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Effect of Core Type on Zoned Earth Dams on Total Water Head and Flux

Haider Mohammed Makkiyah[1], Thamer Ahmed Mohammed[2]* and Rusul Ihsan Abdulridha[2]

[1]Department of Civil Engineering, College of Engineering, University of Baghdad, 10070 Aljadria, Baghdad, Iraq
[2]Department of Water Resources Engineering, College of Engineering, University of Baghdad, 10070 Aljadria, Baghdad, Iraq

ABSTRACT

Most dams constructed worldwide are zoned earth dams with cores of different materials. However, selecting the proper core material in an earth dam will reduce seepage and increase safety. Most of the available information on dam cores was extracted from laboratory experiments. In this study, cores of different materials used in three selected zoned dams of almost the same height were assessed based on acquired field data and numerical simulation. The selected dams are in Iraq and named Haditha Dam (designed with a compound core of compacted dolomite and asphaltic diaphragm), Hemrin Dams (designed with a hard clay core) and Khasa Chai Dam (designed with a silty clay core). The total water head and water flux through the core of each dam were simulated using a two-dimensional SEEP/W model. For high and low water depths in the reservoir of Hemrin Dam, the water flux ratios were found to be 140 and 50 times greater than that of Haditha Dam. For low water depth in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17. Compared with the core of the Hadith Dam, the flux through the core of the Khasa Chai Dam was found to be triple. For studied core samples, the variation in fluxes can be related to the effect of both hydraulic conductivity and geometry of the dam core. The hydraulic conductivity is affected by the core material, while the hydraulic gradient is affected by both the core material and geometry.

Keywords: Acquired data, cores, earth dams, flux, SEEP/W model, total head

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E-mail addresses:
hydmekk@yahoo.com (Haider Mohammed Makkiyah)
thamer.a.m@coeng.uobaghdad.edu.iq (Thamer Ahmed Mohammed)
rusul.a@coeng.uobaghdad.edu.iq (Rusul Ihsan Abdulridha)
* Corresponding author

INTRODUCTION

Earth dams are storage structures constructed from highly compacted, low-permeability earth material. Typically, the components of an earth dam are shells (upstream and downstream), a core, a filter and a drain. Compared with concrete gravity dams,

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earth dams are economical and can be constructed at sites with diverse geological and geographical conditions (Hasan, 2019). Usually, the earth materials used in the construction of earth dams are borrowed from nearby areas. The borrowed soil used for the dam core is categorized as having very low permeability, compressibility, liquid limit, and organic contents. Earth dams have always been associated with seepage through their foundations and embankments. The seepage from earth dams resulted from the high difference in water levels between upstream and downstream and removed soil particles from the embankment. Poor design, construction, and operation may lead to the failure of earth dams due to seepage. Seepage is categorized as the main cause of failure, and it constitutes about 30%–50% of earth dam failures (Salari et al., 2021).

Therefore, the seepage rate should not exceed the acceptable limits. The core is an impermeable barrier within the embankment of a zoned earth dam to reduce seepage to an acceptable limit. The substantial reduction in seepage rate by the core is attributed to the fact that core material has permeability a hundred times lower than that of the shell material. Therefore, most drop-in seepage flow lines occur within the impervious core, and the upstream shell has a negligible effect on seepage. Moreover, the small amount of water that seeps through the central core will flow in the lower layer in the downstream shell and emerge at the dam toe. It justifies why researchers were focused on the performance of various core types. Adnan et al. (2022) analyzed the seepage in Shirin Dam, Iraq, and found that core can reduce seepage by 99%. However, Fikri et al. (2023) concluded that the failure of the Senggarang Coastal Embankment (SCE), Johor, Malaysia, by seepage is imminent if the existing very low cohesion soil of the SCE is not replaced with cohesive soil type. Mohammed et al. (2022) found that the usage of geosynthetic clay liner in a dam embankment can reduce the seepage by 22%.

The seepage rate was reduced by 35.6% when a ratio of 50% of the tire rubber powder was used in a dam core (Shuhaib & Khassaf, 2023). Alternative cores from silty and sandy soils with different additive materials were tested theoretically and experimentally in the laboratory of Alzamily and Abed (2022a, 2022b). The permeability of the alternative cores was found to be smaller than the permeability of the hard clay core used in zoned earth dams. Adamo et al. (2018) focused on the successful use of dolomite in the core of Haditha Dam. The dolomite is available in large quantities in areas surrounding Haditha Dam. Ali et al. (2020) developed a novel method for quantifying the efficiency of seepage control measures in earthfill dams. They found that the overall efficiency of different seepage control measures ranges between 51 and 70%. The effect of core permeability, core width, core base thickness, and core penetration on seepage has been studied experimentally and numerically by Salem et al. (2019) and Mostafa and Zhenzhong (2023).

However, the hydraulic performance of different control methods, such as flat slopes, toe drainage systems, and a catch drain in the tailwater, was evaluated analytically by Magdy

(2016). Harr (1962) classified the methods used to solve seepage problems as analytical, experimental and approximate. A three-dimensional finite element model was developed by Chen et al. (2022) to simulate a typical earth dam with an anti-seepage polymer cutoff wall. Moreover, Amin and Ali (2013) developed and validated new equations for the estimation of seepage rate from earth dams with high precision. The SEEP/W model was used to simulate seepage through small and large earth dams in Iraq (Ali & Odaa, 2014; Maysam & Al-Nadawi, 2020). Seepage below the foundation of Hilla main regulator, Iraq, was studied by Mahdi and Al-Hadidi (2023), while the seepage through Iraq soils (homogeneous and non-homogeneous saturated-unsaturated) was studied by Jassam and Abdulrazzaq (2019). Harpy et al. (2022) used environmental isotopes and hydrochemicals to evaluate the impact of seepage from the reservoir of Dwarege Dam, Iraq, on groundwater.

The stability of the slopes of Hemrin and Haditha Dams under different reservoir water levels was analyzed by using Geo-Studio Software (Al-Nedawi & Al-Hadidi, 2020; Malik & Karim, 2021). However, the Plaxis 3D model was used by Bredy and Jandora (2020) to analyze the slope stability of the Karolinka Dam embankment in the Czech Republic. The height of the dam embankment before and after treatment was considered in the analysis. Flow data and conditions of foundation materials of Haditha and Mosul Dams were analyzed by Ali and Odaa (2014) and Adamo et al. (2018).

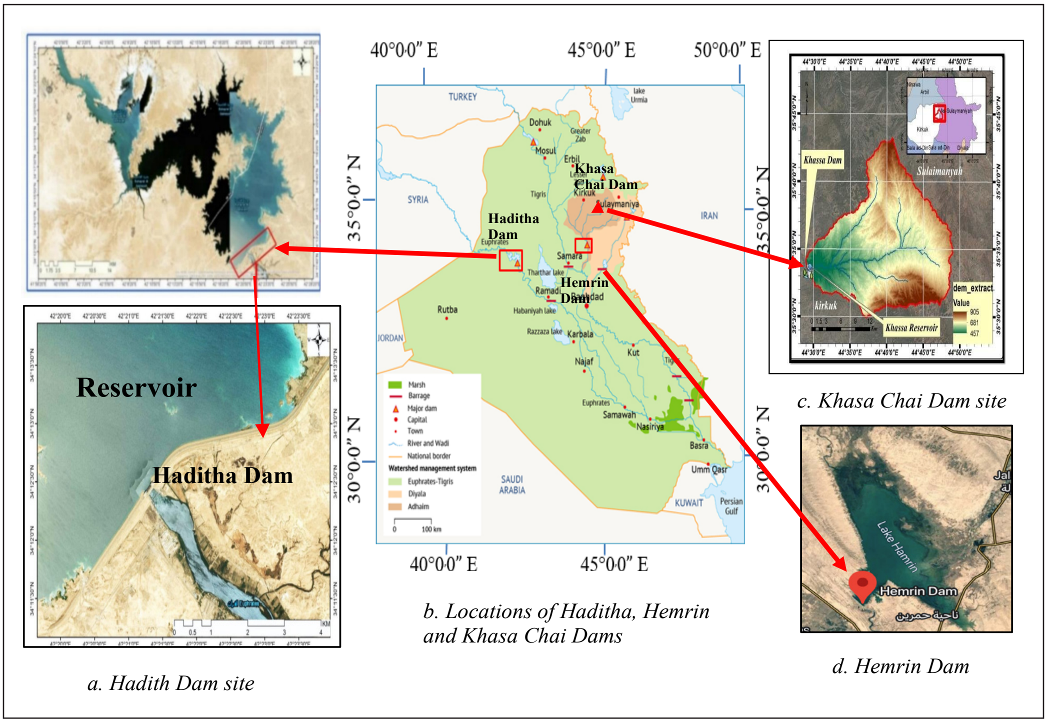
This study investigated the impact of core material and geometry on seepage through three selected earth dams in Iraq based on acquired field data and simulation results from the SEEP/W model.

METHODOLOGY

Three-zone dams were selected to compare the effectiveness of their different cores in seepage control. The selected dams were Haditha Dam, Hemrin Dam and Khasa Chai Dam; the first is located west of Iraq in the Al Anbar Governorate, while the second is located east of Iraq in the Diyala Governorate. The third dam is located northeast of Iraq at Kirkuk Governorate. Figure 1 shows the locations of the dams. Field data and simulation results from the two-dimensional (2D) SEEP/W model were used in the comparison. The data on the selected dams (Haditha, Hemrin and Khas Chai) was acquired from the State Commission of Dam and Reservoir, Ministry of Water Resource. The acquired data includes reservoir water levels, seepage rates, pore water pressure, properties of dam materials and filters and other dam details.

Description and Purpose of Haditha Dam

Haditha dam was constructed on the Euphrates River, Iraq, about 7 km upstream of Haditha city, Al Anbar Governorate, as shown in Figure 1. The multipurpose dam mainly serves irrigation, power generation and flood control. It is an earthen zone dam with a length of



a. Hadith Dam site

b. Locations of Haditha, Hemrin and Khasa Chai Dams

c. Khasa Chai Dam site

d. Hemrin Dam

Figure 1. General views for the locations of the studied dams (SCODR, 2020)

8.7 km, a height of 57 m and a trapezoidal cross-section. The maximum operating discharge from the spillway is 7900 m^3/s, which results in a reservoir water level of 147 m and a storage capacity of 8.2×10^9 m^3. The emergency discharge is 11000 m^3/s, which resulted in a reservoir water level of 150.21 m.

Materials and Geology of Haditha Dam

The core of Haditha Dam includes an asphaltic concrete cutoff, detrital dolomites and sand and gravel combination. These materials were chosen for the dam construction since they were available close to the dam site. Core from suitable traditional materials was not found in adequate quantities during the earliest stage of investigations, and this led to searching for an alternative core material. However, the existence of vast quantities of dolomite near the dam site drew the attention of the designers to use this material in the dam core. Dam authorities claim that dolomite has never been used as a core material in big dams. In addition, an asphaltic concrete diaphragm is used in the center of the dolomite core. A reinforced concrete slab revetment protects the upstream Haditha Dam face, while a rock-mass revetment protects the downstream face. The total volume of materials used in the dam construction is estimated at 30×10^6 m^3. The properties of the materials used in dam construction are shown in Table 1. The information collected from the State Commission of

Dam and Reservoir, Ministry of Water Resource on Haditha Dam was used in the SEEP/W model to draw the dam cross-section shown in Figure 2.

Description and Purpose of Hemrin Dam

Hemrin Dam is 120 km northeast of Baghdad, Iraq, and it was constructed on the Diyala River (one of the tributaries of the Tigris River), as shown in Figure 1. The main purposes of the dam are to control floods, irrigate agricultural lands and generate power. The dam is a rockfill dam with a length of 3.5 km and a height of 53 m. Figure 2 shows the dam cross-section.

The maximum operational water level in the dam reservoir is 104 m, while the level of the spillway crest is 92 m. The maximum operating discharge is 4000 m^3/s, while the actual measurements in 2022 revealed that the discharge does not exceed 1000 m^3/s. The dam reservoir has a maximum storage capacity of 3.9×10^9 m^3. In addition, the dam has four irrigation outlets, and each outlet was designed to discharge up to 250 m^3/s. When the design discharge is 200 m^3/s, the powerhouse can generate 50 MW.

Table 1
Properties of the materials used in the construction of Haditha Dam (SCODR, 2020)

Material	Bulk density(γ) (KN/m^3)	Cohesion (c) (KPa)	The angle of internal friction (Ø°)	Coefficient of Permeability (K_h) (m/s)	Saturated water content %
Dolomite	22	30	26	1.15×10^{-7}	0.29
Clay	18.7	40	15	2.31×10^{-8}	0.47
Dolomite-limestone	22	150	32.5	1.15×10^{-8}	0.29
Compacted dolomite	20.3	0	31.5	1.15×10^{-8}	0.35
Rock muck sandy gravel	17	0	28.5	2.31×10^{-6}	0.39
Asphaltic concrete diaphragm	17.7	0	30.97	1×10^{-9}	0.16

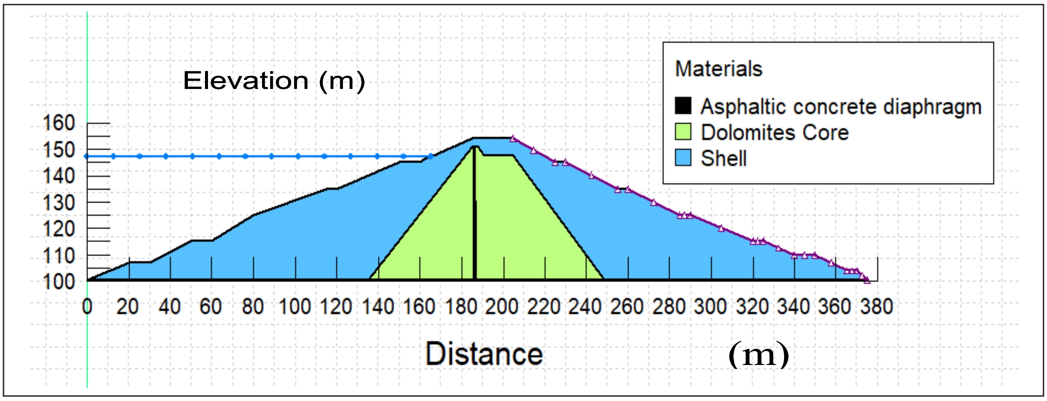


Figure 2. Cross section of Haditha Dam

Materials and Geology of Hemrin Dam

Besides the upstream and downstream shells, the dam has a clay core clad with coarse and fine filters. Data on dam geometry and material were used in the SEEP/W model to draw the dam cross-section, as shown in Figure 3. Table 2 shows the properties of materials used to construct the Hemrin Dam.

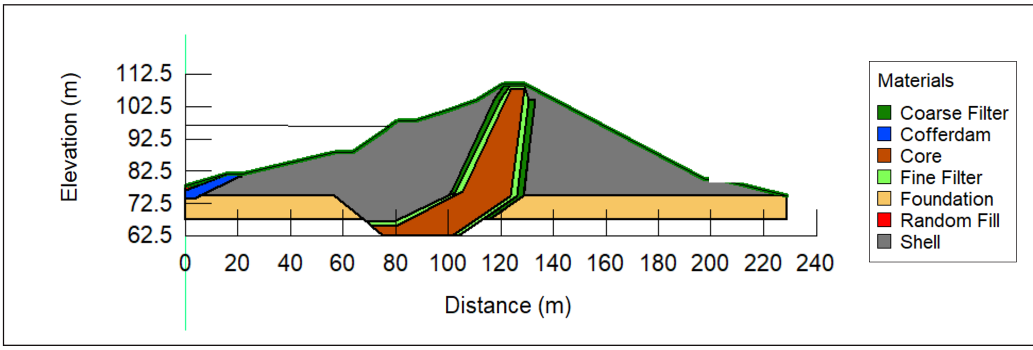


Figure 3. Cross section of Hemrin Dam

Table 2
Properties of the materials used in the construction of Hemrin Dam (SCODR, 2020)

Material	Bulk density (γ) (KN/m^3)	Cohesion (c') (KPa)	The angle of internal friction (ø°)	Hydraulic Conductivity K_h (m/s)	Saturated water content %
Foundation	22	40	15	1×10^{-5}	
Shell	19	-	37	1.69×10^{-5}	0.1275
Clay core	18	30	23	2.31×10^{-9}	0.094
Fine filter	16	-	35	1.2×10^{-5}	0.1275
Coarse filter	16	-	35	0.0001	0.1275

Description and Purpose of Khasa Chai Dam

Khasa Chai Dam is a zoned multipurpose dam located 10 km northeast of Kirkuk City, Iraq. It was constructed on the Khasa Chai River, a seasonal tributary of the Zaghaitun River. The maximum storage and water levels in the dam reservoir are 101.3×10^6 m^3 and 496 m, respectively. The maximum discharge from the spillway is 1686 m^3/s, while the water storage is used mainly for water supply, recharging groundwater and recreation. The dam is 2.36 km long, 58 m high and has a top width of 13 m.

Materials and Geology of Khasa Chai Dam

The earth material used in the dam core is silty clay borrowed from an area near the dam site. The core extended from the dam foundation to a level of 430 to a level of 496.1 m. The top width of the core is 4 m with side slopes of 0.75:1 (H:V) upstream and 1:0.75 (H:V) downstream. On the upstream side of the core, there is a fine filter, while on the downstream side, there is a coarse filter. Both shells upstream and downstream were constructed from sand and gravel and protected by rip rap. Figure 4 shows the dam section. The chimney, blanket and toe drain the seepage water. The geological investigations showed that the dam site is located within a clastic sequence of the Mukdadiya formation that is widely distributed in the foothill and the Mesopotamian plain zones. The formation consists of sand, silt, clay, sandstone, and gravel, with an upwardly increasing diameter, forming a conglomerate with a maximum thickness of 2050 m (Abbas, 2021). The properties of the dam materials are shown in Table 3.

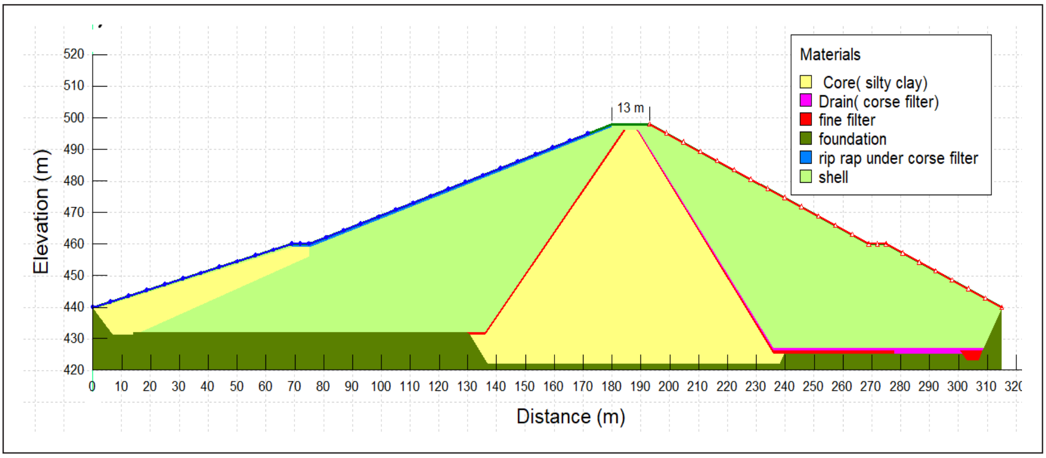


Figure 4. Section of Khasa Chai Dam

Table 3
Properties of the materials used in the construction of Khasa Chai Dam (SCODR, 2020)

Material	Bulk density (γ) (KN/m³)	Cohesion (c) (KPa)	The angle of internal friction (Ø°)	Coefficient of Permeability (K_h) (m/s)	Saturated water content %
Shell (Sand and Gravel)	21.58	0	38	1.25×10^{-5}	0.06
Core (Silty Clay)	17.65	98	30	5.3×10^{-9}	0.19
Fine Filter (Sand)	17	0	37	5.60×10^{-3}	0.06
Coarse Filter (Gravel)	17.7	0	38	1×10^{-2}	0.05

SEEP/W Model: Mathematical Background, Boundary Conditions and Application

The SEEP/W model is formulated to simulate water flow through both saturated and unsaturated soil (Richards, 1931; Childs & Collis-George, 1950). In addition, the model includes several "typical" water content functions that can be used to determine the saturated hydraulic conductivity of different soil types (Geo-Slope, 2012; Genuchten, 1980) as described by Equation 1.

$$k_w = ks \frac{\left[1-\left(a\varphi^{(n-1)}\right)\left(1+\left(a\varphi^{n}\right)^{-m}\right)\right]^2}{\left[\left((1+a\varphi)^{n}\right)^{\frac{m}{2}}\right]} \quad [1]$$

where k_s is saturated hydraulic conductivity (L/T), a, n, and m are curve fitting parameters, φ the required suction range while n is determined by the following Equation 2:

$$n = \frac{1}{1-m} \quad [2]$$

Seepage flow through a homogeneous isotropic medium under steady-state conditions is described by the 3D Laplacian Equation 3 (Geo-Slope, 2012).

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \quad [3]$$

The general governing differential equation for two-dimensional seepage can be expressed as Equation 4 (Geo-Slope, 2012).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \quad [4]$$

where H is the total head, k_x is the hydraulic conductivity in the x-direction(L/T), k_y is the hydraulic conductivity in the y-direction (L/T), Q is the applied boundary flux, θ is the volumetric water content, and t is time (T).

Boundary conditions are required to establish a phreatic line and pore water pressure, which are applied along the dam section. Upstream water level, downstream water level, and zero pressure represented boundary conditions. A potential seepage face boundary (an edge) will also be applied to the downstream face. A potential seepage face is a special boundary condition used when the solver locates a position where a seepage face might develop. The flow chart in Figure 5 shows the steps this study followed to run the SEEP/W model to simulate the seepage from the studied dams.

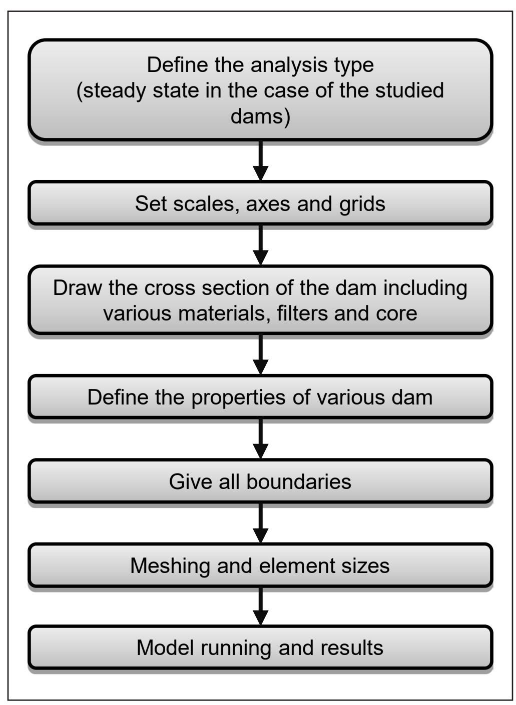


Figure 5. Flow chart for the main steps required to apply the SEEP/W model

RESULTS AND DISCUSSION

Three zoned earth dams with different core types were selected to assess the performance of cores used in zoned earth dams. The dams in Iraq are named Haditha Dam, Hemrin Dam, and Khasa Chai Dam. In the constructions of these dams, compacted dolomite with an asphaltic diaphragm in the center was used as a core in Haditha Dam, while hard clay core and silty clay core were used in Hemrin Dam and Khasa Chai Dam, respectively. The dolomite was used since vast quantities were found near the dam site. The dam authority claimed that the dolomite has never been used as a core in large dams previously. The permeability of the compacted dolomite was 1.15×10^{-8} m/s, while it was 1×10^{-9} m/s for the asphaltic diaphragm.

Moreover, the permeability of the hard clay core used in the Hemrin Dam was 2.31×10^{-9} m/s, while the permeability of the silty clay core used in the Khasa Chai Dam was 5.3×10^{-9} m/s (SCODR, 2020). To give credibility to the method used for core samples assessment, the acquired data on seepage rates and reservoir water levels for the selected dams should be checked for their quality and consistency. The data was plotted first and compared with standard field data and modelling results shown in Figure 6. The relationship between the seepage rates and the reservoir water level of an earth dam in Korea was found to be nonlinear (Lee et al. 2018). However, a linear relationship between seepage rate and reservoir water level was proposed by Ali et al. (2020). Based on the above, the seepage rate is directly proportional to the reservoir water level. The data on seepage rates and water levels in the reservoir of Haditha Dam was plotted and compared with the relationship presented in Figure 6. Figure 7 shows that the seepage data for the Haditha dam was scattered and inconsistent. The strength of the association between the seepage rates and reservoir water level can be found by calculating the coefficient of determination (R^2).

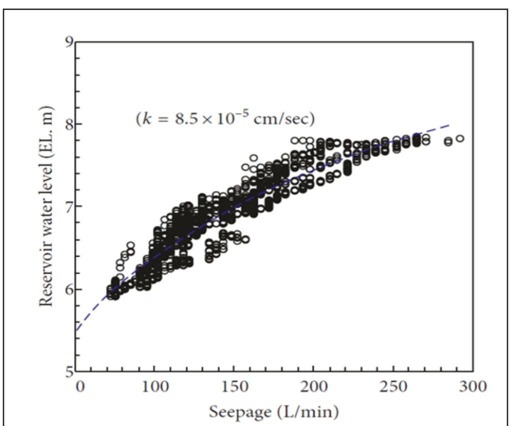


Figure 6. The correlated relationship between reservoir water level and seepage for an earth dam in Korea (Lee et al., 2018)

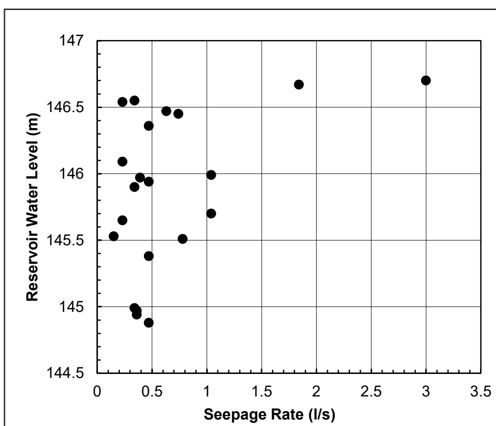


Figure 7. A sample of inconsistent field data for Haditha Dam at station 26+80

However, the association does not imply a correlation, although the terms correlation and association are often used interchangeably in most statistics texts.

However, in a stricter sense, correlation refers to linear correlation, while association refers to any relationship between two variables. Equation 5 is used to determine R^2.

$$R^2 = \left[\frac{N\sum XY - \sum X \sum Y}{\sqrt{\{N\sum X^2 - (\sum X)^2\}\{N\sum Y^2 - (\sum Y)^2\}}}\right]^2 \qquad [5]$$

where X represents the seepage rate while Y represents the reservoir water level.

The value of R^2 for data on seepage rates and water levels in the reservoir of Haditha Dam, shown in Figure 7, was found to be 0.19, which confirmed the weak association between the variables. However, an association's strength depends on the data's characteristics for each variable. However, Ali et al. (2020) considered human error in the measurement to be one of the uncertainties in the seepage data of earthfill dams. For Hemrin Dam, a sample of the available data on seepage rates and the reservoir water level is shown in Figure 8. Although the data was found scattered with gaps, the value of R^2 was 0.84, which confirmed that the degree of association between the variables was high.

To overcome the problem of inconsistency and availability of seepage data, predicted seepage rates obtained from running a two-dimensional SEEP/W model were used to assess the performances of the three selected core types under almost the same operation conditions. The model was calibrated and validated before it was used to simulate the water flux from the core samples. The data of water levels in the reservoir of Haditha Dam that was used to plot Figure 7 were also used in the SEEP/W model to predict the seepage rates, as shown in Figure 9. The value of the R^2 for the simulation was found to be 0.86, which is much higher than the value of R^2 for the acquired data. In addition, Figure 10 shows the

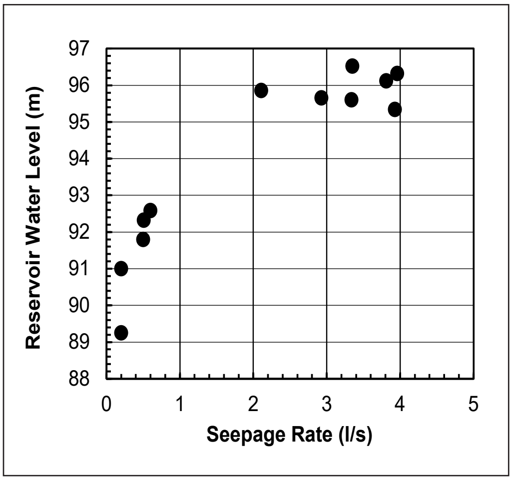


Figure 8. A sample of acquired data for the Hemin Dam

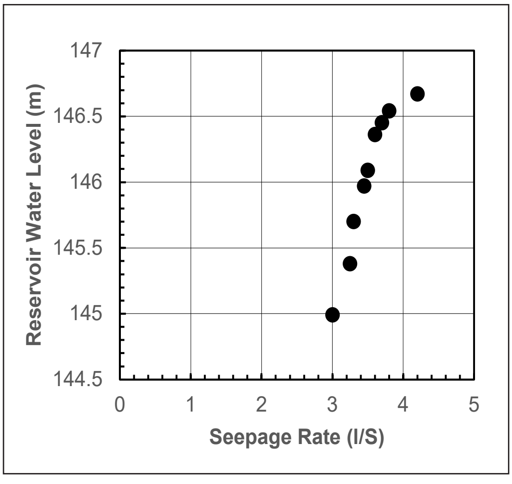


Figure 9. Simulated seepage rates for various water levels in the reservoir of Haditha Dam

simulation results of the seepage rates for Hemrin Dam. The value of R^2 for the simulation results was found to be 0.94, which is higher than that for the acquired data. The data on seepage and water levels in the reservoir of Khasa Chai Dam was found to have a high association. Figure 11 shows the measured data and simulation results for Khasa Chai Dam. The value of R^2 between the observed and predicted seepage rates was found to be 0.97, which confirmed the accuracy of the model predictions (Figure 12).

Compared with the SEEP/3D model, the prediction of seepage (water flux) and total water head by using the SEEP/W (2D) model was found to be more relevant because the prediction of seepage by the SEEP/3D model is costly and requires more running time. Moreover, Fardin et al. (2009) justified that the 3D seepage behavior in an earth dam diminishes when the overall permeability pattern of the abutments and the dam body are compatible. In addition, Niloufar and Saeed (2014) commented on the accuracy of predicted seepage rates obtained from the two-dimensional SEEP/W model and SEEP/3D model compared with measured seepage data collected from two zoned earth dams in Iran. The average calculated error between the output obtained from SEEP/W and SEEP/3D models and measured dam seepage rates were 13.67% and 8.4%,

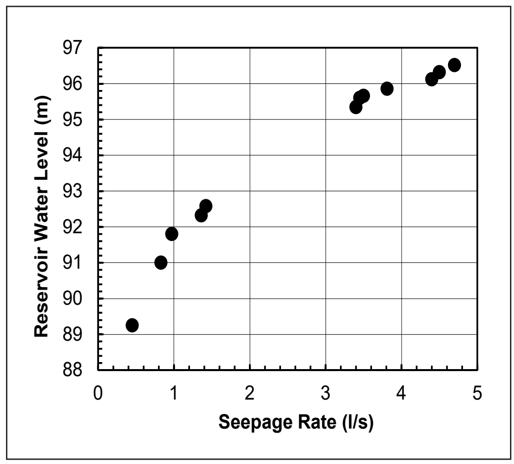


Figure 10. Simulated seepage rates for various water levels in the reservoir of Hemrin Dam

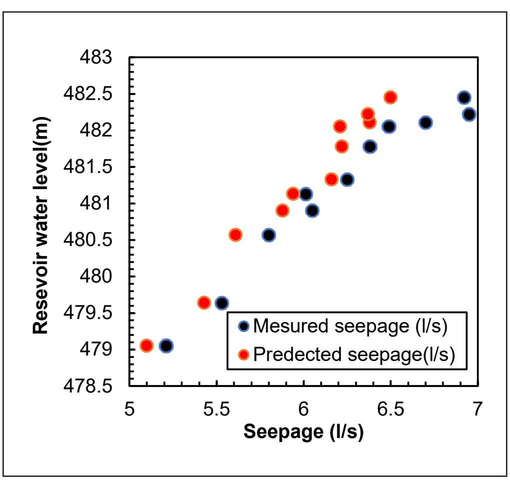


Figure 11. Predicted and measured seepage rates for various water levels in the reservoir of Khasa Chai Dam

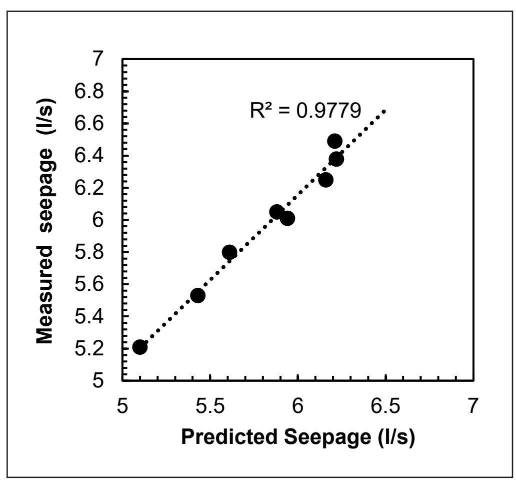


Figure 12. Predicted and measured seepage rates for Khasa Chai Dam

respectively. The simulated seepage rates obtained from SEEP/W and SEEP/3D models showed an insignificant difference.

Eshagh et al. (2016) and Tabari and Mari (2016) confirmed the accuracy of the SEEP/W model compared with the application of other seepage simulation methods, while Adnan et al. (2022) demonstrated the capability of the model to simulate the seepage through the Shirin earth dam under various operational and climatic conditions. Therefore, applying the SEEP/W model to predict the seepage rates through the selected cores is relevant and can be used to study conditions not covered by the acquired data. The SEEP/W model was calibrated for each core sample before application.

For Haditha and Hemrin Dams, water flux (seepage) predictions were conducted for two different water levels (high and low) in their reservoirs. But for Khasa Chai Dam, water flux was only predicted for low reservoir water levels. The high-water level in the reservoir of Haditha Dam was selected as 131.50 m, while that in the reservoir of Hemrin Dam was selected as 107.50 m. However, the low water levels in the Haditha, Hemrin and Khasa Chai Dams reservoirs were selected as 120.00 m, 96.00 m and 460.00 m, respectively. The water levels in the reservoirs of selected dams are different since their geographical locations are different, too. It makes the ground levels at the selected dams' locations different. At any dam, the water level at a point in the reservoir represents the ground level plus the water depth at that point. Therefore, the water levels in the reservoirs of Haditha, Hemrin and Khasa Chai Dams were carefully selected to result in the same water depth. For example, although the values of the selected high-water levels in the Haditha and Hemrin Dams reservoirs differed and were equal to 131.50 m and 107.00 m above mean sea level, respectively, the water depth in their reservoirs was 31.50 m.

In addition, the values of selected low water levels in the reservoirs of the above dams were 120.00 m, 96.00 m and 460.00 m above mean sea level, respectively. However, these water levels resulted in a 20 m water depth in their reservoirs. This selection is essential to demonstrate the performance of different core samples under the same reservoir water depth by taking the hydraulic gradient and water flux (seepage) as indicators. The predicted total heads using the SEEP/W model are shown in Figures 13 to 17 for the high and low water levels in the reservoirs of the selected dams. Table 4 shows the water levels and depths in the reservoirs of the selected dams, the water flux, and the calculated hydraulic gradient. The hydraulic gradients shown in Table 4 were calculated based on the drop in the total heads across the studied core types.

The kinetic head is the kinetic energy per unit weight of seepage water moving through the dam, and it is usually measured using a piezometer. The water fluxes (seepage rates) for high and low water levels in the reservoirs of Haditha Dam were predicted and found to be 5×10^{-7} $m^3/s/m^2$ and 1×10^{-7} $m^3/s/m^2$ respectively (Figures 18 and 19). At the same time, the predicted water fluxes for the high and low water levels in the reservoir of Hemrin

Dam were found to be 7 × 10^{-5} $m^3/s/m^2$ and 5 × 10^{-6} $m^3/s/m^2$ respectively (Figures 20 and 21). The predicted water flux for the low water level in the Khasa Chai Dam reservoir was 3 × 10^{-7} $m^3/s/m^2$. Figure 22 shows the predicted flux through the core of Khasa Chai Dam. For high water levels in the reservoirs of Hemrin and Haditha Dams, the ratios of predicted fluxes through their cores were found to be 140 and 50, respectively. For low water levels in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17.

Compared with the core of the Hadith Dam, the flux through the core of the Khasa Chai Dam was found to be triple. For different core samples, the flux variation can be related to the effect of hydraulic conductivity and core geometry. The hydraulic conductivity of the dam core describes the ease with which the water seeps through it. Therefore, a core with

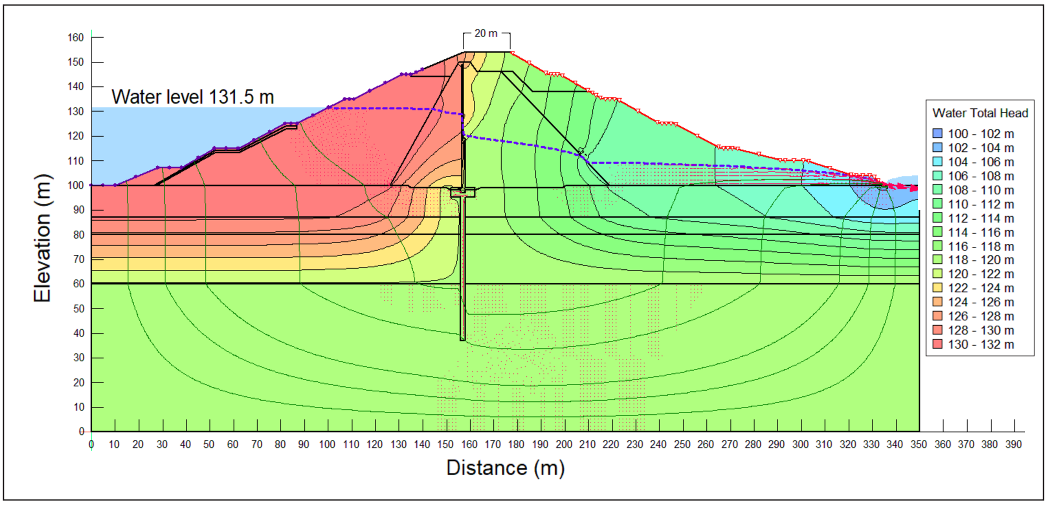


Figure 13. Total head through Haditha dam for the reservoir water level of 131.5 m

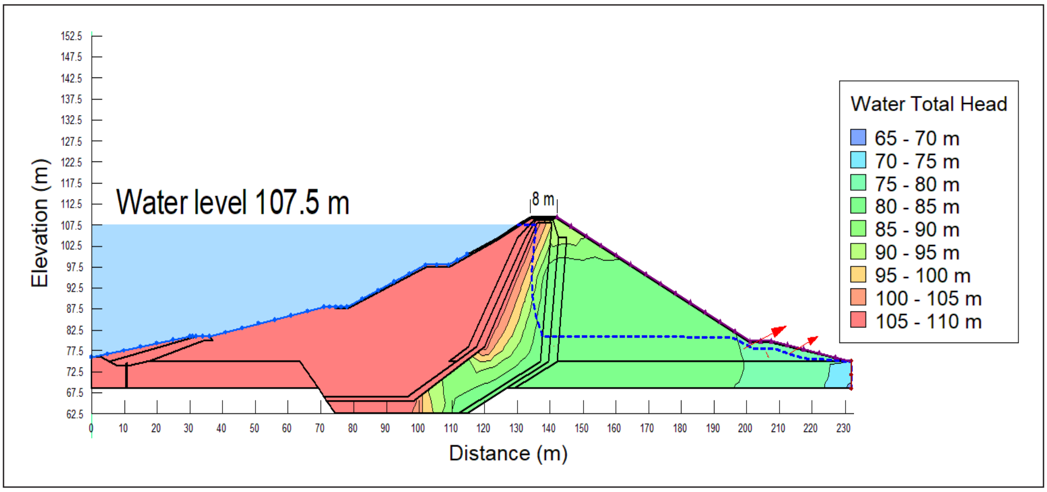


Figure 14. Total head through Hemrin Dam for the reservoir water level of 107.5 m

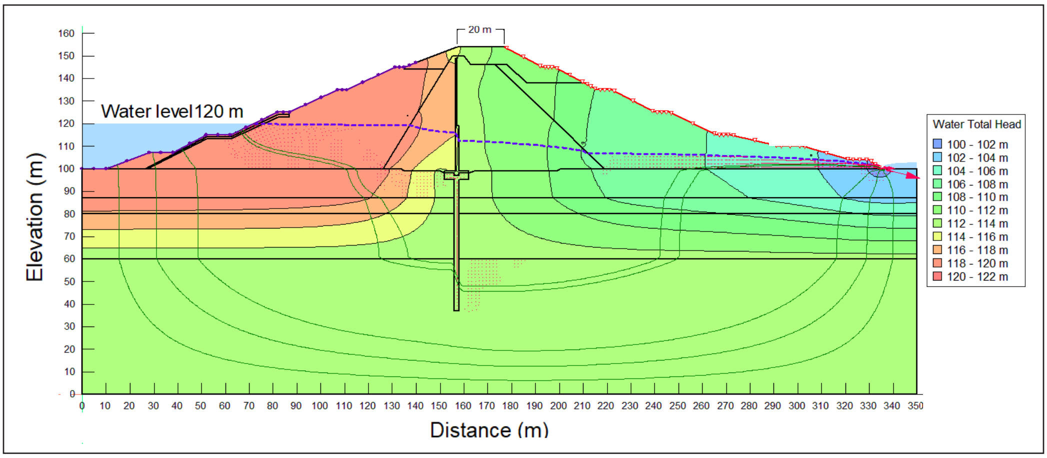


Figure 15. Total head through Haditha Dam for reservoir water level of 120 m

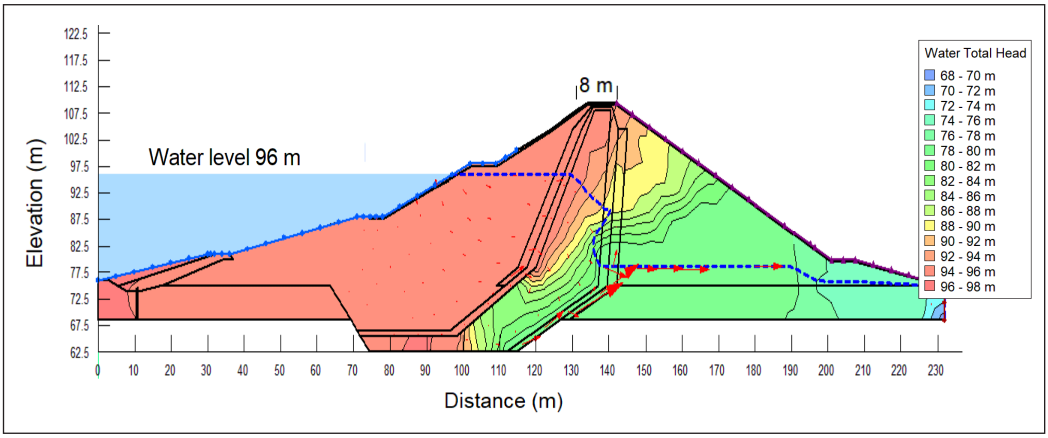


Figure 16. Total head through Hemrin Dam for reservoir water level of 96 m

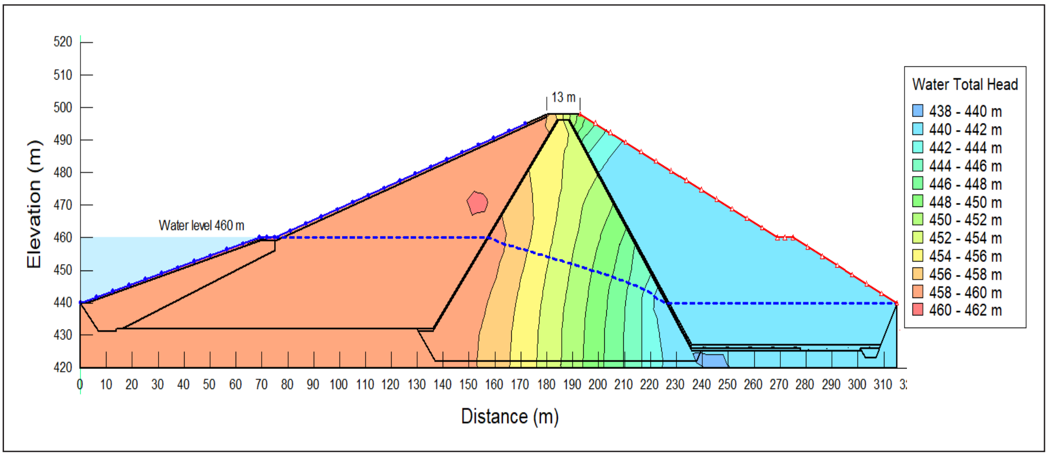


Figure 17. Total head through Hemrin Dam for reservoir water level of 460 m

Table 4
Water fluxes and hydraulic gradients for the study core types

Dam name	Core type	Reservoir water level (m)	Water depth (m)	Hydraulic water gradient (m/m)	Water flux ($m^3/s/m$)
Haditha	Compacted dolomite with asphaltic diapgram	131.5 120.0	31.50 20	0.350 0.164	5×10^{-7} 1×10^{-7}
Hemrin	Hard clay	107.50 96.00	31.50 20	2.010 0.910	7×10^{-5} 5×10^{-6}
Khasa Chai	Silty clay	107.50	31.5	0.290	3×10^{-7}

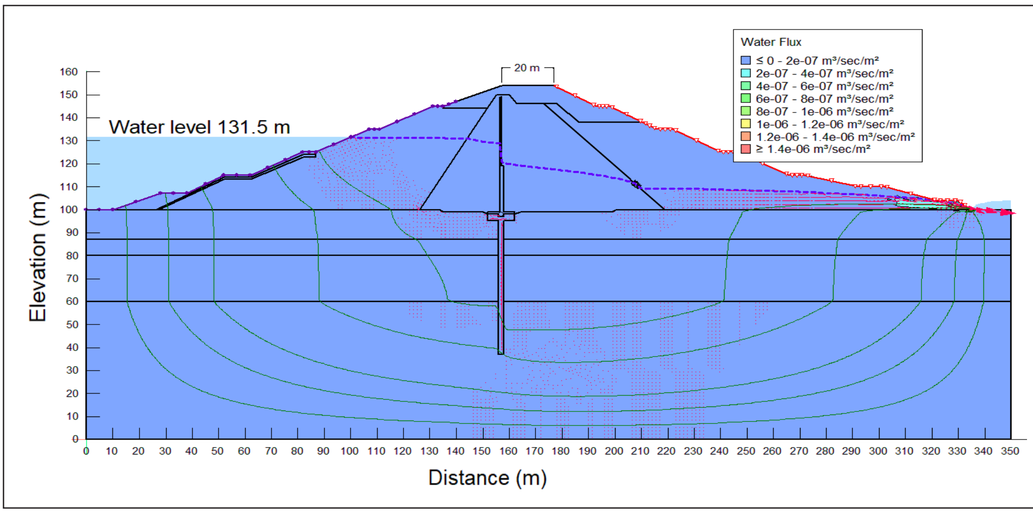


Figure 18. Water flux through Haditha Dam for a reservoir level of 131.5 m

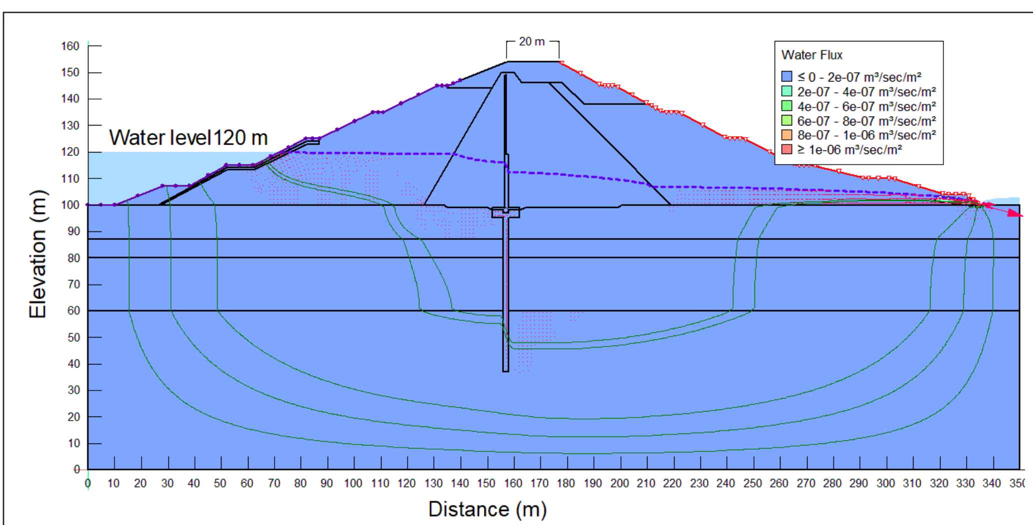


Figure 19. Water flux through Haditha Dam for reservoir level of 120 m

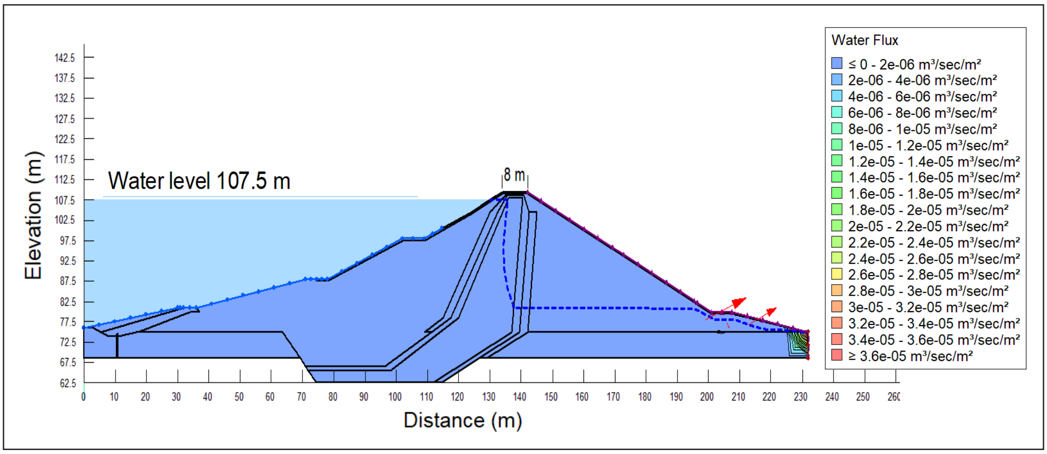


Figure 20. Water flux through Hemrin Dam for reservoir level of 107.5 m

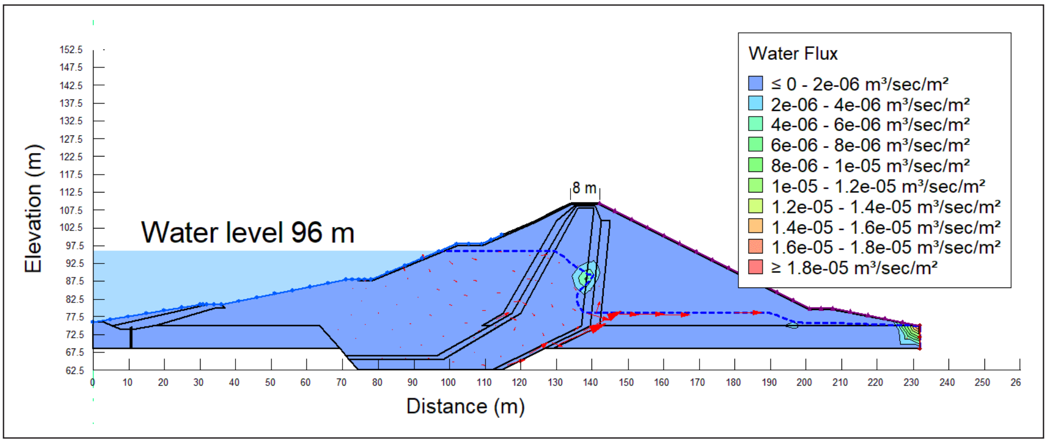


Figure 21. Water flux through Hemrin Dam for reservoir level of 96 m

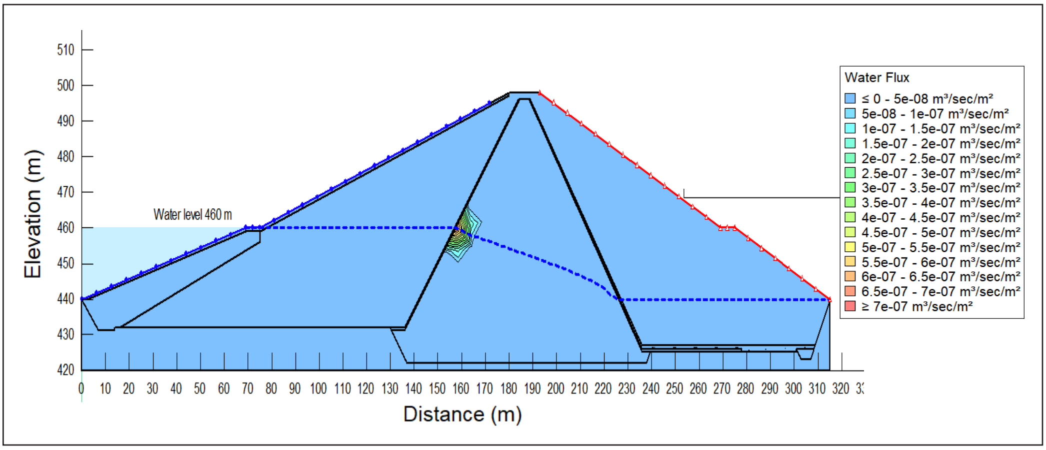


Figure 22. Flux through Khasa Chai Dam for reservoir level of 460 m

lower hydraulic conductivity gives lower flux. In addition, the core geometry affects the hydraulic gradient (the drop in total head through the dam core). In Darcy's law, the water flux is a function of both hydraulic conductivity and the hydraulic gradient. It justifies why the current study used these two variables to assess core samples. Table 4 shows that the lowest flux was found with the dolomite core with the asphaltic diaphragm. Also, the lowest hydraulic gradients occurred through the above core with values of 0.164 and 0.34. The hydraulic conductivities of compacted dolomite and asphaltic diaphragm are 1.15×10^{-8} m/s and 1×10^{-9} m/s, respectively.

The Federal Emergency Management Agency, (2014) considered that using the core made from asphalt in earthfill dams may make it more watertight. Dams with this type of core are called concrete-asphalt core embankment dams. Most concrete asphalt dams use rock and/or gravel as the main filling material. These types of dams are considered especially appropriate for areas susceptible to earthquakes due to the flexible nature of the asphalt core. Although the hydraulic conductivity of the clay core of Hemrin Dam is 2.31×10^{-9} m/s, which is lower than the hydraulic conductivity of the silty clay core (5.3×10^{-9} m/s) used in the Khasa Chai Dam, the flux from the Khas Chai dam was lower than that of Hemrin Dam. This can be attributed to the geometries of the cores, which resulted in a higher hydraulic gradient in the Khasa Chai dam.

For the studied core samples, the variation of water flux with the hydraulic gradient is shown in Figure 23. Salem et al. (2019) analyzed the seepage flow through laboratory-scale embankment dams with an internal core. They concluded that decreasing the core permeability reduced seepage rate, gradient, and pore water pressure. However, they used the ratio between the hydraulic conductivity of the dam core and the dam shell (Kcore/Kshell) to demonstrate the impact of changing the hydraulic conductivity of the dam core on the seepage rate. However, the present study demonstrated the performance of different

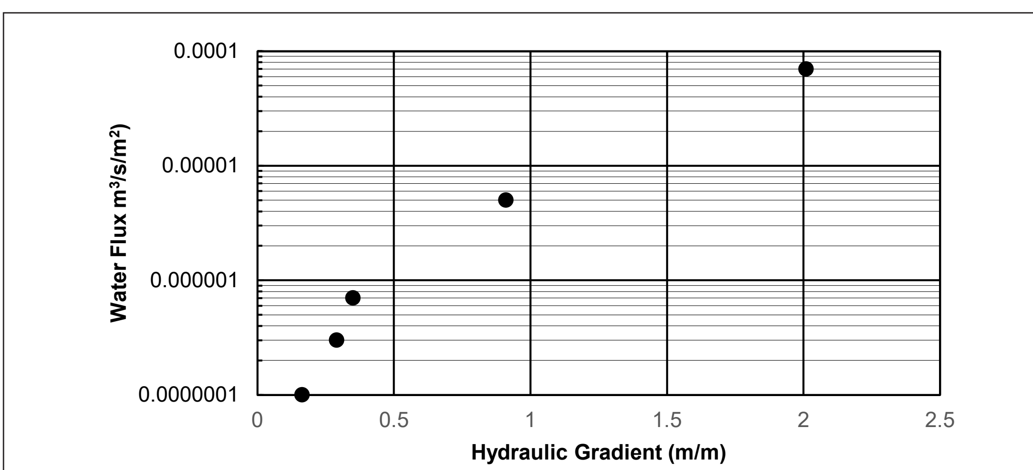


Figure 23. Variation of the water flux with the hydraulic gradient of the studied core samples

core types with their impact on the drop in total head and seepage rate (water flux). The present study is essential for dam engineers since it gives an idea about how selecting core material and geometry can improve the safety of the zone earth dams.

CONCLUSION

In this study, field data on reservoir water level, piezometric head and seepage (water flux) were acquired and used with the simulated results obtained from the two-dimensional SEEP/W model to assess the performance of three different core samples used in selected zoned earth dams in Iraq. The selected dams almost have the same height (H). The names of the dams are Haditha (H=57 m), Hemrin (H=53 m) and Khasa Chai Dams (H=58 m). The core used in the Hadith Dam was compacted dolomite (K= 1.15×10^{-8} m/s) with asphaltic diaphragm (K=1×10^{-9} m/s) in the center while a hard clay core (K=2.231×10^{-8} m/s) was used in the Hemrin Dam. Silty clay core was used in Khasa Chai Dam (K=5.3×10^{-9} m/s). The acquired data for the Haditha and Hemrin Dams were checked and found either inconsistent or with gaps, while the data for the Khasa Chai Dam was consistent. After model calibration and validation, predictions from the running SEEP/W model for high and low water reservoir levels were used to assess the studied core samples. For high and low reservoir water depths, the ratio of water flux through the core of Hemrin Dam was 140 and 50 degrees greater than that of Haditha Dam. For low water depth in the reservoirs of Hemrin and Khasa Chai Dams, the flux ratio was 17. The flux through the core of the Khasa Chai Dam tripled the flux flow through the core of the Hadith Dam. The variation in fluxes is mainly attributed to the core material's hydraulic conductivity and the effect of core geometry. The core geometry affects the value of the hydraulic gradient. For Hemrin Dam, the effect of core geometry on the hydraulic gradient and then on the flux is very obvious.

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