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An Experimental Study of the Core Location and Shape Effect on Seepage and Stability of Zoned Earth Fill Dam

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Keywords:
Seepage; Core; Zoned earth dam; Geo-Studio.

Highlights:

- *Seepage is the Primary Concern.*
- *Role of Clay Core in Zoned Earth Dams.*
- *Investigation of Core Shape and Location Effects.*
- *Utilization of Numerical Modeling.*
- *Effectiveness of Trapezoidal Core Shape.*

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Abstract: Seepage is the main problem of earth dams; most failures occur due to excessive amounts of seepage. In zoned earth dams, clay core minimizes seepage quantity, and its dimensions and shape influence seepage quantity. The shape and location of the core impact on the seepage were investigated in this paper, as sand, a percentage of bentonite clay, and gravel were used to build the physical model inside the hydraulic conductivity device to calculate the amount of seepage through the dam body and to specify the seepage phreatic line. Four core shapes were considered: rectangular, wedge-shaped, forward inclined, and backward inclined with (25%) percent amounts of bentonite clay and various core dimensions and lateral inclinations. A numerical model is adopted using the Geo Studio program to simulate the experimental models and compare results, which showed high agreement in results with (r^2=99.4%) correlation factor. The results showed that the trapezoidal core shape was the most effective in reducing drainage, as it reduced drainage by about (62% - 79%) compared with the rectangular core shape at various core side slopes. In addition, the inverse proportions for the core crest to dam crest width ratio affected seepage discharge for all core shapes. There was a direct proportion for the core side slope effect for the trapezoidal core shape and an inverse proportion for the forward and backward-inclined core shapes.

دراسة مختبرية لتاثير موقع وشكل اللب على التسرب واستقرار السدود الترابي

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الخلاصة
النضح هو المشكلة الرئيسية للسدود الترابية حيث تحدث معظم حالات الفشل بسبب كمية النضح المفرطة. في السدود الترابية المقسمة إلى مناطق، تعمل النواة الطينية على تقليل كمية النضح، كما أن أبعادها وشكلها لها تأثير فعال على كمية التسرب. دُرِسَ في هذا البحث تأثير شكل وموقع النواة على النضح، حيث أُستخدم الرمل ونسبة من طين البنتونيت والحصى لبناء النموذج التجريبي داخل جهاز النفاذية لحساب كمية النضح من خلال جسم السد وتحديد خط النضح. أخذت أربعة أشكال للنواة: مستطيلة وإسفينية ومائلة إلى الأمام ومائلة إلى الخلف وبنسبة (٢٥٪) من طين البنتونيت وبأبعاد أساسية وميول جانبية مختلفة. أعتمد نموذج عددي باستخدام برنامج Geo Studio لمحاكاة النماذج التجريبية ومقارنة النتائج المستحصلة والتي أظهرت توافق عالي للنتائج بمعامل إرتباط (r^2=٩٩,٤٪). توصلنا إلى أن شكل النواة شبه المنحرف هو الشكل الأكثر فعالية في تقليل التصريف، حيث أنه يقلل من التصريف بحوالي (٦٢٪ - ٧٩٪) مقارنة بالشكل المستطيل لمختلف الميول الجانبية. بالإضافة إلى ذلك، هناك تناسب عكسي لتأثير نسبة عرض قمة القلب إلى قمة السد على تصريف التسرب لجميع أشكال النواة. في حين أن هناك تناسب طردي لتأثير الإنحدار الجانبي للنواة ذات الشكل شبه المنحرف وتناسب عكسي للنواة ذات الأشكال المائلة للأمام والمائلة للخلف.

الكلمات الدالة: التسرب، اللب، سد ترابي مخصص، جيو ستوديو.

1.INTRODUCTION

Dams serve multiple purposes, including water storage for various needs like domestic use and irrigation, flow regulation, flood and drought mitigation, and electricity generation. Earth-fill dams encompass two main types: fully uniform embankment dams and non-uniform ones like zoned and diaphragm dams. Cores within these dams are crucial in reducing seepage, lowering the phreatic level, and consequently minimizing the wetted area on the dam's downstream face. To achieve these advantages, the core material, such as clay, silt, or silty clay, must possess low hydraulic conductivity, while the outer shell of the dam tyFigally consists of porous material like coarse sand [1].However, earth dams have lower rigidity, increasing the likelihood of collapse due to hydraulic failure (e.g., overtopping and erosion caused by wave action), seepage-related issues (e.g., piping and sloughing), or structural failures (e.g., slope slides on the upstream and downstream sides). Researchers employed various computer software types utilizing numerical methods like finite elements to simulate seepage flow through the dam section. Additionally, some studies explored experimental investigations of dam sections to understand these phenomena further. Sazzad and Alam [2], SEEP/W was employed to analyze and comprehend the seepage behaviors exhibited by different types of earth dams. These protected homogeneous dams, zoned dams with a transition filter, and diaphragm dams offer an impervious rock core. Kheiri et al. [3], using SEEP/W, studied an embankment dam with a center, cutoff wall, and horizontal drain. The objective was to evaluate the effect of the cutoff wall's position and depth on seepage beneath the dam. Zahedi and Aghazani [4] studied zoned earthfill dams using Geo Studio software. They explored various center kinds, including vertical, inclined, and diaphragm configurations, together with different slope variations and geometries. Their research was centered on understanding the seepage patterns during the dam structure and especially delved into the impact of the middle's anisotroFig houses. Li et al. [5] studied the Shizihe earth-rock dam using ABAQUS software. Jamel [6] examined the upstream and downstream slopes of both the dam and its core. They evaluated the seepage quantities flowing through a cored earth dam, using SEEP/W for analysis and evaluation. Salmasi et al. [7] used SEEP/W to simulate the seepage and hydraulic gradients of a zoned earth dam with a clay core, evaluating and comparing vertical and upstream-inclined cores and balance via LEM and FEM. Several researchers numerically studied the impact of center traits on the seepage amount of zoned earth dams using simulation software [8, 9]. Salem et al. [10] experimentally analyzed the seepage through earth dams with internal cores. They experimentally studied the effect of core hydraulic conductivity, width, base thickness, and penetration for an earth dam with and without an internal core. Also, they used SEEP/W to numerically verify the experimental model. Refaiy et al. [11] modeled the effect of downstream drain geometry on seepage through earthfill dams. The authors showed that the experimental data was reliable and offered acceptable accuracy in modeling earth dams. Bredy and Jandora [12] evaluated the safety factor in the Karolinka dam's body and foundation. In addition, they studied the effects of dam height on the dam's stability. The observed data showed a good agreement with the numerical results from the finite element method in Plaxis 3-dimension software. Also, El-Hazek et al. [13] conducted experimental and numerical modeling for slope stability and seepage water of earth fill dam. Alzamily and Abed [14] conducted multiple experiments to determine the hydraulic conductivity of silty and sandy soil with different additive materials used in the core for zoned earth-fill dams and compared seepage through them. Aude et al. [15] discussed the analysis of slope stability and soil liquefaction in earth dams using geotextile reinforcement. The study utilized GeoStudio 2018 software to evaluate the stability and seepage analysis of the Al-Adhaim Dam in Iraq. The effects showed that the dam was stable in static conditions; however, it experienced decreased factors of protection and soil liquefaction at some point of earthquake shaking. Zedan et al. [16] utilized the finite detail method to analyze the stableness of the Sharin Earthen Dam underneath various conditions using the Geostudio application. Finally, Aziz et al. [17] studied the effect of the center shape on the stability of the lateral slope of the earth dam using the Slide 6 software to examine the aspect of safety of the lateral slopes of the dam. The outcomes showed that safety decreased by growing the core's lateral slopes and the dam's upper width. Previous studies have studied the impact of the form and location of the core on leakage in zoned earth-fill dams experimentally to determine the best form that reduces leakage. They accomplished some sensible experiments and verified them numerically with the GeoStudio 12 program to achieve the minimum amount of water leakage through those earthen dam fashions.

2.MATERIALS AND THEIR ANALYSIS

The dam production used three excellent soil types for the center, filling fabric, and drain. The three substances used in the test contained a percentage of water of seven. To confirm the critical of the filling cloth, laboratory assessments, including a sieve analysis and hydraulic conductivity (k-check), were conducted. The sieve evaluation outcomes revealed that the filling material consisted of poorly graded coarse sand with a minimal share of fine substances. This composition renders it suitable for use inside the hydraulic conductivity tank apparatus because its low quality diminishes capillary results, ensuring correct and dependable effects. The outcomes of the sieve analysis have been on semi-logarithmic graph paper, Fig. 1. It was found that the filling cloth's hydraulic conductivity was (7×10^{-3}cm/sec). The core material was clayey sand composed of a mixture of sand with 25% bentonite and had (2.1×10^{-7} cm/sec) hydraulic conductivity. The hydraulic conductivity values were calculated using laboratory assessments. The Filling fabric's hydraulic conductivity was determined through a hydraulic conductivity check. The middle fabric's hydraulic conductivity was also determined through a hydraulic conductivity check. The drain fabric's hydraulic conductivity was determined through a separate hydraulic conductivity check. These assessments involved measuring the waft of water through the substances and calculating the hydraulic conductivity based on the drift fee and the dimensions of the samples. Finally, drain materials were coarse gravel with (0.05 cm/sec) hydraulic conductivity.

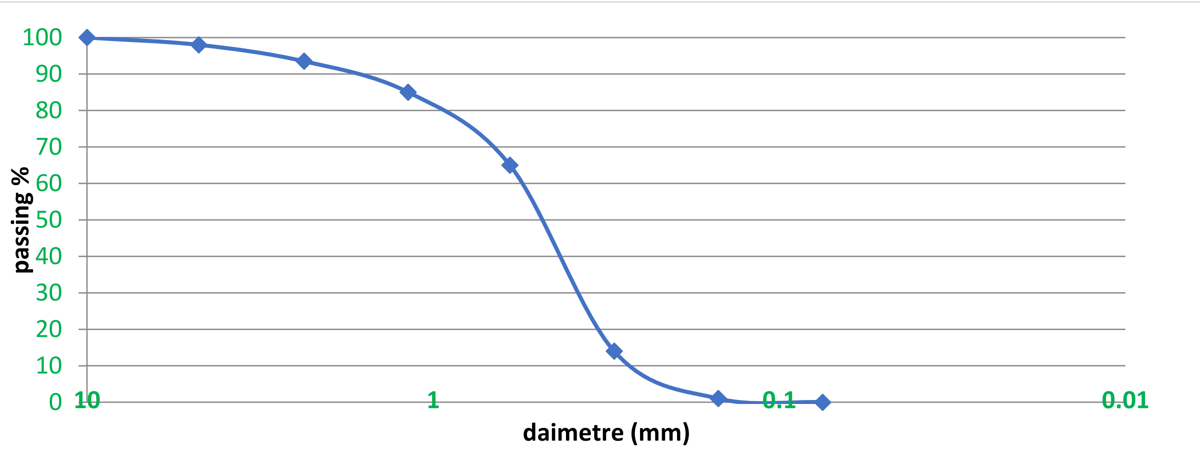


Fig. 1 Sieve Analysis Curve (GSD).

3.EXPERIMENTAL WORK

After conducting laboratory tests on the materials involved in building the model, they were placed in the hydraulic conductivity tank, manufactured with dimensions of (180 cm) in length, (70 cm) in height, and (30 cm) in width, made of iron and with a fiberglass interface to observe the leakage occurring. It contains thirteen piezometers distributed every (10 cm) along the iron rear wall, used to measure the height of the water rising inside the dam body, as shown in Fig. 1. Thirty physical models were built, including four shapes core: rectangle, trapezoid, and forward and backward inclined shapes. The inclination slopes were (1:0.25, 1:0.50, and 1:0.75), and the ratio of the core crest width to dam crest width was (0.25, 0.50, and 0.75). The dimensions and details of the selected tyFigal zoned earth fill dam are shown in Table 1. A 1:25 scale was adopted to replicate the proportions of a standard earth dam within the laboratory setting, aligning with the available dimensions of the laboratory apparatus. The resulting dimensions of the dam, following this scaling, are presented for reference in Table 2.

Fig. 2 Hydraulic Conductivity Tank.

Table 1 Dimensions Details of a TyFigal Cross-Section of a Zoned Earth Dam.

	Description	**Symbol**		**Value**		
Dam	Height	H		10 m		
	Base width	B		33.75 m		
	Freeboard	F_b		1.25 m		
	Crest width	b_d		3.75 m		
	U/S and D/S slope	S_u and S_d		1.5		
	Hydraulic conductivity	k_d		7×10^{-3} m/sec		
	Soil type	Coarse Sand				
Core	Height	H		10 m		
	U/S and D/S slope	S_c		1:0.25	1:0.50	1:0.75
	Crest width	b_c		0.94m	1.88m	2.81m
	Base width	B_c		(5.94-17.81) m		
	Hydraulic conductivity	k_c		2.1×10^{-7} m/sec		
	Shape	rectangular	trapezoidal	forward inclined		backward inclined
	Soil type	Clayey sand				
	Base length	l_f		2.25 m		
Drain	Height	h_f		1.5 m		
	Hydraulic conductivity	k_f		0.05 m/sec		
	Soil type	Coarse Gravel				

Table 2 Dimensions of the Scaled Zoned Earth Dam Models.

	Description	**Symbol**		**Value**		
Dam	Height	H		40 cm		
	Base width	B		135 cm		
	Freeboard	F_b		5 cm		
	Crest width	b_d		15 cm		
	U/S and D/S slope	S_u and S_d		1.5		
	Hydraulic conductivity	k_d		7×10^{-3} cm/sec		
	Soil type	Coarse Sand				
Core	Height	H		40 cm		
	U/S and D/S slope	S_c		1:0.25	1:0.50	1:0.75
	Crest width	b_c		3.75cm	7.5cm	11.25cm
	Base width	B_c		(23.68-71.24) cm		
	Hydraulic conductivity	k_c		2.1×10^{-7} cm/sec		
	shape	rectangular	trapezoidal	forward inclined		backward inclined
	Soil type	Clayey Sand				
Drain	Base width	l_f		9 cm		
	Height	h_f		6 cm		
	Hydraulic conductivity	k_f		0.05 cm/sec		
	Soil type	Coarse Gravel				

The geometric shape of the dam with the required dimensions is shown in Table 2, drawn on the fiberglass interface. The dam component materials were stacked in layers every (5 cm) with appropriate compaction, Fig. 2. After completing the construction of the model, the device was filled with a constant water level at (35 cm) height. After the out-flow seepage water stabilized and reached a steady state flow, the quantity of water coming out over time was measured several times using a timer and a test tube to ensure accuracy and the phreatic line drawn from piezometric readings, Fig. 5. To manage the uniformity of the stacking approach in all fashions, the subsequent steps can be observed: 1. Ensure correct dimensions: The geometric shape of the dam with the specified dimensions must be accurately measured and recorded to ensure consistency in the production of all fashions. 2. Use appropriate compaction: During the stacking technique, every layer of dam issue substances must be compacted nicely to achieve uniformity in the density and balance of the dam structure. 3.

Maintain constant layer thickness: The dam aspect materials must be stacked in layers with a consistent thickness, including every five cm, to retain uniformity in all models. 4. Use a dependable measuring tool: To ensure accuracy in measuring the amount of water coming out over time, a timer and a tube can be used to acquire reliable records for evaluation. 5. Monitor the phreatic line: The phreatic line, which represents the water table inside the dam, must be monitored using piezometric readings to understand the seepage behavior and ensure uniformity in the flow patterns. By following these steps, the uniformity of the stacking method can be controlled in all models to conduct accurate experiments and obtain reliable results for further analysis.

Fig. 3 First Layer Compacting.

Fig. 4 The Drainage Area in the Dam Model.

Fig. 5 Experimental Dam Model with Trapezoidal Shape Core.

A- Central Rectangle Core. B- Backward Inclined Core.

Fig. 6 Piezometric Head Recording.

Also, upstream slope stability against sliding was monitored for all models at a critical state. The rapid drop of water level in the reservoir after reaching a steady state in water seeping and saturation of the seepage zone represents the critical state of dams. That behavior is due to the reverse flow movement of water drained from the saturated body of the dam toward the reservoir, which leads to the sliding of the upstream surface soil of the dam shell, Fig. 5. After the experiment ended, the device was cleaned, and the experiment was repeated with the following model. The experimental results are listed in Table 3. The experimental modeling scenarios are clarified in Fig. 8.

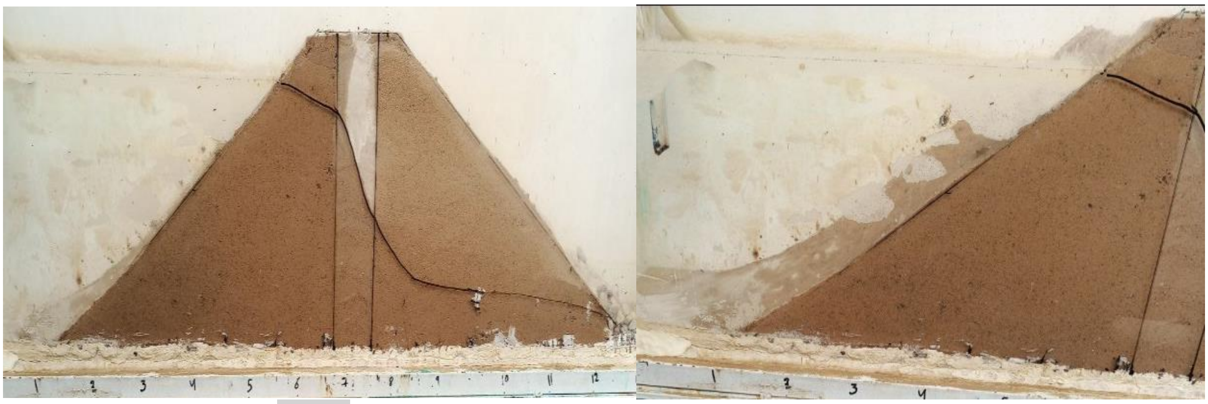


Fig. 7 Upstream Slope Sliding Stability for Dam Model.

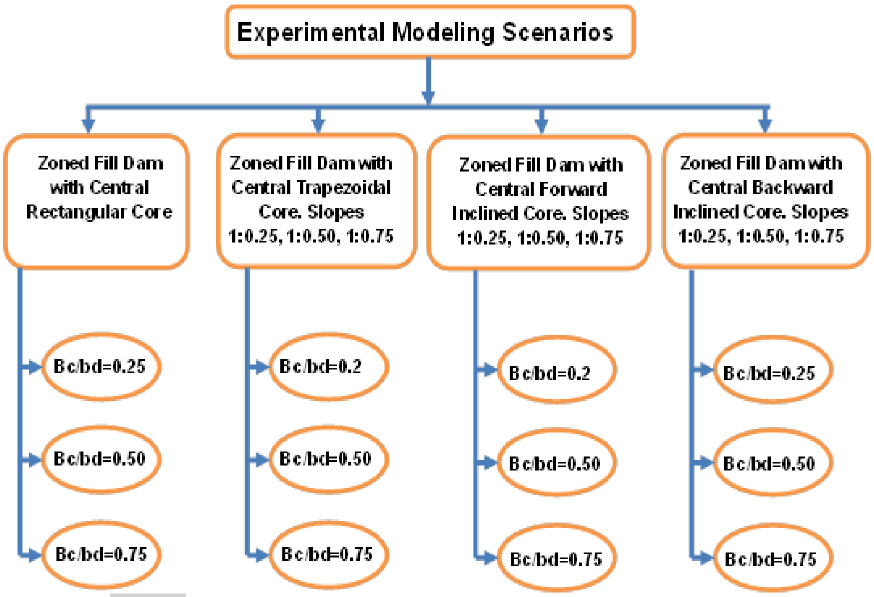


Fig. 8 Experimental Modeling Groups Scenarios Chart.

4.NUMERICAL MODELS

Thirty numerical models with the same dimensions and characteristics as the experimental models were performed using Geo Studio 12 software (SEEP/W) to ensure the validity of the experimental results. Examples of four core shapes are shown in Fig. 9. Seepage magnitude results are listed in Table 3. The Geo Studio 12 software program (SEEP/W) was used to create numerical fashions that simulate the experimental models of zoned earth-fill dams. The software was used to ensure the validity of the experimental outcomes by comparing them with the outcomes obtained from the numerical models. The software permits the creation of thirty numerical models with identical dimensions and characteristics of the experimental models. These models included four unique middle shapes: square, trapezoidal, ahead-inclined, and backward-inclined. The seepage magnitude consequences obtained from the numerical fashions are listed in Table 3. The software program was used to simulate the seepage glide through the dam body and calculate the amount of seepage and the seepage phreatic line. The numerical models were compared with the experimental models to decide the agreement in effects, i.e., measured using the correlation element (R^2). In this case, the effects confirmed an excessive settlement with a correlation factor of 99.4. The results also highlight the effectiveness of the trapezoidal middle shape in decreasing drainage compared to the square center form. It was found that the trapezoidal center shape reduced drainage by about 62-79% compared to the rectangular middle form at various center-side slopes. The results also showed that the ratio of the middle crest width to the dam crest width affected seepage discharge for all center shapes. Overall, the Geo Studio 12 software was used to create numerical models that simulate the experimental models of zoned earth-fill dams. The software permits the analysis of seepage behavior and the evaluation of consequences with the experimental information to ensure the validity of the experimental results.

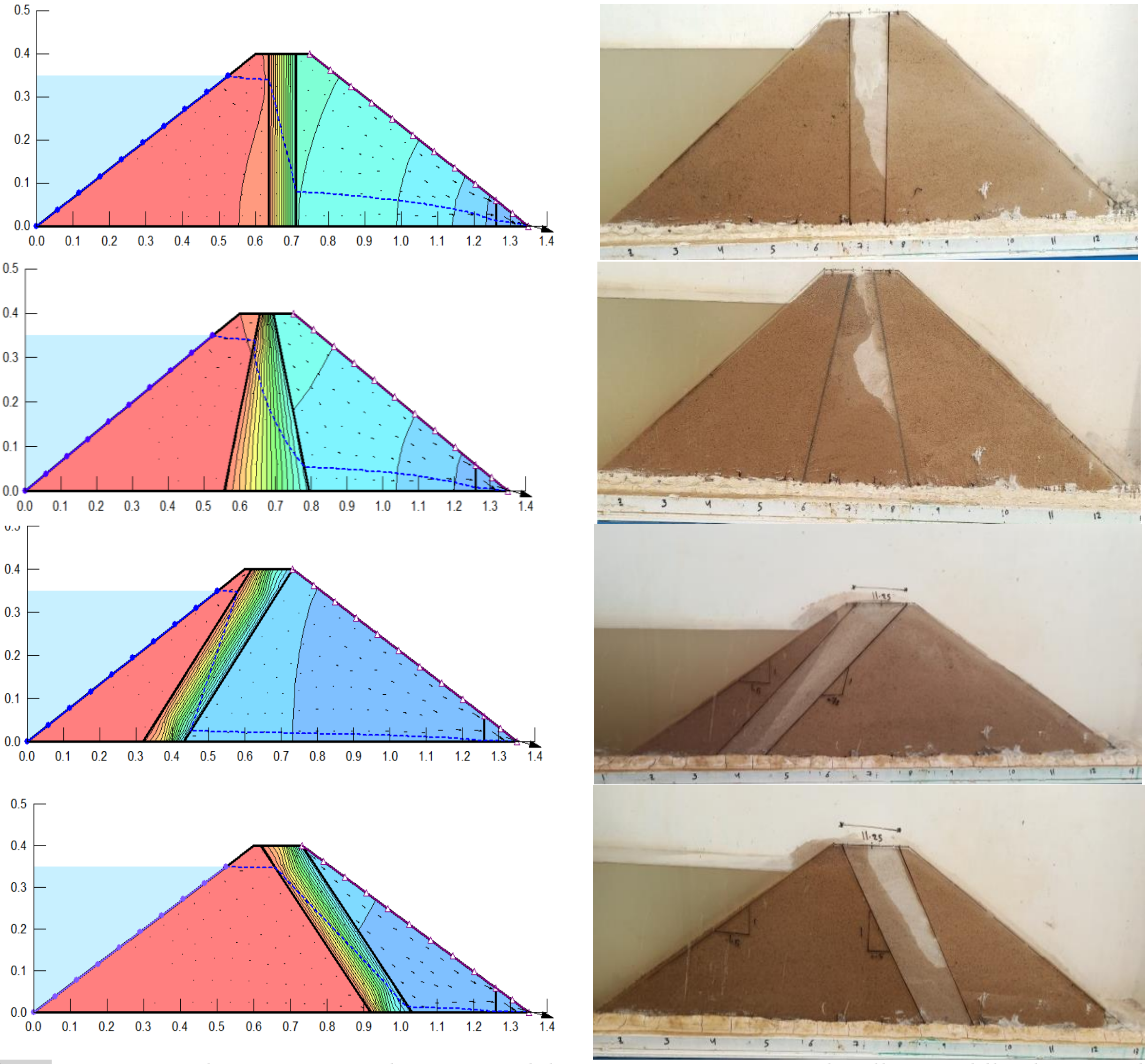


Fig. 9 (a) Rectangular Core Form, (b) Trapezoidal Core Form, (c) Forward Willing Middle Shape, and (d) Backward Inclined Core Shape.

5.RESULTS

Experimental models were built using one-of-a-kind middle shapes and dimensions, and the quantity of seepage via the dam body was measured. The results were compared with numerical simulations using the Geo Studio program, showing high agreement. The study found that the trapezoidal core shape was the most effective in reducing drainage compared to the rectangular core shape. The core crest-to-dam crest width ratio also affected seepage discharge for all core shapes.

Table 3 Seepage Discharges for Experimental and Numerical Models.

Core Shape	b_c/b_d	Slope (S)	Numerical Q (m^3/sec)	Experimental Q (m^3/sec)	Q Difference Percent (%)
Trapezoidal	0.25	1:0.25	2.6323E-07	2.5270E-07	-4
		1:0.50	1.904E-07	1.7517E-07	-8
		1:0.75	1.5884E-07	1.3978E-07	-12
	0.50	1:0.25	1.8809E-07	1.7680E-07	-6
		1:0.50	1.4212E-07	1.3786E-07	-3
		1:0.75	1.322E-07	1.1237E-07	-15
	0.75	1:0.25	1.490E-07	1.3410E-07	-10
		1:0.50	1.1687E-07	1.1103E-07	-5
		1:0.75	1.0199E-07	9.2811E-08	-9
Forward inclined	0.25	1:0.25	7.2242E-07	6.7907E-07	-6
		1:0.50	8.3143E-07	7.2334E-07	-13
		1:0.75	9.9542E-07	9.6556E-07	-3
	0.50	1:0.25	3.8582E-07	3.6653E-07	-5
		1:0.50	4.4693E-07	4.0671E-07	-9
		1:0.75	5.4572E-07	5.2389E-07	-4
	0.75	1:0.25	2.6285E-07	2.4971E-07	-5
		1:0.50	3.024E-07	2.9333E-07	-3
		1:0.75	3.677E-07	3.2725E-07	-11
Backward inclined	0.25	1:0.25	7.2106E-07	6.9222E-07	-4
		1:0.50	8.267E-07	7.6056E-07	-8
		1:0.75	9.8963E-07	9.5994E-07	-3
	0.50	1:0.25	3.8617E-07	3.7072E-07	-4
		1:0.50	4.4592E-07	3.6565E-07	-18
		1:0.75	5.4226E-07	4.6634E-07	-14
	0.75	1:0.25	2.6253E-07	2.4940E-07	-5
		1:0.50	3.0144E-07	2.7431E-07	-9
		1:0.75	3.6479E-07	3.2831E-07	-10
Rectangle	0.25	-	6.9434E-07	6.7351E-07	-3
	0.50	-	3.6594E-07	3.5130E-07	-4
	0.75	-	2.4957E-07	2.3709E-07	-5

Piezometric head readings obtained from experimental work were used to draw the phreatic line for all experimental models and compared with others obtained from numerical models. Several of these drawings are shown in Fig. 9. The study's findings, detailed in Table 3 and illustrated in Figs. 10, 12, and 13, lead to several conclusions, as follows:

1- Agreement Between Experimental and Numerical Results: Seepage discharge values from experimental and numerical models strongly correlate (R^2 = 99.4%). Generally, experimental values were 3% to 18% lower than numerical values.

2- Effect of Core Shape and Location on Seepage: The shape and position of the core significantly impacted water seepage through the zoned earth fill dam. Changing from a rectangular to a trapezoidal core decreased seepage by 62%, and reducing the core slope from 1:0.25 to 1:0.75 increased seepage by 79%. Altering the core slope also showed variations in seepage levels for inclined cores.

3- Impact of Core Crest Width Ratio: Adjusting the core crest width to the dam crest width ratio from 0.25 to 0.75 led to diverse effects on seepage. For instance, increasing this ratio decreased seepage for trapezoidal core shapes and specific slopes while causing an increase for forward and backward-inclined core shapes.

4- Overall Effects of Core Crest Width Ratio Increase: Across different core shapes and slopes, increasing the core crest width to dam crest width ratio from 0.25 to 0.75 resulted in substantial seepage reductions, ranging from 34% to 65%.

5- Stability Against Sliding: Monitoring the stability of the dam's upstream surface against sliding at critical states revealed its high resistance, except for minor areas near the base for rectangular and backward core shapes, as shown in Fig. 5.

Figure 11 compares the seepage quantity for different core shapes at various core side slopes. It demonstrates that the trapezoidal core shape was the most effective in reducing drainage, with a 62-79% reduction compared to the rectangular core shape. Figure 11 highlights the importance of core shape in minimizing seepage in zoned earth-fill dams. Figure 12 shows the effect of the core crest-to-dam crest width ratio on seepage discharge for all core shapes. It suggests an inverse proportion among the core crest-to-dam crest width ratio and seepage discharge for all core shapes. Figure 12 emphasizes the importance of the core crest width ratio in controlling seepage in zoned earth-fill dams. Figure 13 presents the effect of the core facet slope on seepage discharge for one-of-a-kind center shapes. It indicates a right-away percentage between the center aspect slope and seepage discharge for the trapezoidal core shape. At the same time, there is an inverse percentage for the forward and backward-inclined center shapes. Figure 13 highlights the influence of the core facet slope on seepage behavior in zoned earth-fill dams. Figure 13 provides visual evidence and assists with concluding. They enhance the knowledge of the experimental consequences and contribute to the overall discussion on the impact of core shape and place on seepage in zoned earth-fill dams.

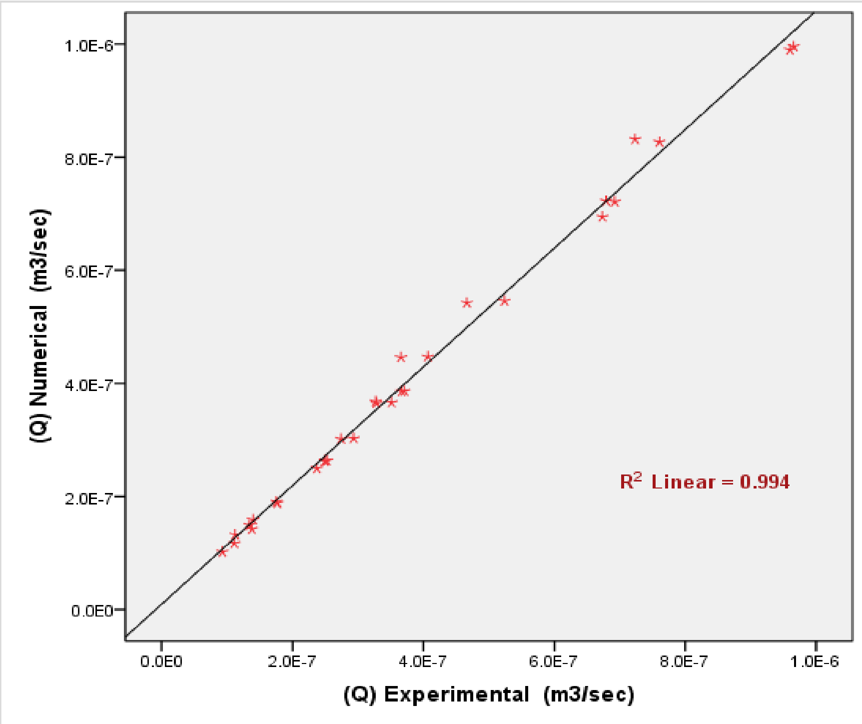
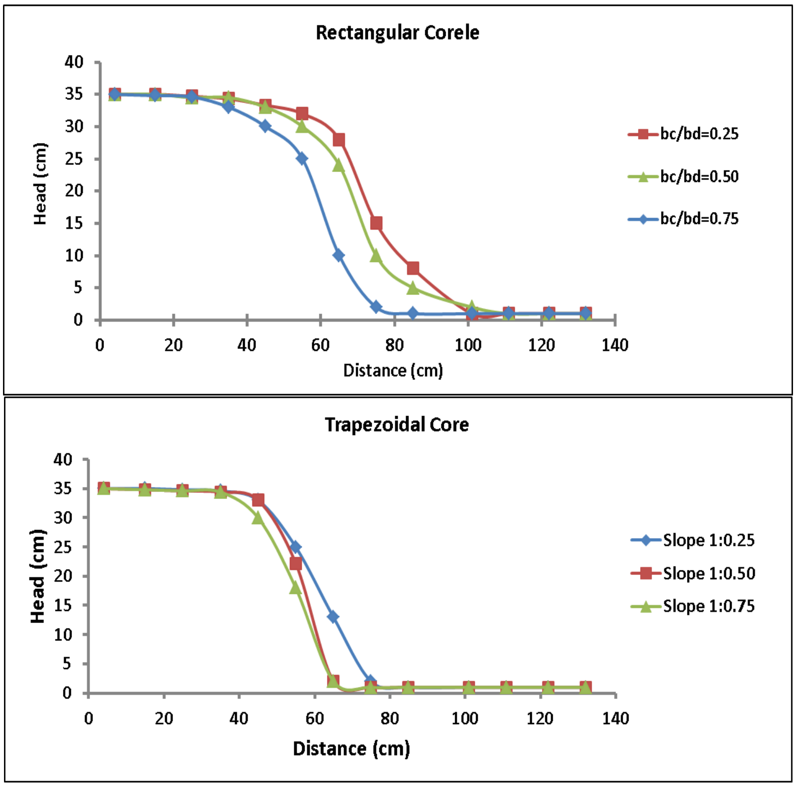
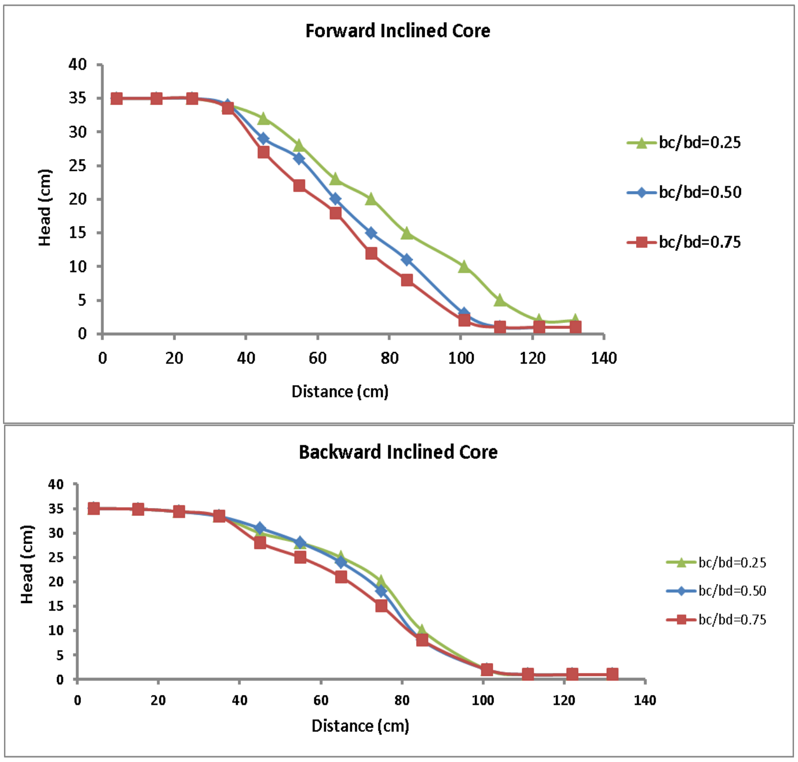


Fig. 10 Comparison of Experimental and Numerical Seepage Discharges.

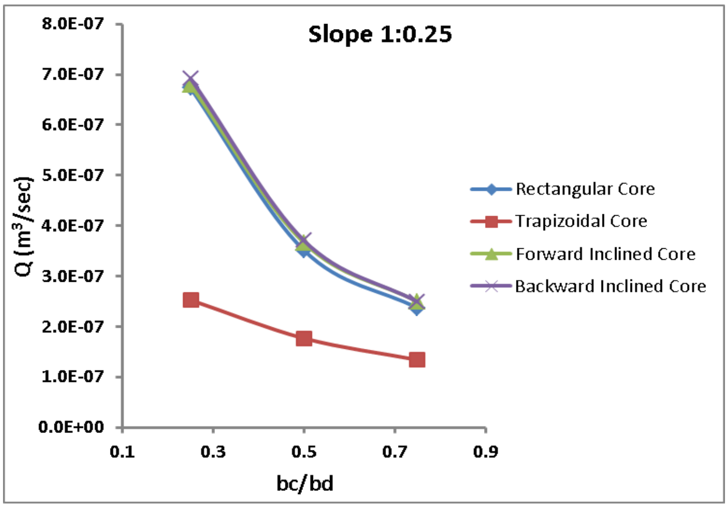


(a)



(b)

Fig. 11 (a) Seepage Quantity Reduction with Trapezoidal Core Shape, and (b) Seepage Quantity Reduction with Rectangular Core Shape.



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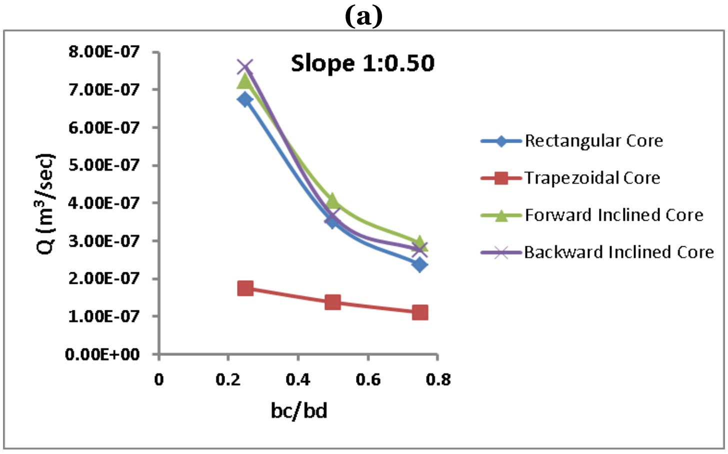

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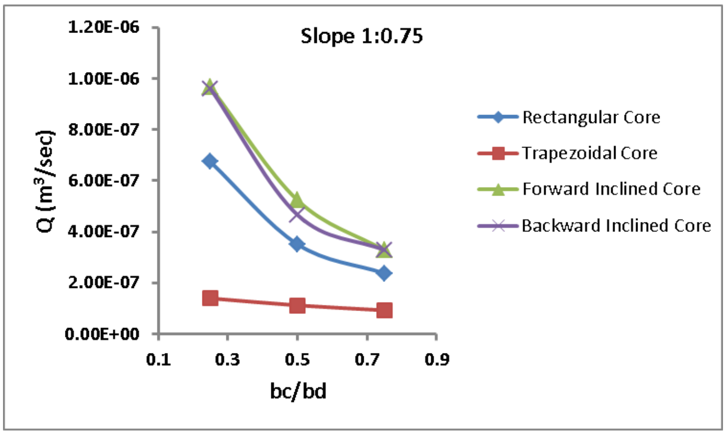

(c)

Fig. 12 (a) Direct Proportion of Core Side Slope Effect for Trapezoidal Core Shape, (b) Inverse Proportion of Core Side Slope Effect for Forward Inclined Core Shape, and (c) Inverse Proportion of Core Side Slope Effect for Backward Inclined Core Shape.

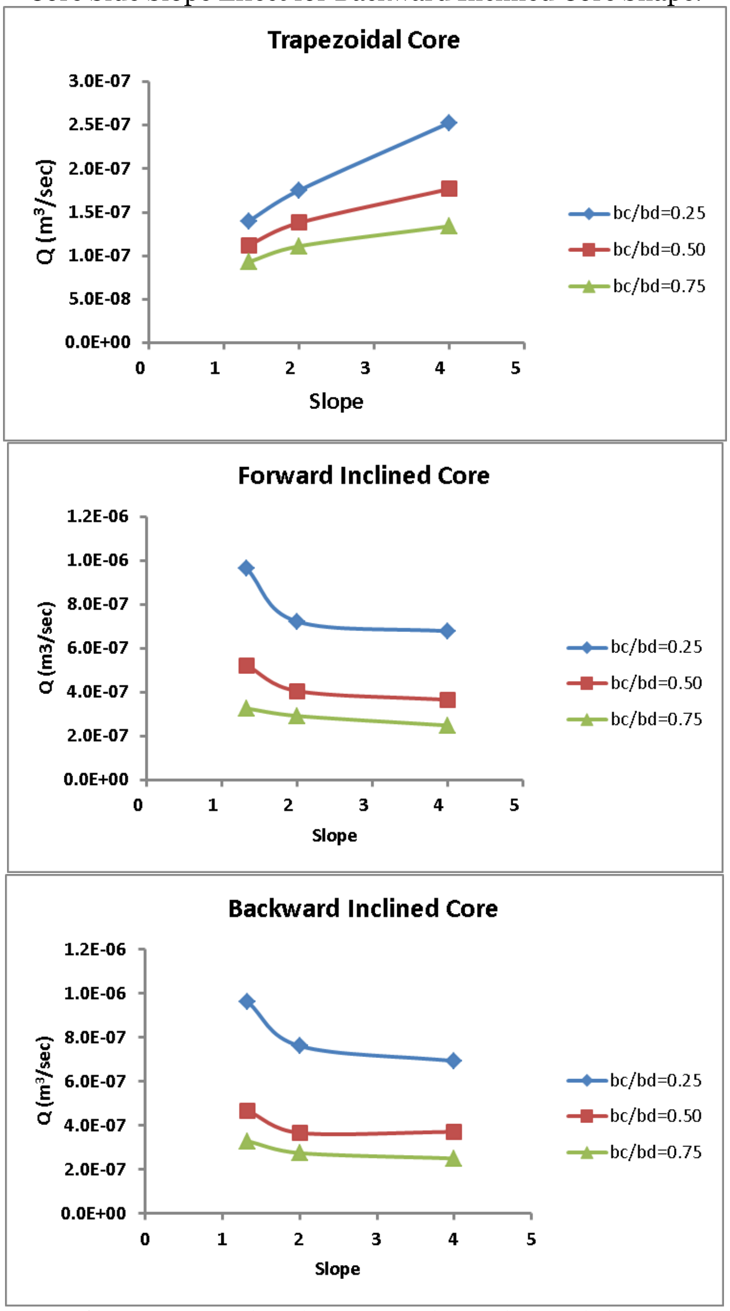

Fig. 13 (a) Comparison of Experimental and Numerical Results, and (b) High Agreement in Effects with Correlation Factor r^2= 99.4.

6.CONCLUSION

The study investigated the effect of the shape and area of the center on seepage in zoned earthfill dams. The researchers conducted practical experiments and demonstrated them numerically using the GeoStudio 12 software. The results showed that the trapezoidal core shape became the handiest in decreasing drainage, reducing drainage by about 62-79% compared to the rectangular core form. The core crest-to-dam crest width ratio also impacted seepage discharge for all center shapes. The study highlighted the importance of clay cores in zoned earth dams and used numerical modeling to understand seepage behaviors.

NOMENCLATURE

B	base width, cm
bc	Crest width, cm.
Bc	Base width, cm.
b_d	Crest width, cm
F_b	Freeboard, cm
H	Height, cm
h_f	Height, cm (Drain)
I_f	Base width, cm(Drain)
kc	Hydraulic conductivity, cm/sec (Core)
k_d	Hydraulic conductivity, cm/sec (Dam)
k_f	Hydraulic conductivity, cm/sec
Q	Discharge (m^3/sec).
S_c	U/S and D/S slope (Core)
S_u and S_d	U/S and D/S slope (Dam)

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