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A study on seepage data utilized in the safety assessment of Haditha Dam: A simulation by SEEP/W model

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Abstract

Background: Special attention should be given to the seepage in dams since it may cause failure. Seepage is not considered in the total risk factor calculated using the International Commission of Large Dams (ICOLD), the United States Bureau Reclamation (USBR) while the description of the dam seepage condition is given a weightage in the Brazilian method.

Methods: Haditha Dam, Iraq, was constructed on varying degrees of limestone beds of the Euphrates and Ana formations. Therefore, seepage from the dam should be continuously monitored and accurately measured. In the present study, a methodology was proposed to overcome the problem of inconsistent seepage data. The inconsistent seepage rates can be replaced by the predicted seepage rates obtained from SEEP/W model.

Results: The predicted seepage rates for different water levels in the reservoir of Haditha Dam were found in association ($R^2 = 0.96$). In addition, the value of mean absolute error (MAE) for the model accuracy was found to be 0.0106. According to the Brazilian index, the weightage for the seepage condition of Haditha dam was in the second category and equal to 3.

Conclusion: For Haditha Dam, the seepage data cannot be used in the dam risk assessment since it was inconsistent with gaps, and it can be replaced by the consistent predicted seepage rates predicted by SEEP/W model. Generally, the aging and other dam problems result in increasing seepage rate. This highlights the importance of efficient management that follows resilient monitoring and surveillance programs that ensure dam safety.

Keywords: Inconsistency, Seepage, Haditha dam, SEEP/W, Safety

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Introduction

The resilient design method of an earth dam should enable the designer to try many types of impermeable cores and shells in a dam section. However, the designer will recommend the combination of shell and core that will result in minimum possible seepage. This shows how an earth dam's resilient design method will contribute to dam safety. On the other hand, the allowable seepage rate from an earth dam varies from dam to dam depending on the material used in the construction and degree of compaction. For example, for Burn Creek Dam, Oklahoma, USA, the average seepage rate was 82 L/day (1).

Dam safety is coordinated activities related to dam surveillance and visual monitoring that follow approved international procedures. The activities may be conducted daily, weekly, monthly, biannually, and annually, and include data collection and monitoring including the condition of dam components. A dam may be owned by the government or private company, and dam safety is the main responsibility of the owner (operator). According to the study by Salari et al (2), about 30%–50% of earth dam failures result from seepage through the dams. However, seepage was the second cause of dam failure in the United States (3). Therefore, it is important to accurately monitor the seepage rate from earth dams and compare it with the allowable rate. Many studies focused on the simulation of seepage through earth dams in Iraq using SEEP/W model (4-7). Al-Nedawi and Al-Hadidi (8) studied the impact of minimum, normal, and maximum water levels in the reservoir of Hemrin Dam in Iraq on seepage, pore water pressure, phreatic line, and stability of the downstream slope of the dam using SEEP/W and SLOPE/W. The same methodology was followed by Al-Hadidi and Hashim (9) for Kongele Earth Dam, Iraq. Whereas, Zedan et al (10) analyzed the seepage in Shirin Dam, Iraq, and found that the dam core can reduce seepage by 99%.

Many studies investigated the effects of dimensions, geometry, and side slopes of earth dam zones on seepage rates (8,9,11-14). However, Aboelela (15) tested the performance of different seepage control methods. On the other hand, mathematical solutions were developed to study the efficiency of seepage control measures in earth-fill dams (16,17). To increase the accuracy of the seepage measurement from earth dams, Lee et al (18) highlighted the importance of excluding rainfall from the seepage rate. Figure 1 shows the correlation between the water level in the reservoir of a dam in Korea with the measured and predicted seepage rates (18). The predicted seepage rate for the above-mentioned dam was obtained by applying a simplified two-dimensional finite element method proposed by Chapuis and Aubertin (19).

The seepage in an earth embankment dam was arranged using probability methods (20). The effect of different characteristics of the dam shell and core materials on seepage was simulated experimentally using a laboratory scale model and numerically using SEEP/W model (12,21-23). Salem et al (22) concluded that the SEEP/W model is sensitive to materials of core and shell, core geometry, and upstream and downstream slopes while Okeke et al (24) showed that the simulated seepage rates by SEEP/W model have been greatly affected by dam materials. The abnormal seepage in an earth dam was investigated using resistivity tomography by Lin et al (25) while the investigation was followed to develop strategies for minimizing seepage from an earth dam by Saberi Mehr and Field (26).

In this study, the acquired data on seepage rates and water levels in the reservoirs of Haditha Dam, Iraq, were cataloged and checked for their accuracy and consistency before they can be recommended to be used in dam safety assessment. A solution to replace the inconsistent seepage data of Hadith Dam with consistent data predicted by SEEP/W model was proposed. The predicted seepage rates by SEEP/W model were statistically tested for their accuracy and association with the reservoir water level. This makes this study important when compared to other published studies that were mainly focused on using SEEP/W model to simulate the impact of different core materials, core geometry, shell materials, side slopes, dam geometry, and control methods on seepage rates.

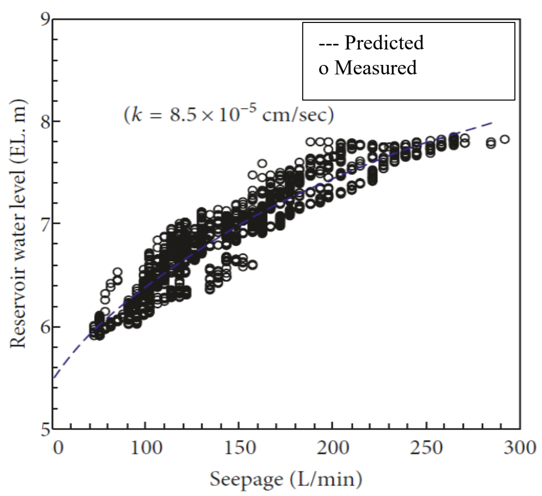

Figure 1. The correlated relationship between reservoir water level and seepage for an earth dam in Korea (18)

Materials and Methods

The methodology of the study includes the selection of the case study, data acquisition, data cataloging, checking the quality of seepage data, simulation of seepage rates (water flux rates) using SEEP/W model, validation of the model predictions, and prediction of seepage rates through Haditha Dam for various reservoir water levels. Ethically, the methodology to generate quality seepage data using a computer model is safer than employing technicians to collect the data at the dam site. Figure 2 summarizes the activities of the study methodology.

Description of Haditha Dam (the case study)

Haditha Dam is a zoned earth-fill dam located on the upper catchments of the Euphrates River, north of Haditha city, Al Anbar Governorate, Iraq. The location of the dam obtained by the State Commission of Dams and Reservoirs is shown in Figure 3 (27). The main objective of the dam construction is to produce electricity, regulate the flow of the Euphrates River, and supply irrigation water. Haditha Dam is the second-largest hydroelectric dam in Iraq. The dam construction began in 1977 and was completed in 1986. The dam embankment was constructed by the Ministry of Energy of the former Soviet Union while the power station was designed, equipped, and built by a consortium of companies from the former Republic of Yugoslavia (4).

The dam is located in a narrow section of the Euphrates Valley where a small auxiliary channel diverges from the main channel of the Euphrates River. The auxiliary channel was 50 m wide and houses the hydroelectric station while the main channel was 350 m wide. The Haditha Dam is 9064 m long, 57 m high, and with the hydropower station located 3310 m from the dam's southern edge. The dam's crest is 20 m wide and at 154 m above sea level (m.a.s.l.). The operational level of the reservoir is 147 (m.a.s.l). The Haditha reservoir has a maximum water storage of 8.3 km^3, which resulted in a maximum surface storage area of 500 km^2. The power station contains six Kaplan turbines capable of generating 660 MW. The maximum discharge over the spillway is 11 000 m^3/s. Two bottom outlets of the dam can pass a discharge of 3000 m^3/s for irrigation. The outlets and the spillway are controlled by tainted gates.

Characteristics of dam materials

The dam core includes an asphaltic concrete cutoff ($K = 1 \times 10^{-9}$ m/s), followed by mealy detrital dolomites

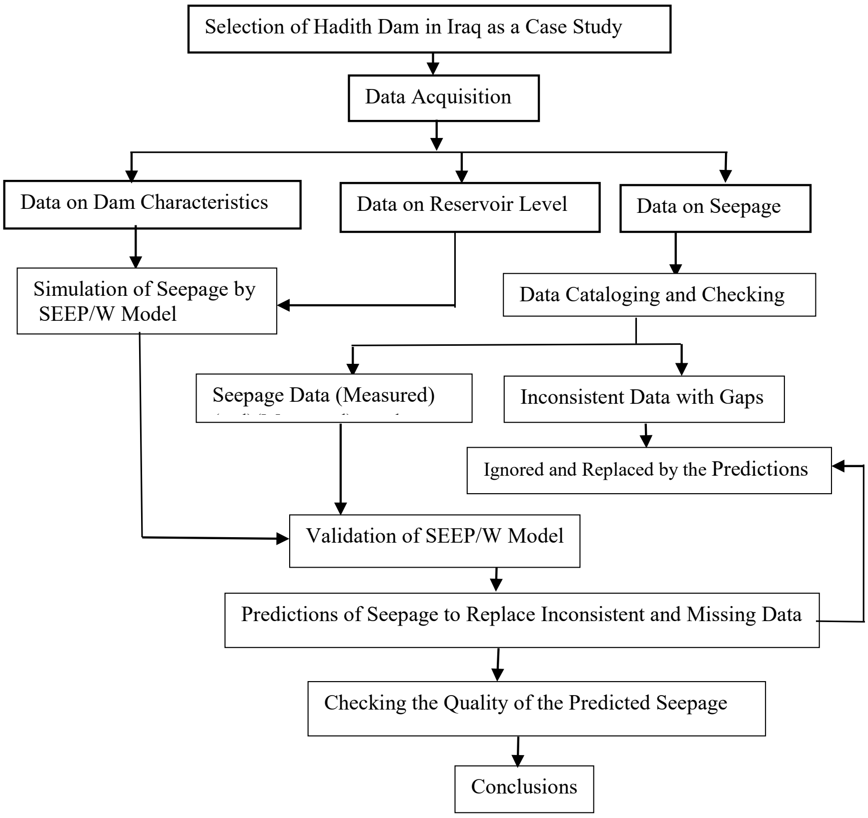

Figure 2. Flow chart of the study methodology

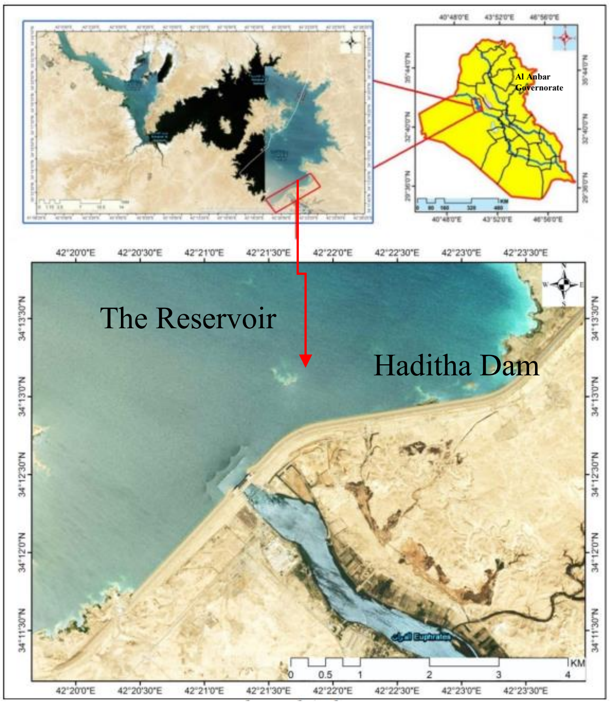

Figure 3. Location of Haditha Dam (26)

(1.15×10^{-8} m/s), and the dam shell was constructed from a sand and gravel combination ($K = 2.31 \times 10^{-6}$ m/s). These materials were chosen for the dam construction since they were available close to the dam site. Suitable traditional types of core materials were not found in adequate quantities during the earliest stages of the investigations, necessitating the search for an alternative solution.

The existence of vast quantities of dolomite drew the attention of the engineers to this mineral as a prospective construction material. It is claimed that dolomite has never been used as the primary construction material in a big dam previously. The dam was protected on the upstream side by a reinforced concrete slab revetment and on the downstream side by a rock-mass revetment. The total volume of materials used in the dam construction was 0.03 km^3. In this study, the data concerning Haditha Dam was acquired from the State Commission of Dams and Reservoirs, Ministry of Water Resources, Baghdad, Iraq.

Background of SEEP/W model

SEEP/W model is a numerical model used to simulate quantitatively a real physical process related to flowing water through porous media. SEEP/W is a submodule of the GEOSTUDIO simulation package and is based on the solution of the governing partial differential equation (Equation 1) using the finite element technique (28). The present study applies the SEEP/W to simulate the seepage (Flux rate) from Haditha Dam at three different locations and the simulation results after validation will be used for dam safety procedure.

$$\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial x} \qquad (1)$$

Where, H is hydraulic head (L); k_x and k_y are hydraulic conductivity values in x and y directions respectively (L/T), Q is applied boundary flux (L^3/T); t = time domain (T), and θ = volumetric water content (%).

The SEEP/W model is limited to be used for analyzing unconfined flow through an earth dam; and the results include total head contours, velocity vectors, and the location of the water table or zero pressure contour (28).

Checking the quality of the acquired data

The acquired data were arranged based on the dates at which seepage rates and reservoir water levels were measured at the dam site. To check the quality of the acquired data, seepage rates and reservoir water level for Haditha Dam were arranged in an ascending order (cataloged). The data cataloging will help check how the seepage through the dam varies with the reservoir water level. Simulation of seepage for various reservoir water levels is an alternative to replace the inconsistent data.

In SEEP/W model, seepage through Haditha Dam was defined as a steady state, and the scales, axes, and grids were fixed in the worksheet. In addition, the cross-section of Haditha Dam was drawn. Afterward, the material properties used in the construction of Haditha Dam as well as the boundary conditions were defined. However, the element sizes for the dam meshing of Haditha Dam should be selected in both horizontal and vertical directions. The model output was validated using measured seepage data at selected stations along the dam.

Results

The data were acquired from the State Commission of Dams and Reservoirs, Ministry of Water Resources, Baghdad, Iraq. The data included dam characteristics, location maps and dam sections, daily water level in the reservoir from 2002 to 2023, and the seepage rate in three selected stations in 2020. For reservoir water levels from 144.88 m to 146.67 m, the seepage rates through Haditha Dam were taken at three stations 25 + 05 m, 30 + 05 m, and 47 + 14 m. The seepage data were cataloged and checked before being used in dam safety assessment. The water level in the reservoir of Haditha Dam was plotted against the measured seepage rates. Table 1 and Figure 4 show that the variation of seepage rates with reservoir water levels was inconsistent. For example, when the reservoir water level was 144.88 m, the recorded seepage rates were 0.070 L/s, 0.14 L/s, and 0.23 L/s at stations of 25 + 07 m, 30 + 05 m, and 47 + 14 m, respectively. However, when the reservoir water level was increased to 145.97 m, the recorded seepage rates at the same stations were found to be 0.06 L/s, missing, and 0.24 L/s. Therefore, such inconsistent data cannot be used for the safety assessment of Haditha Dam. Alternatively, the simulation of seepage through Haditha Dam using SEEP/W model can replace the inconsistent seepage data. The simulation was conducted when the geometrical and material characteristics of Haditha Dam were defined in the SEEP/W model.

In addition, the simulation requires drawing the dam section with proper scale and defining the materials used in the construction of Haditha Dam. The permeability of dam materials was taken as 2.31×10^{-6}, 1.15×10^{-8}, and 1×10^{-9} m/s for shell, core (compacted dolomite), and asphaltic diaphragm, respectively (27). The mesh sizes and shapes were determined based on the accuracy of the model output. Figure 5 shows the cross-section of the

Table 1. Seepage data in 2020 arranged based on the increasing water levels in the reservoir of Hadith Dam

Date	Reservoir water level (m)	Seepage rate at Station 25 + 07 (L/s)	Seepage rate at Station 30 + 05 (L/s)	Seepage rate at Station 47 + 14 (L/s)
10/9	144.88	0.07	0.14	0.23
27/8	144.94	0.08	0.14	0.24
23/7	144.97	0.08	0.14	0.24
24/9	144.99	0.08	0.14	0.24
13/7	145.38	0.1	0.13	0.24
2/1	145.51	0.05	N.A.	0.25
28/1	145.53	0.05	N.A.	0.24
18/10	145.65	0.09	0.15	0.26
6/2	145.70	0.05	N.A.	0.24
25/2	145.90	0.06	N.A.	0.24
27/10	145.94	0.1	0.16	0.24
20/2	145.97	0.06	N.A.	0.24
12/3	145.99	0.06	N.A.	0.24
19/4	146.09	0.11	0.11	0.25
1/11	146.36	0.11	0.17	0.26
22/11	146.45	0.11	0.18	0.254
24/6	146.47	0.13	0.14	0.26
13/12	146.54	0.11	0.19	0.28
24/12	146.55	0.11	0.18	0.29
31/5	146.67	0.13	0.14	0.26

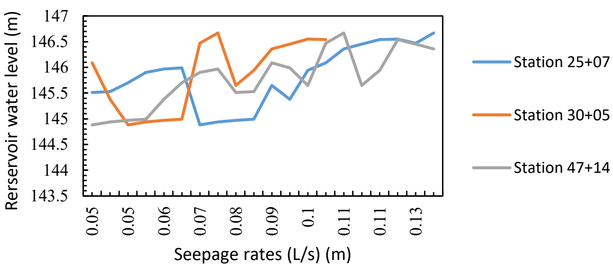

Figure 4. Variation of the recorded seepage rates with the water levels in the reservoir of Haditha Dam

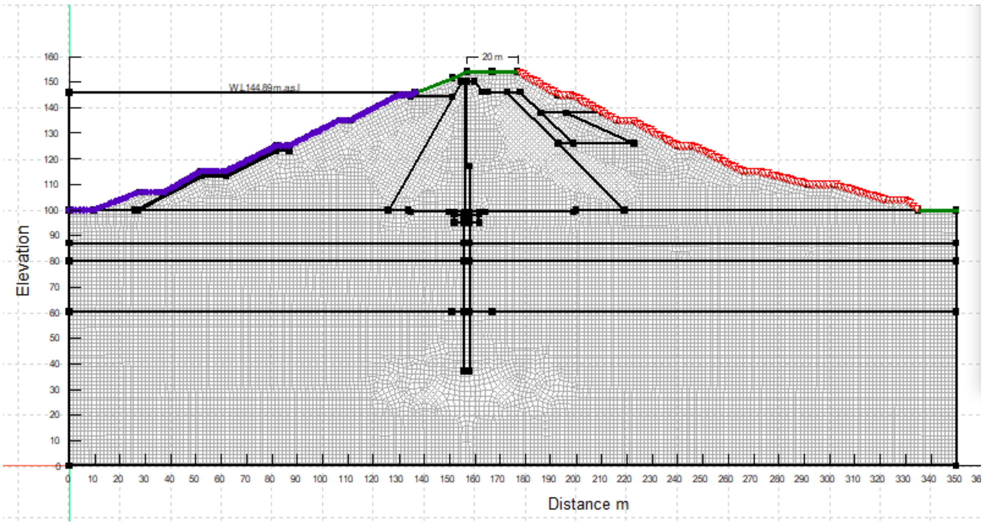

Figure 5. The meshing of Haditha Dam

dam with the meshing system. The total number of nodes and elements used in the dam section were found to be 19608 and 19353, respectively.

The measured seepage rates at a selected dam station were used to validate SEEP/W model as shown in Figure 6. The phreatic line (the topmost seepage line) of Haditha Dam for the reservoir water level of 144.88 m is shown in Figure 7. The predicted seepage rates for different reservoir water levels at three selected stations along Haditha Dam are shown in Figure 8.

According to the Brazilian index, the seepage conditions of a dam should be categorized and given a proper weightage as shown in Table 2. The weightage for the seepage condition of Haditha Dam was defined based on the monitoring and site observations. The seepage condition of Haditha Dam falls under the second category of Table 2 with a weightage of 3. For dam risk categorization, the weightage for the seepage condition of a dam should be determined to calculate the Brazilian index.

Discussion

Based on the field measurement and simulation results of a dam in Korea, Lee et al (18) proposed a nonlinear and direct relationship between the above-mentioned variables as shown in Figure 1. However, a general direct linear relationship between measured seepage rate and reservoir water level has been proposed by Torabi Haghighi et al (16). In addition, human error in the measurement is considered as one of the uncertainties in the seepage data of earth-fill dams (16). For Haditha Dam, the acquired data on seepage rates and reservoir water levels were cataloged and arranged in ascending order as shown in Table 1. The relationship shown in Figure 4 confirmed the inconsistency between the seepage rates and the water levels in the reservoir of Haditha Dam. Logically, the seepage rate increases the increase in the

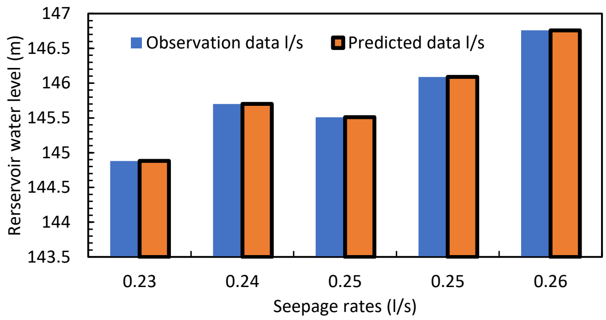

Figure 6. The validation of SEEP/W model

reservoir water level as shown in Figure 1. The degree of association between the recorded seepage rates and water levels in the reservoir of Haditha Dam at the stations of 25 + 07, 30 + 05, and 47 + 14 was assessed statistically by calculating the coefficient of determination (R^2). The values of the R^2 for the above-mentioned stations were found to be 0.35, 0.24, and 0.58, respectively. From the calculated values of R^2, it can be interpreted that the degree of association between the seepage rate and water level in the reservoir of Haditha Dam was found to be positive and weak at stations 25 + 07 and 30 + 05 while it was positive and moderate at station 47 + 14. Notably, high-quality seepage data should be used in the risk assessment of Haditha Dam or any other dam. Ansari et al (29) and Mohammad Rezapour Tabari and Mazak Mari (30) confirmed the accuracy of the SEEP/W model compared with the application of other seepage simulation methods while Zedan et al (10) demonstrated the capability of the model to simulate the seepage through Shirin earth dam under various operational and climatic conditions. Therefore, applying the SEEP/W model to predict the seepage rates through Haditha Dam is a solution to overcome the problem of inconsistency in the acquired seepage data. Before the application of SEEP/W model, the model was calibrated and validated using measured

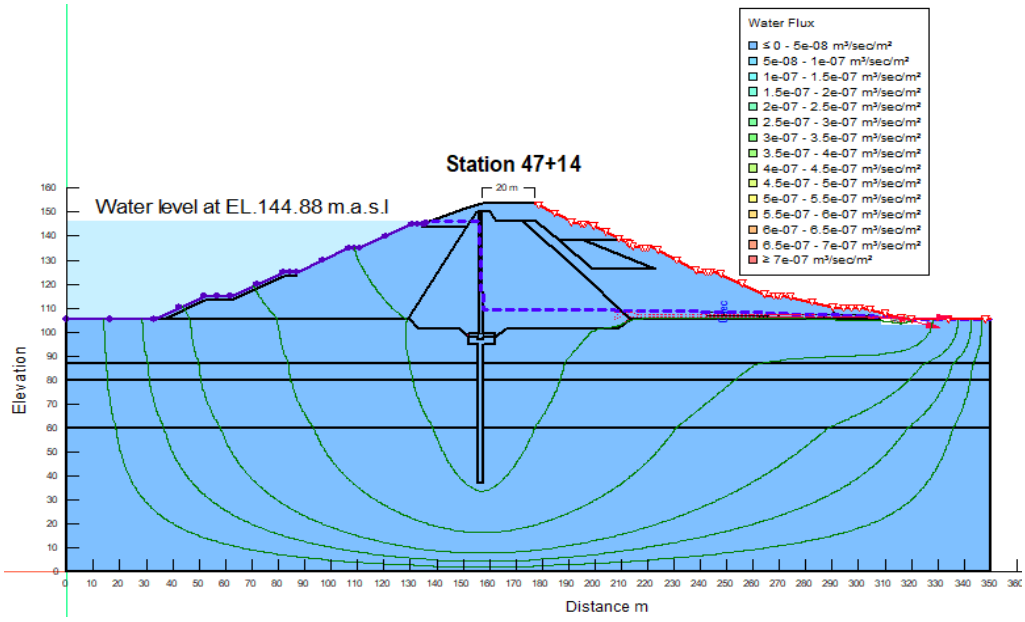

Figure 7. Simulation of the phreatic line and water flux (seepage rate) for Haditha Dam at station 47 + 14

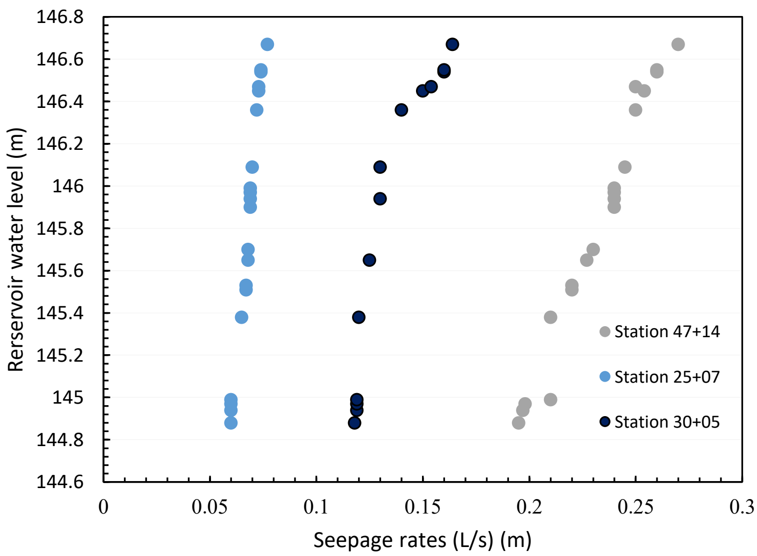

Figure 8. Variation of predicted seepage rates by SEEP/W model with the water levels

Table 2. Description of seepage conditions and their weightage as given by the Brazilian index (3)

No.	Description of dam condition	Weightage in total risk factor
1	Seepage is totally controlled by a drainage system	0
2	Stabilized and monitored wet areas in downstream areas, slopes, or abutments	3
3	Wet areas in downstream areas, slopes, or abutments without treatment or under investigation	5
4	Seepage emerging in downstream areas, slopes, or abutments with soil migration or increasing flow	8

seepage data. Figure 6 confirms the agreement between the predicted and measured seepage rates at a selected station of Haditha Dam ($R^2 = 0.93$). Also, the mean absolute error (MAE) was determined and found to be 0.0106, which confirms the accuracy of the model predictions. The MAE is a common measure of error in a model forecast. As shown in Figure 8, the predicted seepage rates at stations 25 + 07, 30 + 05, and 47 + 14 of Haditha Dam were found to be consistent with a high degree of association with the reservoir water levels. This is because the calculated values of R^2 for the predicted seepage rates of the above-mentioned stations were found to be 0.98, 0.96, and 0.98, respectively. In addition, the values of R^2 showed that the correlation between the predicted seepage rates and the water levels in the reservoir of Haditha Dam was positive and very strong.

Seepage is one of the important parameters used in dam safety since many dams were constructed on deep limestone beds in which the seepage through these dams became a critical issue. For example, the leakage through the foundation and abutments of Anchor Dam located in northwest Wyoming, the United States was related to the combination of gypsum karsts, limestone karsts, and other geologic features in the dam site. However, only a small quantity of water has been held in the reservoir (31). Geologically, Haditha Dam was constructed on various degrees of limestone beds of the Euphrates and Ana formations in the shape of fissures, cracks, and nearly isolated sinkholes. Adamo et al (32) reported the development of sinkholes at the site of Haditha Dam. In case of the collapse of sinkholes, the dam will be subjected to the risk of failure by seepage. To highlight the importance of seepage consideration in dam risk assessment, the Brazilian procedure allocated a weightage for a dam seepage condition as shown in Table 2. However, other existing dam safety procedures such as United States Bureau Reclamation (USBR), International Commission of Large Dams (ICOLD), New Zealand, and Malaysia do not include any weightage for the seepage conditions or seepage rate in dam safety assessment. On the other hand, the seepage conditions shown in Table 2 are also descriptive, subjective, and mainly depend on visual inspection at a dam site. In addition, there is no clear rating analysis for the dam risk index and class found in the Brazilin method. Conversely, ICOLD and USBR are described as indicator-based risk methods. According to Table 2 and based on site observations, the seepage condition of Haditha Dam can be described as wet areas of seepage that were stabilized downstream and it was given a weightage of 3. The seepage conditions of Haditha Dam were decided based on the site observations. Compared with the seepage rates of other dams, the seepage rates through Haditha Dam were found less than the critical values.

Conclusion

In this study, the acquired data on seepage rates and reservoir water level for Haditha Dam was cataloged and checked. The data were found inconsistent with gaps. Although the values of current seepage rates from Haditha Dam were not critical, but with the aging of the dam it may increase and become critical. Therefore, the consideration of seepage through Haditha dam in the risk assessment is crucial since the dam was constructed on various degrees of limestone beds of the Euphrates and Ana formations. Additionally, it was reported that sinkholes were developed near the dam site. As a consequence of the damaging and geological condition of the dam site, a special focus on the seepage through the dam is required. The acquired seepage data for the dam was checked and found to be inconsistent with the water level in the reservoir of Haditha Dam. Therefore, the current seepage data cannot be used in dam safety assessment. To overcome the inconsistency in the data, the SEEP/W model was used to predict the seepage rates through Haditha Dam for various reservoir water levels. Safety procedures such as ICOLD and USBR do not include the seepage in their dam risk assessment or total dam risk factor while the Brazilian index for dam risk estimation includes weightage points for the seepage condition of a dam. According to the Brazilian index, the seepage condition of Haditha dam was found in the second category with a weightage of 3. In conclusion, special attention should be given to getting quality seepage data since it is used in the safety assessment of Haditha Dam.

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Authors' contributions

Conceptualization: Thamer Ahmed Mohammed.
Data curation: Alyaa Jumaah Hadi.
Formal analysis: Thamer Ahmed Mohammed.
Investigation: Aida Tayebian.
Methodology: Thamer Ahmed Mohammed.
Software: Alyaa Jumaah Hadi.
Supervision: Thamer Ahmed Mohammed.
Validation: Alyaa Jumaah Hadi.
Visualization: Aida Tayebian.
Writing–original draft: Alyaa Jumaah Hadi.
Writing–review & editing: Thamer Ahmed Mohammed.

Competing interests

The authors declare that there is no conflict of interests.

Ethical issues

The authors acknowledge that the data used in the manuscript were acquired from the State Commission of Dams and Reservoirs, the Ministry of Water Resources, Baghdad, Iraq, and the data were used solely for this manuscript.

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