2021) used the finite element method through a computer program called (Geo-Studio) and its subprogram (SEEP/W 2018) to analyze the seepage under or inside the Kunjali earth dam or at the place where the two sides come into contact under pressure due to the difference in water level in the subsurface and deep structure. Several tests were conducted through the Kunjali dam in different scenarios, such as empty reservoir conditions and normal and maximum water head conditions. The final results of the analysis study revealed that the dam is safe. **(Ghali and Azzubaidi, 2021)** developed a one-dimensional hydraulic model for flow simulation as they examined flood outlet management for Hamrin Dam. Eighty-two cross-sections were obtained from the digital elevation model of the outlet points to serve as engineering data. The designers proposed to install a spillway at the outlet inlet location. **(Alzamily and Abed, 2022)** studied the proposal to use clay soil in the core of the dam, where several experiments were conducted to test the permeability of clay and sandy soils with additives. The numerical model was selected using (Geo-Studio) program in the branch (SEEP/W). The comparison between the simulated and actual cases showed that the two cases were in good agreement with the seepage lines as well as with the specified amount of seepage water. **(Zedan et al., 2022)** studied the applicability of the finite element method in analyzing the stability capacity of soil under different conditions. All these data were used in (Geo-studio) software to determine the stability of the dam. The seepage to varying stages of the seep reservoir, maximum, average, and minimum, was calculated. Other parameters, such as the permeability of layers, were also included, and the results indicated that as the permeability of the layers increases, the exit slope decreases with the increase of seepage through the dam body. The safety values of upstream and downstream slope stability reached the minimal required standards for all levels of water.

(Malik and Karim, 2021) studied the slope stability of Haditha Earth Dam by analyzing the slope stability of the dam and finite element modeling. To evaluate the seepage, the maximum water level at the time of seepage was continuously taken into account. Three different water levels, including maximum, normal, and minimum, were used to analyze the slope stability limits, which included nine different balanced slope stability limits, and it can be observed that the dam is safe in terms of stability despite the modified earthquake conditions in Iraq**.**

(Anjali and Hangargekar, 2017) used the finite element method of (Geo-Studio) software and analyzed the seepage of the Ujani Dam located in Maharashtra. Seepage losses through the earthen dam and from the graph were determined, and the individual series water line of the dam was constructed. Actual field results were compared with the results obtained from the SEEP/W sub-product. If the values indicate good agreement, we can recommend this model for such use. **(Fattah et al., 2012)** studied the sedimentation rate and pore water pressure dissipation rate mainly through soil permeability. Laboratory and field tests showed that permeability changes during the loading and consolidation process. Its effect on the consolidation properties of the clay layer was studied. The finite element method was used in the analysis, and the Geo-Slope package was adopted by linking (SIGMA/W) and (SEEP/W) software. The relationship between applied pressure and permeability was determined experimentally for three samples. It was concluded that the effect of permeability is obvious at later times of consolidation due to the decrease in void ratio and, hence, slower dissipation of pore water pressure.

(Jassam and Abdulrazzaq, 2019) used the SEEP/W program to measure the amount of seepage flow through homogeneous and heterogeneous earth dams whose dimensions were well known. The analysis results showed that the variation between seepage and water height from the top of the dam to the length of saturated soil was curvilinear for the homogeneous dam. At the same time, it was linear and increased with water height from the top of the dam to the size of the heterogeneous dam. Also, seepage was higher in saturated soil, and the minimum seepage analysis was obtained for both homogeneous and heterogeneous earth dams.**(Ali and Al-Hadidi, 2024)** prepared a numerical model using Geo-Studio software, which proves that concrete piles can be used as breakers to control seepage effectively. The Al-Kifil regulator was chosen as a test case, and an accurate reproduction was created with the help of a reading study of the measuring device, which was satisfactory and used to confirm the effectiveness of concrete piles. Three cases were used (with and without the pull-out technique), and it was observed that the safety factor against lifting pressure would decrease to a lower value than in the case where the pull-out technique was applied. Thus, the pull-out reduces the safety factor against lifting pressure. Lebanese broken concrete piles as breakers or reduced seepage over time need to be provided with hydraulic structures to minimize seepage. **(Al-Sultani and Al-Hadidi, 2023)** used Geo-studio SEEP/W software to determine the amount of seepage flow that occurred under the AL-Hindiya Dam under different conditions, including source water level and outflow water level. This case was studied, and the efficiency of the cut-off wall feasibility was proven in the worst case. This is one of the safety criteria of the AL-Hindiya Dam. The finite element method was applied to the cut-off walls and downstream filters, and their ability to control the hydraulic outflow slope of the seepage and the uplift forces of the dams. **(Zarif Sanayei and Javdanian, 2020)** studied analytical solutions to steady-state water seepage problems through dams with asymmetric boundaries in the two-dimensional and three-dimensional world.

(Sissakian et al., 2021) analyzed and discussed the influence of karst rocks at the dam and reservoir site on the length and lateral span considerations of the Haditha Dam.**(Abbas and Al-hadidi, 2021)** used GeoStudio to analyze the seepage through the Al-Wind Dam using Seep/w and to ensure that the dam is safe from seepage**. (Danoosh and Al-Hadidi, 2022)** studied the seepage effect and slope stability analysis for three cycles using finite element

modeling through (Geo-Studio) software on the Permana earth channel during rapid drawdown conditions.
Therefore, the main objective of this research is to evaluate and calculate the amount of seepage in modern dam foundations under conditions of maximum water levels in line with the applicable standards for foundations using (Geo-studio 2018) program and (SEEP/W) subprogram during the past three decades.

2. METHODOLOGY

2.1 The Study Area

Haditha Earthen Dam is the second-largest dam in Iraq in terms of water storage and hydroelectric power generation. Located on the Euphrates River, 270 km northwest of Baghdad, between two latitudes. 34°11' 30'' - 34°13' 30'' north, longitudes 42°20'00" - 42°23'30" east, and 7 kilometers north of Hadith city **(Ibrahim et al., 2022)**. The location of Haditha Earth Dam is shown in **Fig. 1**

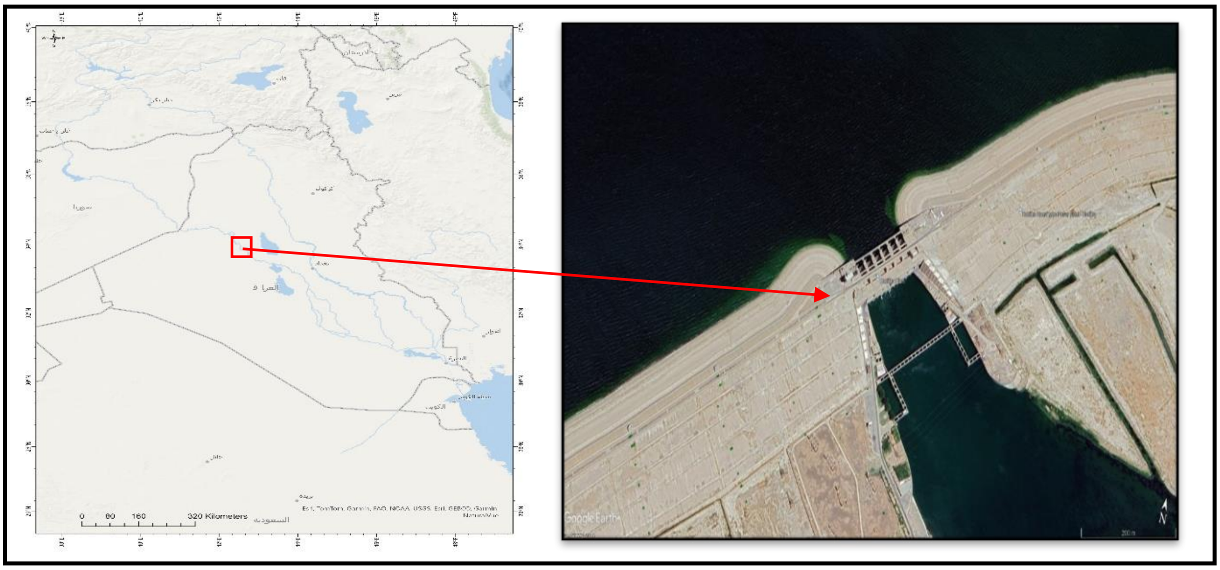
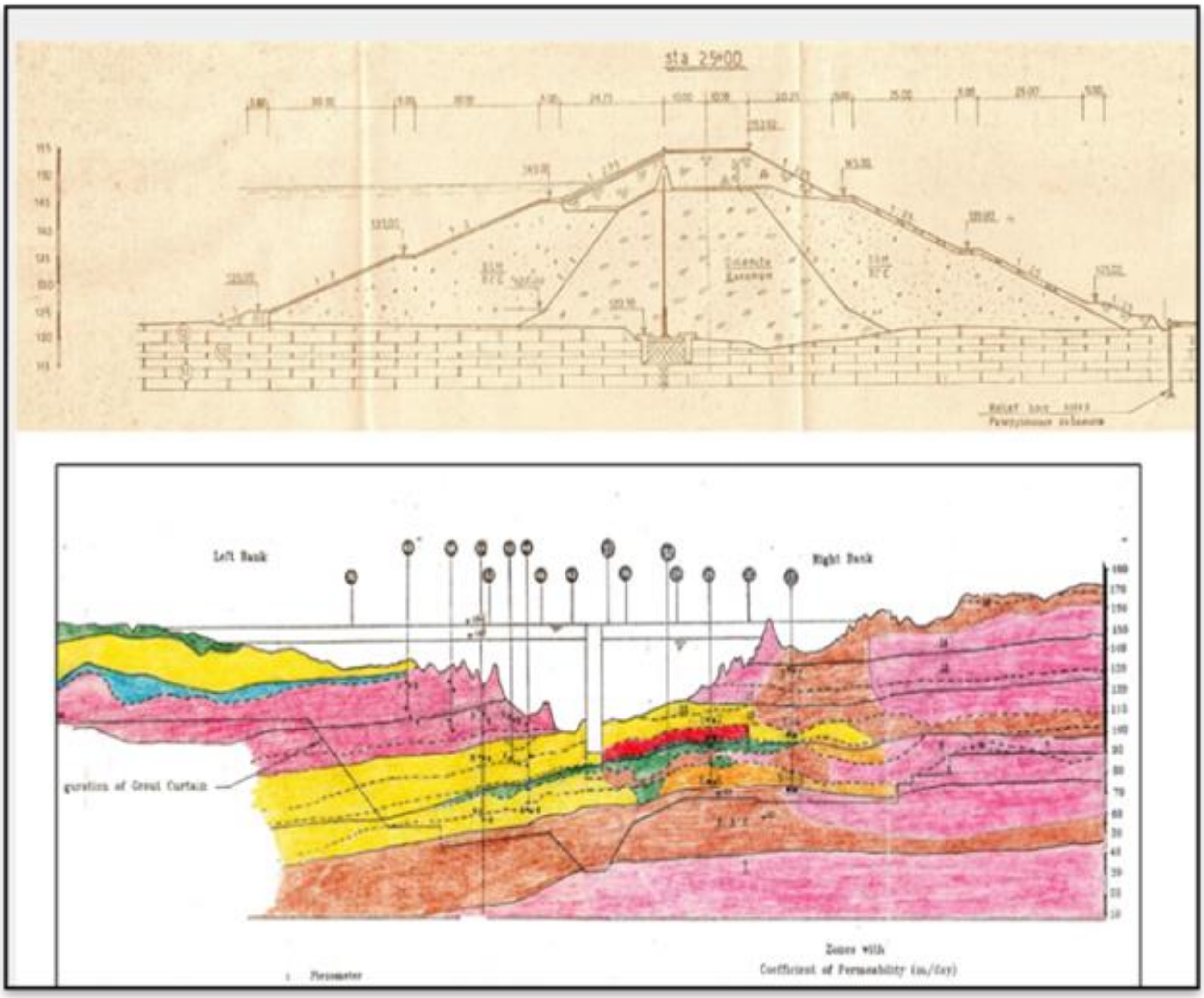


Figure 1. Location of Haditha Dam (Scale 1:200 m) (Google Earth).

In this study, the analysis of seepage in an earthen dam will utilize Haditha Dam as its main case study. It is one of the major dams that control the Euphrates River. Downstream from Haditha Dam, the level of the Euphrates River sits at nearly 110 m.a.m.s.l, and this level of the dam gradually decreases to 54 meters above sea level at Ramadi. Haditha Dam was built to store water and generate hydroelectric power **(Hashim and Azzubaidi, 2023)**.
The Dam is 9064 m long and 57 m in Maximum height. The crest of the dam is 20 m in width and has a top elevation height of 154 meters above sea level (m.a.s.l.). The formation of the actual body of the dam includes an asphaltic concrete cutoff **(Adamo et al., 2018**). Storage volume at operating level 8.28 billion cubic meters, storage surface area 500 square kilometers, flood level 150m above sea level (m.a.s.l.). The total storage capacity at flood level is 9.8 billion cubic meters, the minimum operational level is 129. 5 meters above sea level, and dead storage is 0.23 billion cubic meters **(Malik and Karim, 2020).**

The body of the dam consists of dolomite (core) and, on both sides (front and back), a mixture of gravel and sand (SMG), followed by a layer of stone (rip rap) on the back side and lined with concrete from level 125 to 154 .An asphalt concrete membrane was provided to extend inside the dam's core. The gaps between the dam foundations were sealed using an injection curtain, and the axis was extended to the right and left sides to reduce seepage (**The State Commission of Dams and Reservoirs, 2020).** Water content, volumetric water content, and residual water content in the dam casing are the most important factors, while hydraulic conductivity is the key element in the dam core **(Alzamily and Abed, 2022).**
Ninety cross sections were made in the dam on the right and left sides. The length of the right bank is 3310 m **(Adamo et al., 2018).**

We were provided with information about the dam's engineering, physical properties, and piezometric readings monitored by the Ministry of Water Resources for (section 25) of the dam located on the right side, after comparing the continuous data with the results generated by the program and with the rise in water levels in the dam reservoirs for the years (1989-2022), as shown in **Fig. 2**.



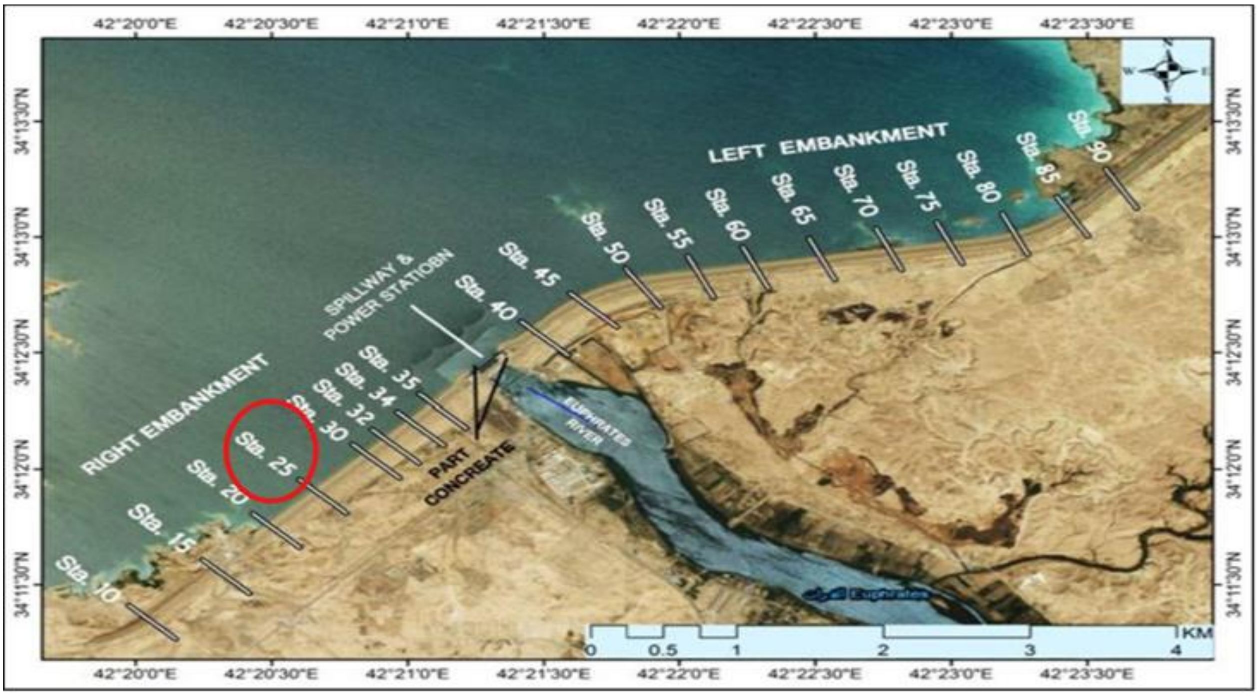


Figure 2. Typical Cross Station 25 of Haditha dam **(Ministry of Water Resources)**.

2.2 The Objective of Seepage Analysis

Due to the water scarcity in recent years and the drying up of some rivers, it has become necessary to monitor and calculate the seepage in earth dams to conserve water and suggest ways to reduce seepage under these dams.

3. SEEPAGE ANALYSIS OF HADITHA DAM

3.1 Geotechnical Characteristics of Haditha Dam

The following geotechnical properties of Haditha dam construction materials need to be specified in the software for modeling and calculating the amount of seepage, as shown in **Table 1.**

Table 1. Geotechnical characteristics of Haditha dam

Material		Saturated water content (%)	Coefficient of Permeability (m/s)	KY/KX Ratio
	Dolomites (Core)	0.35	1.15E-06	1
	SMG (Shells)	0.39	2.31E-04	1
	Rock	0.39	2.31E-04	1
	Grout certain	0.29	2.31E-06	1
	Asphaltic concrete diaphragm	0.16	1.00E-10	1
	Bench 1-12	0.29	4.63E-05	1
	Bench 10-11	0.29	5.79E-05	1
	Bench 9	0.29	1.74E-05	1

	Bench 8	0.29	8.10E-05	1
	Bench 6-7	0.29	5.79E-06	1
	Bench 5	0.29	1.74E-04	1
	Bench 2-3-4	0.29	5.79E-08	1

3.2 Boundary Conditions of the Model Upstream

I. Upstream (reservoir water level)
II. Downstream (zero pressure in the location of a relief well).

3.3 Finite Element Method and Formed Mesh by using (Seep/W) Software

The cross-section of station 25 was chosen for the seepage estimation because it is most exposed to the reservoir water pressure due to its location near the river bed and the high depth of the water in addition to the availability of a piezometer reading, with a length of 290 meters and a top elevation height 154 meters.
Three(two-dimensional) models of the body and foundations of the Haditha earthen dam were created based on the numerical simulation in the program for the period (1989-2022) divided into three decades according to the highest level in each decade in which the seepage is evident and according to the permeability of the soil layers. A suitable mesh of 9477 and 9647 nodes of the quadrilateral element type with a size of 2 m was chosen. The FEM mesh consists of four types of elements with triangular, square, rectangular, and trapezoidal shapes as shown in **Fig. 3.**

3.4 Validity of Model

Model validation is a crucial step in developing any model, ensuring that the model performs well on new data and achieves its intended purpose.
A simulation model incorporating all parameters of Haditha Dam was created for verification. In the Geo Studio program, the pore water pressure and piezometer readings were calculated by the program and compared with the field readings obtained from the Ministry of Water Resources.
It was noted that the piezometer reading in the program matches the field readings in a certain period, but does not match in another period.
After several attempts to create the model, we concluded that a model should be made for each period (10 years) to obtain a high-accuracy model due to the presence of gypsum soil in unspecified places in the dam foundations, which affects the change in the permeability of the layers. According to published research, the percentage of gypsum is (35.98%)**(Obead et al., 2020).**

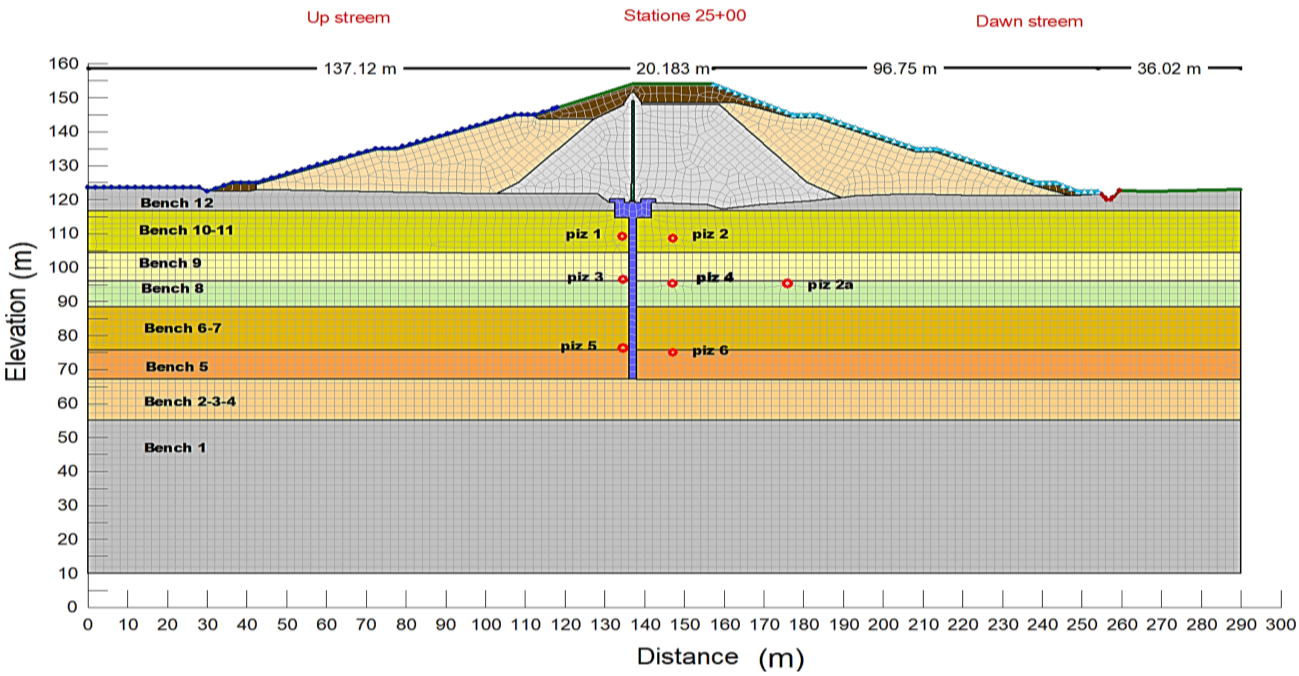


Figure 3. Finite element mesh of seepage analysis.

4. RESULTS AND DISCUSSION

4.1. Piezometer Reading and Pore Water Pressure

Three models were created for each period, estimated at 10 years; the cross-sections of the dam model below were obtained through (Geo-Studio) program. Note that in some years, the water levels are very low, and some piezometers are in a state of maintenance, so they are not included. The following figures show the results obtained from the models representing the period (1989-2022) where the piezometer reading (observed Head) and p.w.p (simulated Head) were calculated, as shown in **Figs. 4** to **10.**

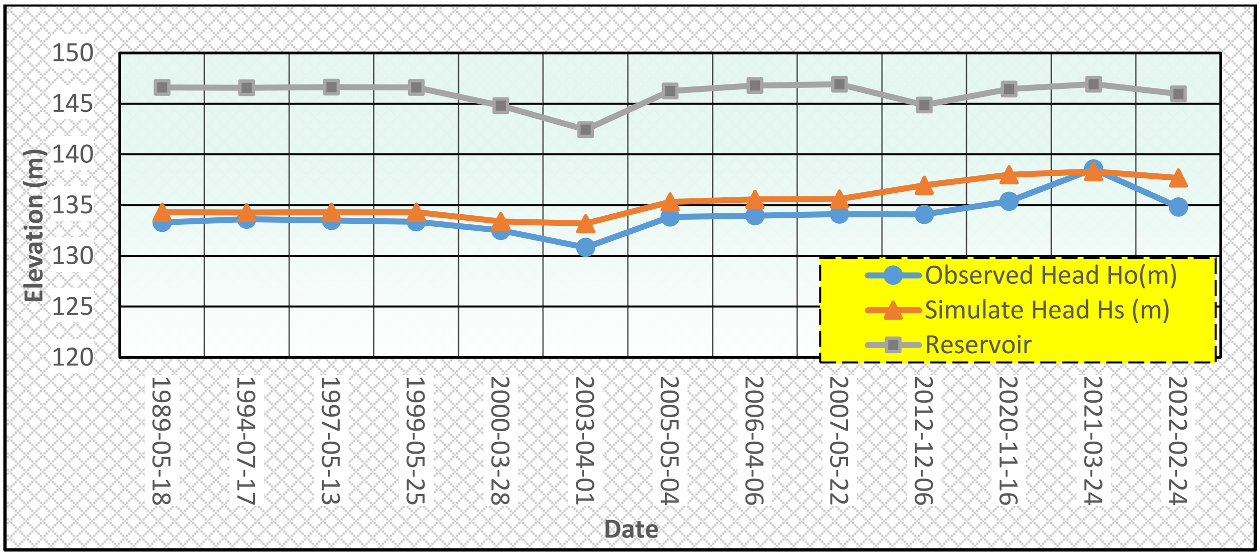


Figure 4. (Pizo25-1) observed Head (Ho), simulated Head (HS), and reservoir level.

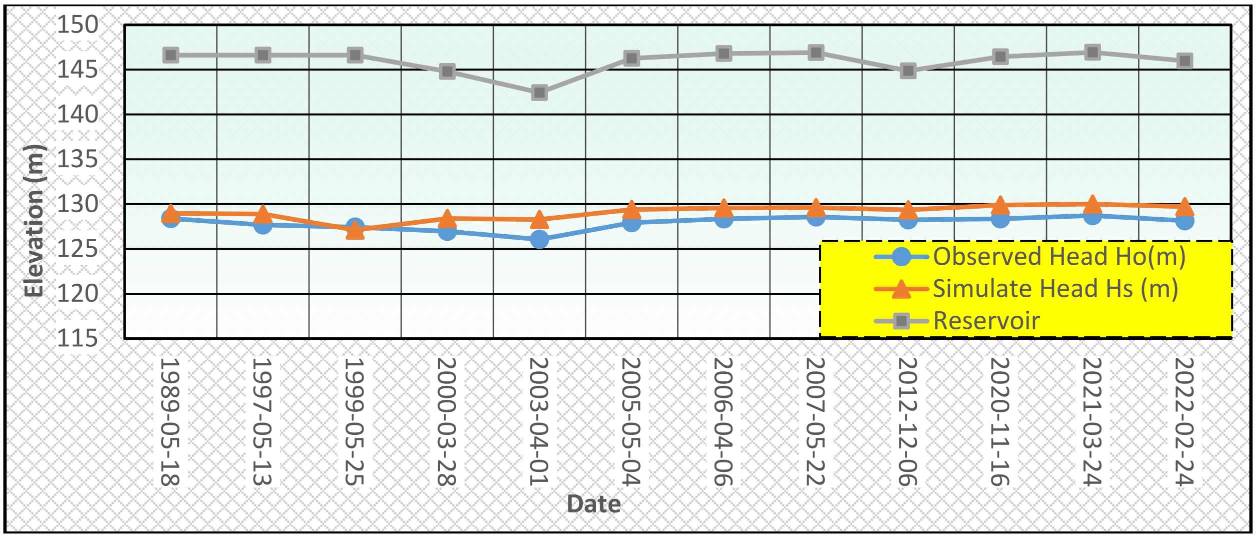


Figure 5. (Pizo25-2) observed Head (Ho), simulated Head (HS), and reservoir level

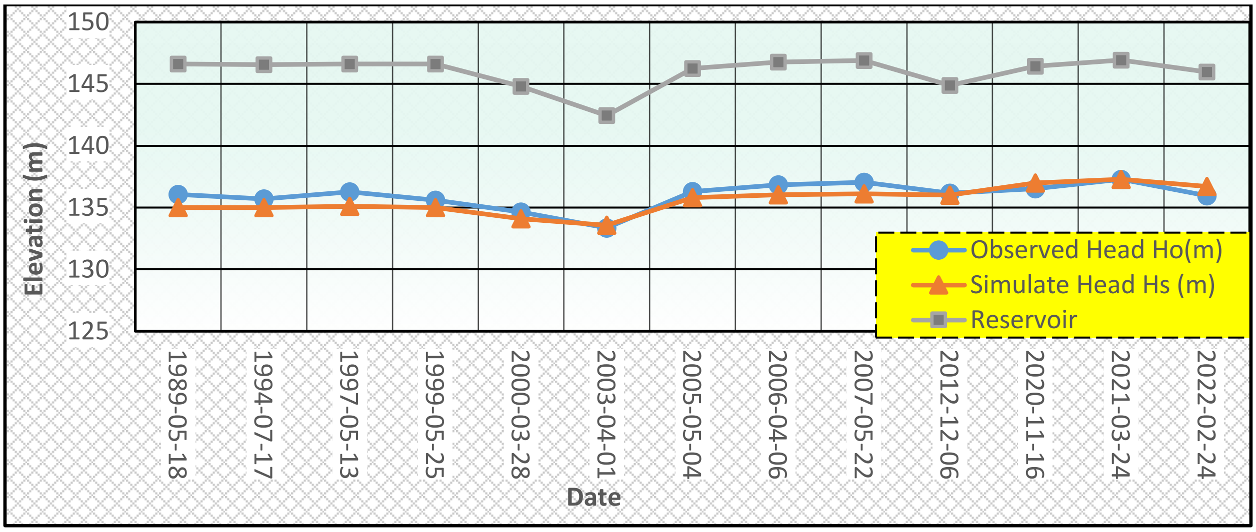


Figure 6. (Pizo25-3) observed Head (Ho), simulated Head (HS), and reservoir level

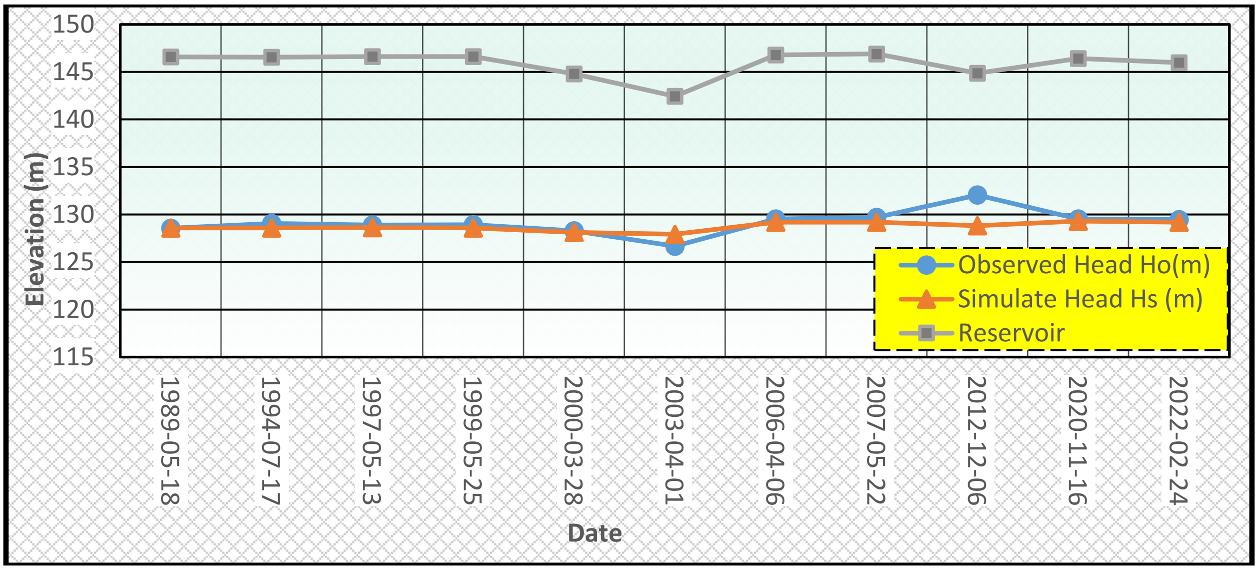


Figure 7. (Pizo25-4) observed Head (Ho), simulated Head (HS), and reservoir level.

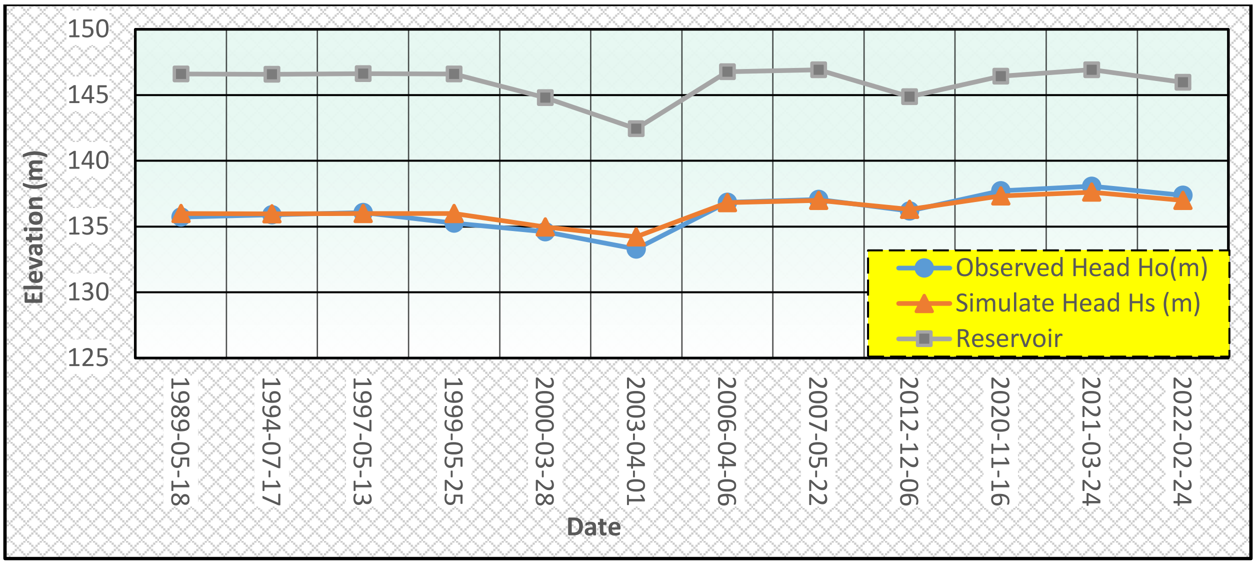


Figure 8. (Pizo25-5) observed Head (Ho), simulated Head (HS), and reservoir level.

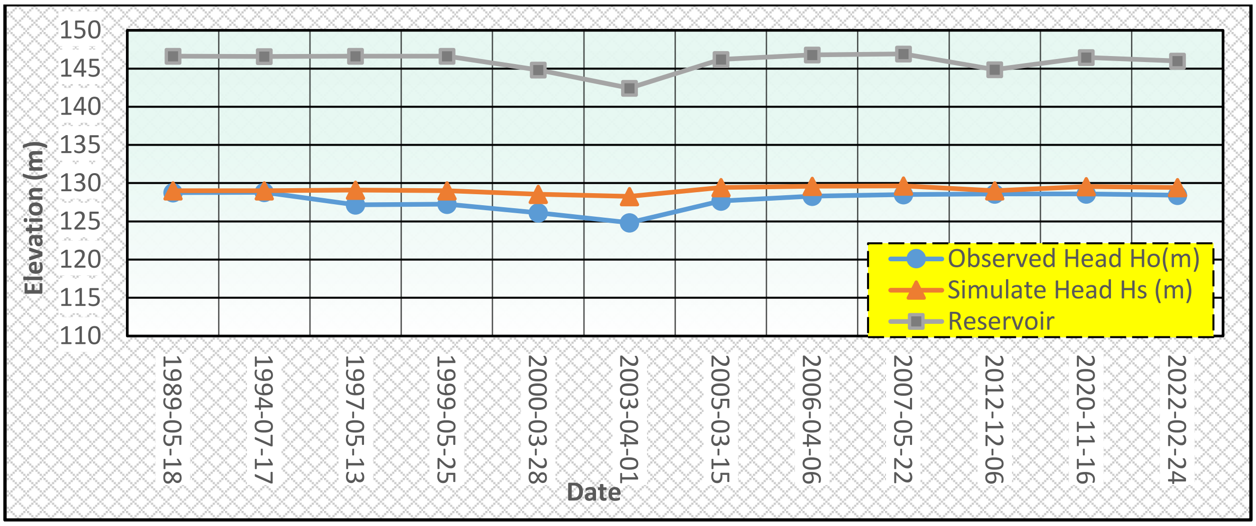


Figure 9. (Pizo25-6) observed Head (Ho), simulated Head (HS), and reservoir level.

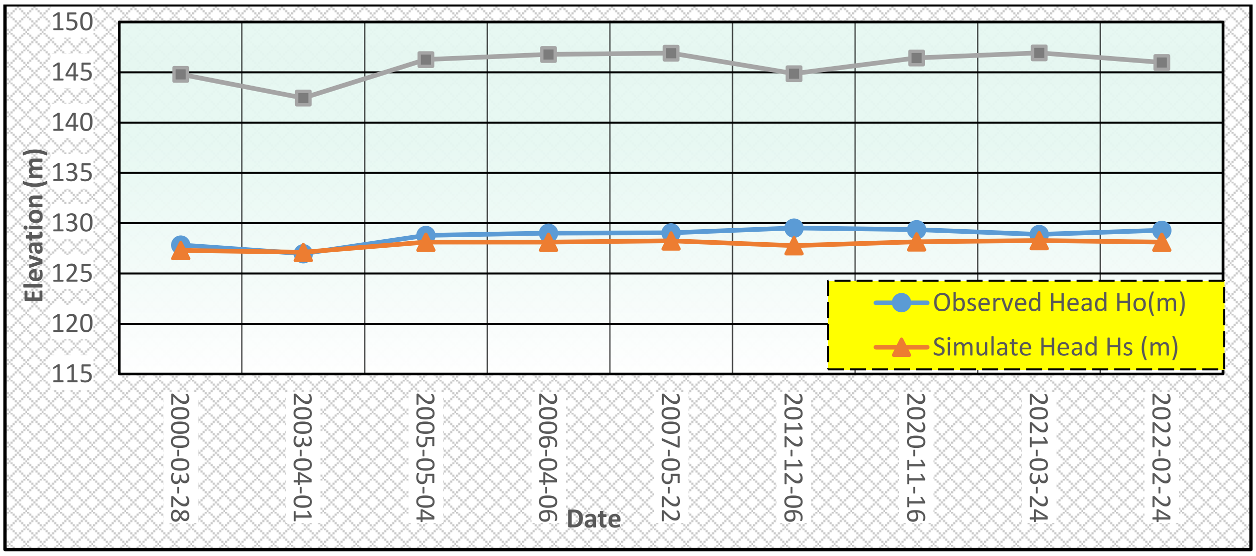


Figure 10. (Pizo25-2a) observed Head (Ho), simulated Head (HS), and reservoir level.

4.2 Statistical Analysis

In this analysis, the model performance and validity are evaluated using available data. Any model is measured with the help of statistical criteria; some of these criteria are Root Mean Square Error (RMSE) and Model Efficiency (EF), which have been used to evaluate the performance of the model. The Statistical parameters are shown in **Table 5**.

Table 5. Statistical parameter model.

Model no.	Statistical parameters	
	Root Mean Square Error (RMSE)	**Model Efficiency (EF) %**
1	0.9317	91.66
2	0.9190	90.36
3	0.9165	90.26

Correlations (Root Mean Square Error (RMSE) for the three models are shown in **Fig.11**

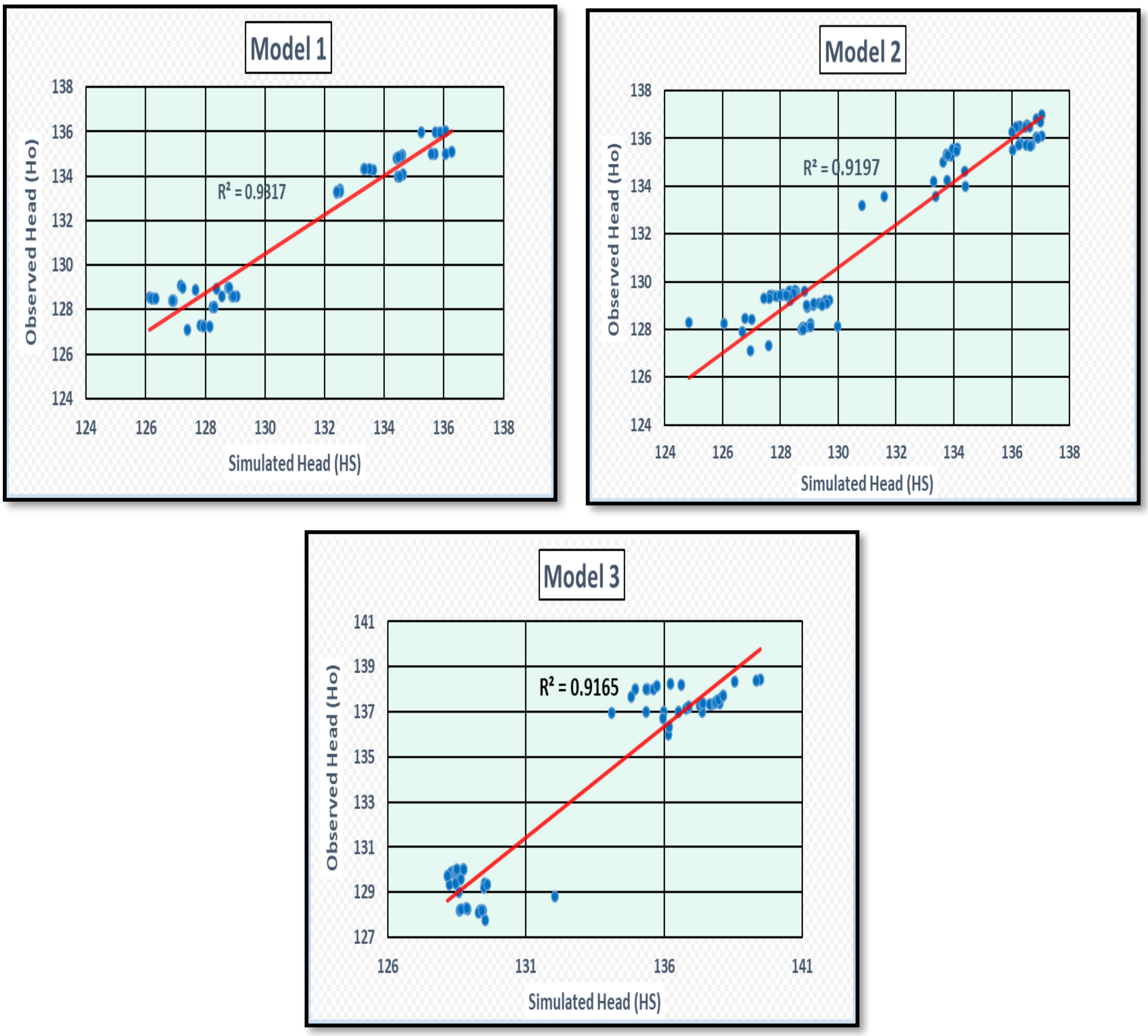


Figure 11. Root Mean Square Error (RMSE) for the three models

4.3 Seepage at Maximum Level

After completing the three models, demonstrating their efficiency, and knowing the amount of seepage over the past decades.
It was concluded that if the water level reaches the highest level, which is the operational level of 147.08 (m.a.s.l), then the amount of seepage obtained from the three models is shown in **Table 6.**

Table 6. Amount of seepage in the three models.

Model no.	water level	amount of seepage (m^3/sec)
1	147.08	0.0002913
2		0.0003135
3		0.0003696

The difference in seepage between the first and second models for the first and second decades for the highest water level reached by the reservoir is (7.62%) and the percentage of seepage between the second and third models for the second and third decades is (17.89%) Therefore, the dropout rate of seepage is increasing. The following figures obtained from the (Geo-Studio) program show the amount of seepage through the dam foundations when the water level reaches 147.08 m, which is the highest level reached by the reservoir during the past decades. When the seepage in the first model is shown in **Fig. 12**, the seepage in the second model is shown in **Fig. 13**

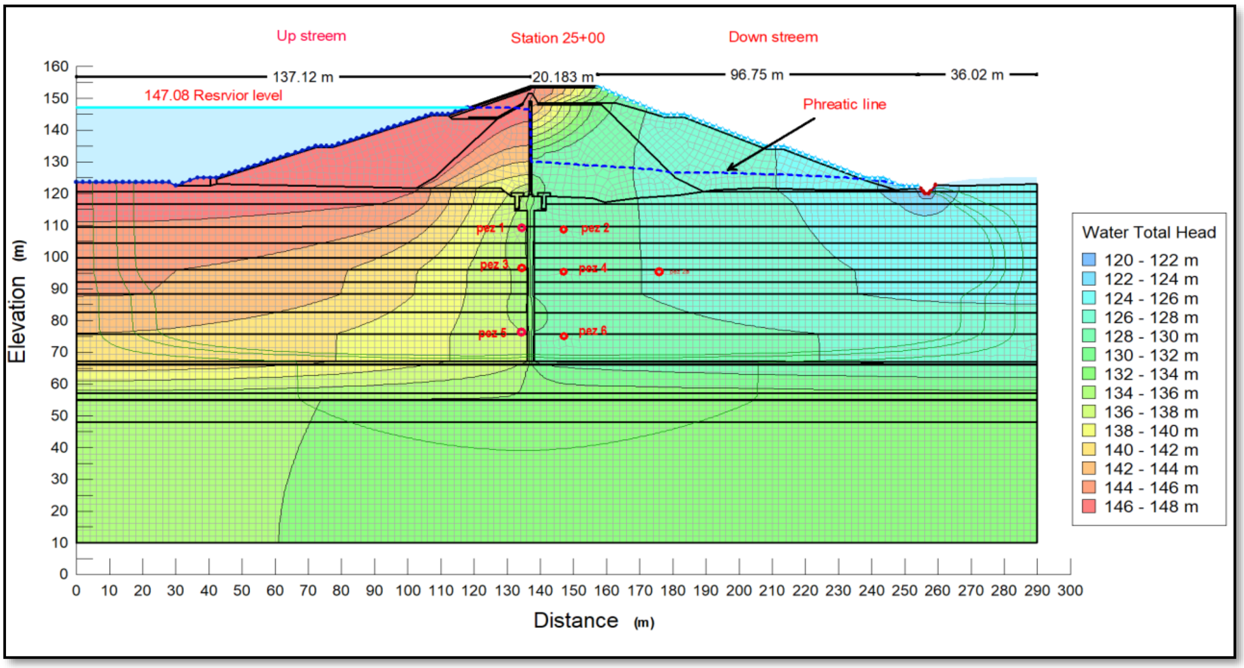


Figure 12. Seepage analysis at water level (147.08) in the first model period (1989-2000).

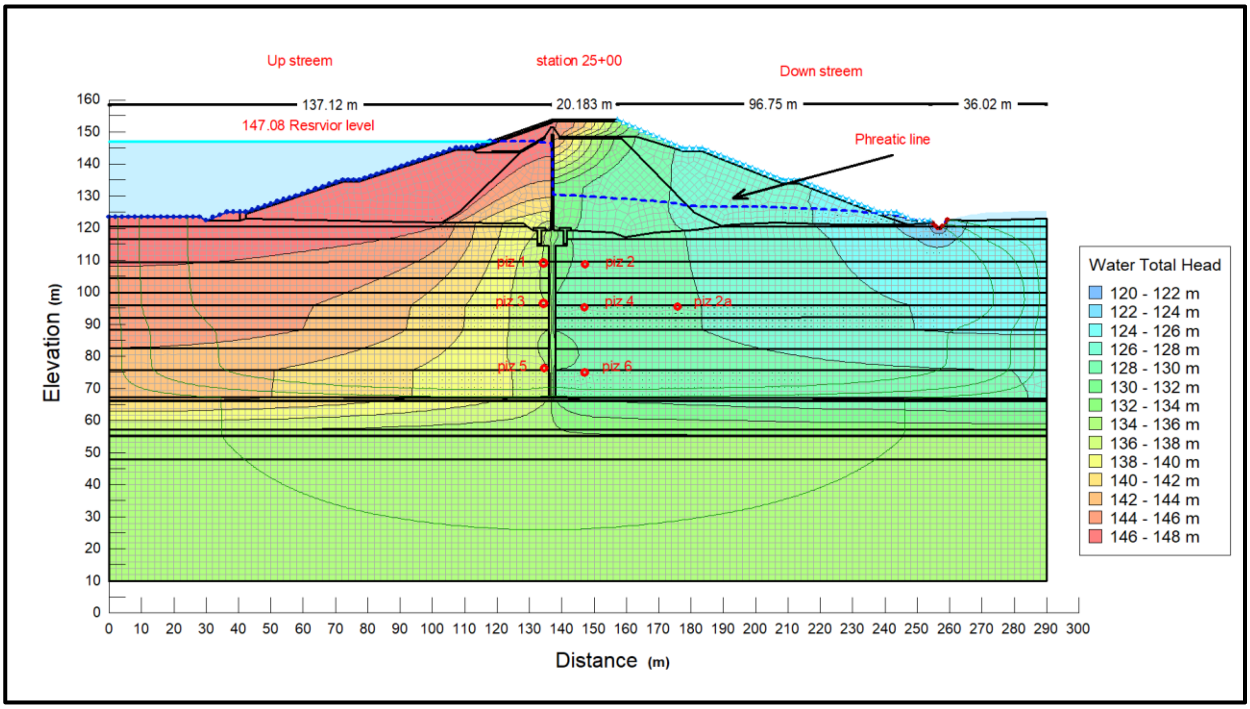


Figure 13. Seepage analysis at water level (147.08) in the second model period (2001-2010).

The seepage in the third model is shown in **Fig. 14**

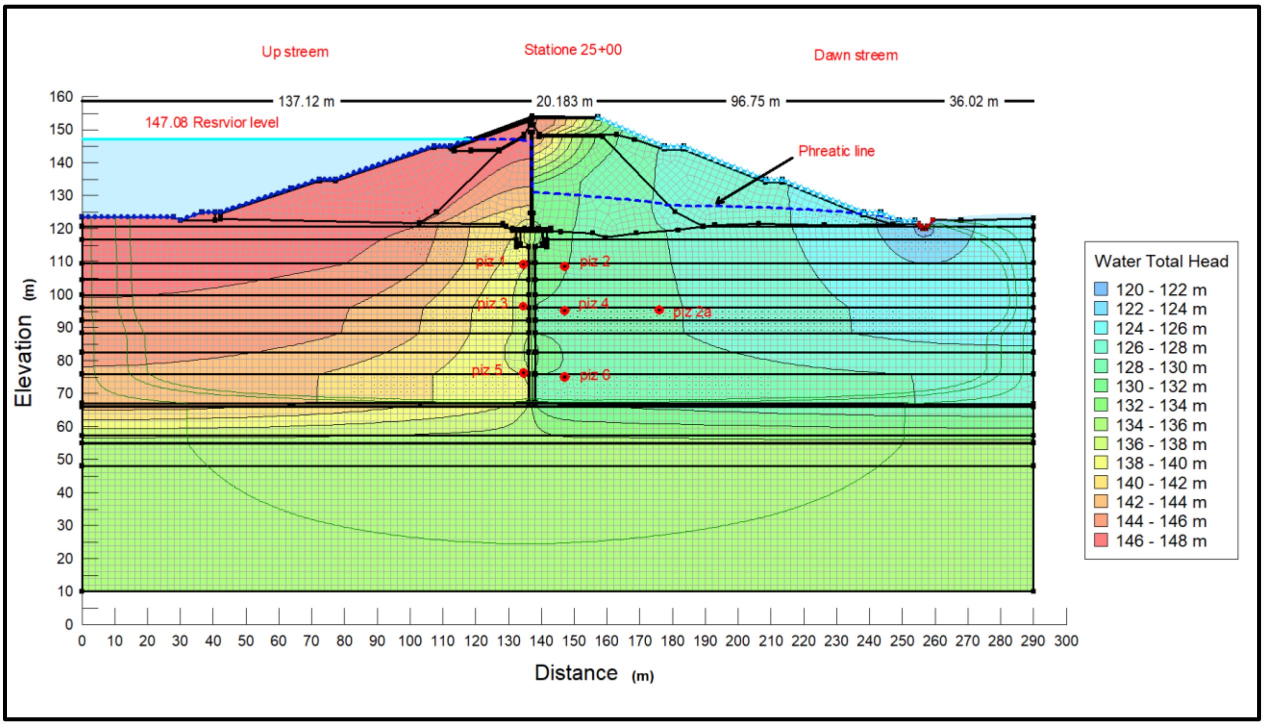


Figure 14. Seepage analysis at water level (147.08) in the third model period (2011-2022).

5. CONCLUSIONS

In this study, the Geo-Studio (SEEP/W) program was utilized to calculate seepage in the Haditha Earth Dam. Based on the analysis, the following conclusions were drawn:

1- The SEEP/W program effectively simulated seepage conditions in the dam. The computed seepage values closely matched field measurements, demonstrating the program's reliability in modeling real dam conditions.

2-Through the results obtained, it was found that when the water level reached its highest level in the dam during the past three decades (147.08 m), the seepage amount increased between the first and second decades by (0.000022 m^3/s) or (7.62%), and increased between the second and third decades by (0.000056 m^3/s) or (17.89%), indicating a change in soil permeability that can be attributed to the presence of soluble gypsum materials over time and thus a change in the foundation layers of the dam or due to the earthquakes that Iraq is exposed to as it is located within the earthquake zone.

3 -These increases are considered small for a long period, three decades, and do not affect the stability of the dam. While climate change affected the Middle East severely, especially our country, Iraq, reducing seepage loss in dams will be an important research topic to be recommended for future works.

Acknowledgments

The author would like to thank the General Authority for Dams and Reservoirs and the Haditha Dam Administration of the Ministry of Water Resources in Iraq for their cooperation in providing him with the necessary data for this research. Also, the author would like to extend his thanks to the Department of Water Resources Engineering at the College of Engineering at the University of Baghdad also helped in completing this research.

Credit Authorship Contribution Statement

Ola Mohammed Suad: Writing the original draft, Software, Validation, and Methodology. Maysam Thamer Al-Hadidi: Results analysis and proofreading.

Declaration of Competing Interest

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

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تحليل التسرب في أساس سد حديثة خلال العقود الماضية

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الخلاصة

التسرب تحت السدود الترابية يعتبر عاملاً رئيسياً في استقرارها.وقد أظهرت الإحصائيات أن 40% من حالات فشل السدود ناجمة عن تسرب الأساس. في هذه الدراسة، تم استخدام طريقة العناصر المحدودة لحساب مقدار التسرب تحت (سد حديثة) الواقع على نهر الفرات. تم إنشاء نموذج محاكاة لكل عقد من الزمن، وتم حساب مقدار التسرب لثلاثة عقود. أظهرت النتائج تطابقاً في القيم وأن مقدار التسرب بين العقد الأول والثاني زاد بمقدار (0.000022 م³/ث) أو (7.62%). كما زاد مقدار التسرب بين العقد الثاني والثالث بمقدار (0.000056 م³/ث) أو (17.89%). هذه الزيادة تعتبر قليلة لثلاثة عقود ولا تؤثر على استقرار السد. لذلك، مع التغيرات المناخية وتراجع مصادر إمدادات المياه، من الضروري معالجة هذه المسألة ووضع الحل الأفضل لها.

الكلمات المفتاحية: سد حديثة, جيو–ستوديو, موديل, تحليل التسرب