(Online) ISSN 2712-0554
Heritage and Sustainable Development *Original Research*
Vol. 8, No. 2, July 2026, pp.103-114
https://doi.org/10.37868/hsd.v8i2.2262

Seepage control in earthen canals using alkali-activated geopolymer lining

Amer Hasan Taher[1], Mustafa Ahmed Yousif[2], Lubna Abdulrahman[3], Ahmed Mancy Mosa[4*]
[1,2] Civil Engineering Department, Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq
[3] Civil Engineering Department, AL-Mansour University College, Baghdad, Iraq
[4] Highway and Transportation Engineering Department, Faculty of Engineering, Mustansiriyah University, Baghdad, Iraq

*Corresponding author E-mail: ahmed.mancy@uomustansiriyah.edu.iq

Received Feb. 3, 2026
Revised May. 26, 2026
Accepted Jun. 6, 2026
Online Jul. 17, 2026

Abstract

Earthen canals suffer from serious water loss due to seepage, directly impacting water transport efficiency. This problem is exacerbated by the increasing demand for water resources. Geopolymers can be used effectively to line the canals, reducing these losses. This study aims to examine the effects of new geopolymers on seepage in earthen canals. Fine ash-based geopolymers were chosen because fine ash is a byproduct of brick plants and is freely available in abundant quantities. Therefore, it can be considered a promising alternative to fly ash-based geopolymers. Literature lacks an integrated framework for permeability, lining geometry, and water level effects. The study included four parameters: permeability coefficient, lining layer thickness, lining orientation, and water level. To achieve the study objectives, a two-phase methodology was adopted. First, investigating the effect of fine-ash doses on soil permeability using laboratory testing. Second, using SEEP/W numerical simulation to explore seepage from an earthen canal lined with fine ash-based geopolymer under different doses. The results showed that the ratio of lining permeability to that of the original soil (KL/K) significantly affected seepage rates. KL/K ratios less than 0.05 achieved a very high reduction efficiency of about 85–95%, corresponding to 30% of activated fine ash. Lining orientation is an important factor. Full lining of the channel was the most effective configuration. However, partial lining with bottom and side linings yielded less efficient results, reducing losses by about 60% and 50%, respectively, compared with an unlined canal. This confirms that vertical seepage through the channel bottom is the primary loss mechanism. The result shows that increasing the thickness of the activated geopolymer liner significantly improved channel performance. These geopolymer liners reduced seepage by 70–90% in several cases, including one with a bottom-width-to-height water-level ratio of 6, although a positive relationship between water level and seepage remained evident. Using alkali-activated geopolymer in more than 15% of the dry soil effectively controlled canal seepage.

Keywords: Seepage control, Earthen canals, Alkali-activated geopolymer, Lining

1. Introduction

Despite advances in technology across various fields, water resources remain the cornerstone of human life. The world faces a severe shortage of usable water for several reasons, such as mismanagement and pollution [1]. UNICEF and WHO reported that 2.2 billion people lack access to safe drinking water [2]. FAO states that 70% of water is consumed for agricultural purposes [3]. A reassessment conducted by FAO and the UN on water management in agriculture revealed that unlined earthen canals lose 30–50% of their water due to seepage [4]. Climate change may also exacerbate the problem. The World Bank predicts that by 2050, water scarcity could reduce agricultural production by 10–25% as a result of water losses due to evaporation caused by global warming [5]. Therefore, studying irrigation systems is crucial, especially for sustainability.

Water management systems aim to optimize the use of water resources, especially by enhancing water conveyance systems. The conveyance of water by irrigation canals is the oldest way to distribute water. Among these, earthen canals are simple, inexpensive, and practical. However, these canals experience water losses due to seepage, which exacerbates global water scarcity. Extreme water losses due to seepage can be found in high-permeability soils such as sandy soil with permeability coefficient (K) $\geq 10^{-5}$ [6]. To reduce these losses, two traditional alternatives are available. The first one is using closed canals (pipes). However, this type is difficult to construct, requires a high initial cost, and involves complex and costly maintenance operations. The second one is lining, which incorporates the advantages of pipes in terms of reducing losses due to seepage, in addition to overcoming the complexities of construction and maintenance in the case of pipes. However, different types of lining have different disadvantages. First, Portland cement concrete lining is a suitable alternative due to its impermeability and surface smoothness. However, its high cost and carbon footprint make it an undesirable alternative [7]. Second, asphalt lining is also a suitable alternative. However, the complexities of its construction, cost, maintenance, heat sensitivity, and environmental impact make it impractical [8]. Third, inexpensive clay lining materials are a good option for simple projects. However, such materials are susceptible to cracking and require periodic maintenance due to shrinkage-swelling behavior [9]. Therefore, finding a sustainable, practical, and inexpensive alternative that combines the advantages of other alternatives and avoids their disadvantages is highly needed. To explore the available alternatives, a comprehensive literature review of the most recent studies in the field was conducted [7–15]. The review revealed several points. First, some types of lining can reduce seepage by 99%. Second, geopolymers can be adopted effectively in the lining of earthen canals to reduce water losses due to seepage [16]. However, only limited studies were found in this domain. These limited studies utilized fly-ash-based geopolymer. However, the amount of fly ash, which is the main component in this type of geopolymer, is very limited worldwide and continuously decreases, as it is a byproduct of coal-fired power plants that are now a thing of the past. Third, fine-ash-based geopolymers are used in several construction applications, as reported in [17–19]. Fine ash is widely available in huge quantities, especially in Iraq, as it is a byproduct of brick plants. Therefore, it can be considered a promising alternative to fly-ash-based geopolymer, especially when considering sustainability. However, to the best of the authors' knowledge, no such study has adopted this type of geopolymer in the lining of earthen canals. This is a significant research gap in this domain. Another gap in the literature was identified: the absence of a unified framework that combines the effects of chemical action, lining geometry, and canal application. Therefore, this study aims to fill these gaps by conducting a novel investigation to examine the effects of fine-ash-based geopolymer on water seepage in earthen canals. The study included four parameters: permeability coefficient, lining layer thickness, lining orientation, and water level.

To attain the study objectives, a methodology composed of two phases was adopted. First, the effect of fine-ash doses on soil permeability was investigated by means of laboratory testing. Second, a numerical simulation using SEEP/W was adopted to explore the effects of the four mentioned parameters on water seepage from an earthen canal lined with fine-ash-based geopolymer using different doses. This approach provides a combined experimental and numerical assessment of the potential of fine-ash-based geopolymer as a sustainable canal lining material. It also enables the evaluation of how material properties and lining configurations influence seepage reduction under different canal conditions.

2. Laboratory phase

To start this phase, Mishkhab in Najaf City, Iraq, was selected as the study area, as shown in Figure 1. Mishkhab is an agricultural area that relies on a traditional irrigation system of open, unlined canals branching from the Euphrates River. Samples were collected from open canals in this area to investigate the soil properties. The selected soil properties are shown in Table 1.

Table 1. Basic properties of the soil in the study area

Property		Unit	Value	ASTM standard specification
Specific gravity		-	2.76	D 854
Particles analysis	Gravel	%	0	D 6913
	Sand	%	7	
	Silt	%	58	D 7928
	Clay	%	35	
Atterberg limits	Liquid state limit, LL	%	35	D 4318
	Plastic state limit, PL	%	23.8	
	Plasticity index, PI	%	11.2	
OMC		%	18	D 1557
MDD		kN/m3	17.8	
Permeability		m/s	2.8×10-4	D5084

Figure 1. Inlining canal in Mishkhab area

As shown in Table 1, the soil permeability is considered high, leading to significant water loss. Therefore, different doses of fine ash were added to decrease its value, control water seepage, and reduce losses. A sufficient quantity of fine ash was brought for free from a brick factory in the Nahrawan area in Baghdad City. Fine ash is a black material with particle sizes less than 74 micrometers and a specific gravity of 2.1. Its chemical composition is summarized in Table 2 from which is obvious that the sum of silica, alumina, and iron oxide contents exceed 70%. Based on this result, fine ash can be classified as Class F according to ASTM C618.

Table 2. Chemical composition of Nahrawan brick factory fine ash

Composition	Value (%)
SiO_2	63
Al_2O_3	24
Fe_2O_3	7
CaO	3
MgO	1
Loss on ignition	2

Fine ash acts as a filler material and may slightly affect the soil's permeability without bonding the soil particles. To produce the binding effect, the composition needs to be activated. In this study, fine ash was activated with an alkaline solution composed of sodium silicate and lime at an activator-to-fine-ash ratio of 0.4 to form a geopolymer and enhance its effect. The activation breaks the bonds via dissolution, liberating silica (SiO_2) and alumina (Al_2O_3), thereby enabling the polycondensation reaction to bond the soil [20]. Consequently, fine ash is activated with an alkaline solution to obtain a geopolymer, as shown in Equation 1.

$$Al2O3{\cdot}2SiO2+NaOH/Na2SiO3 \rightarrow N\text{-}A\text{-}S\text{-}H\ gel \quad (1)$$

Different doses of geopolymer (5%, 10%, 15%, 20%, 25%, and 30% by weight of the soil) were added to the soil to investigate their effects on permeability. These doses were recommended in the literature [21]. The samples mixed with these doses were tested according to ASTM D5084. The testing results showed that the permeability values were 9.8×10^{-5}, 7.84×10^{-5}, 7.84×10^{-6}, 1.568×10^{-6}, 7.84×10^{-7}, and 7.84×10^{-8} for the samples mixed with 5%, 10%, 15%, 20%, 25%, and 30% of the geopolymer, respectively, as shown in Figure 2. These values represent 0.35, 0.28, 0.028, 0.0056, 0.0028, and 0.00028 of that measured for the control sample, respectively. A significant decrease in permeability reflects a significant decrease in water losses due to seepage. These values were adopted in the second phase, as described in Section 3.

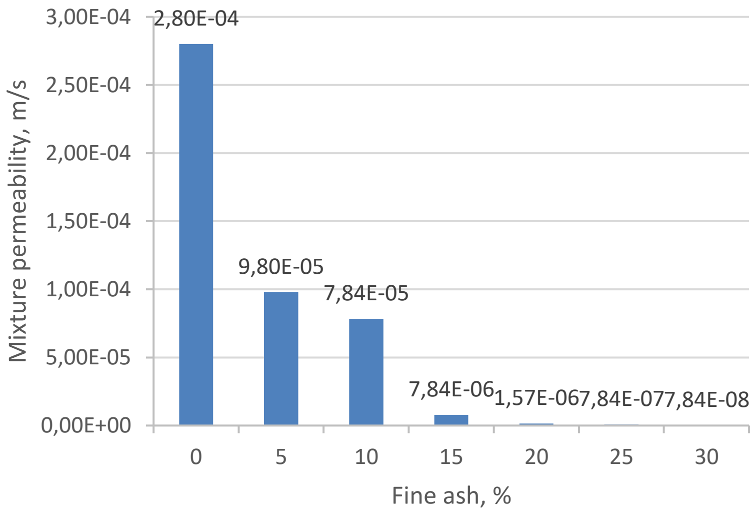


Figure 2. The variation of permeability according to adding pre-selected fine ash (%)

3. Numerical simulation phase

3.1 Canal problem modeling

To model the canal in the problem under study, SEEP/W software was used. Steady-state flow conditions were selected to simplify the representation especially it is a common case in such problems. The geometry of the canal is determined by preselecting the bed width, sidewall-only, and or combined lining. In the reference case, the untreated soil properties were defined. The treated soil was placed in a layer of defined thickness, and it was assumed to be homogeneous and isotropic. The adopted mesh size of 0.50 m provides an optimal compromise between computational efficiency and solution accuracy. The mesh sensitivity was done. The drainage-type boundary condition was adopted as shown in Figure 3 to make the problem more realistic.

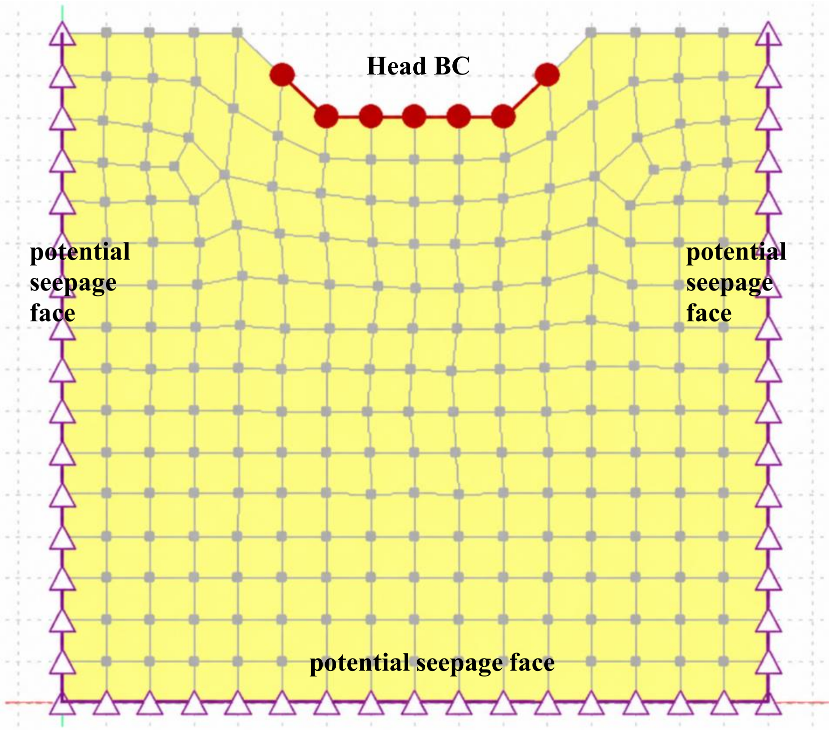


Figure 3. Layout of finite element mesh and boundary conditions used

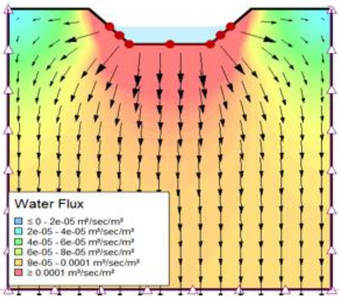
3.2 Parametric study

To study the targeted four parameters, a numerical representation was implemented. First, the permeability parameter in terms of (KL/K), where K and KL are the permeability coefficients for the control soil and lining, respectively, was adopted as (0.35, 0.28, 0.028, 0.0056, 0.0028, and 0.00028) for the lining soil mixed with different doses of geopolymer, as mentioned in Figure 2. Second, the lining layer thickness parameter in terms of TL/H, where TL is the layer thickness and H is the water height, was adopted as (0.2, 0.5, 1.0, and 1.5). Third, the lining orientation parameter was represented by three cases: bed-only, sidewall-only, and combined lining. Fourth, the water level parameter in terms of (b/H), where b is the canal bottom width and H is as previously defined, was adopted as (0.6, 1, 2, 3, 4, and 6). Figure 4 shows selected cases modelled using SEEP/W. Some impractical values were used to indicate the system's sensitivity. This parametric setup enabled a systematic evaluation of how each selected variable influences seepage behavior in lined earthen canals.

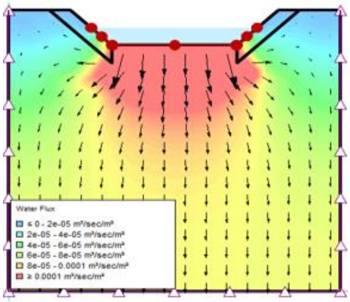
4. Presentation and analysis of results

4.1 Influence of the ratio of lining permeability on the origin soil KL/K

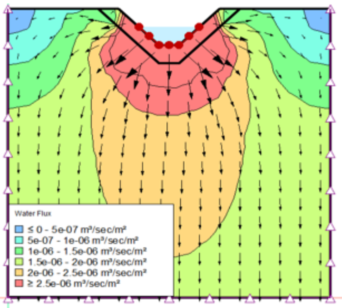
To study the influence of the lining's permeability on seepage in the selected site soil, the lining thickness-to-water height ratio was fixed at TL/H = 0.5. The simulation results indicate a clear trend, as shown in Figure 5; as the KL/K ratio increases, seepage losses also increase for all studied ratios (b/H). A lining with a KL/K ratio of 0.5 provides only a modest reduction in seepage, typically 10–30% compared to an unlined canal. Reducing it further to 0.05 significantly improves efficiency, reducing seepage losses by more than 85–95% across all b/H ratios. The most pronounced improvement occurs when the KL/K ratio is ≤ 0.0028, at which seepage losses are almost eliminated, with reductions of up to 99%. This may be attributed to the alkali-activated geopolymer (5% fine ash) acting only as a filler (Figure 2). The large difference observed in the alkali-activated geopolymer (20% fine ash) case is due to a reduction in pore volume from geopolymer filling. Increasing the geopolymer content increases the blocking of connected and semi-connected paths in the soil. This confirms that reducing the lining permeability is the dominant factor controlling seepage losses in lined earthen canals, especially when the treated layer reaches a sufficiently low KL/K ratio. Therefore, increasing the geopolymer dose improves seepage resistance by filling voids, blocking connected and semi-connected flow paths, and developing a more bonded and less permeable lining layer.



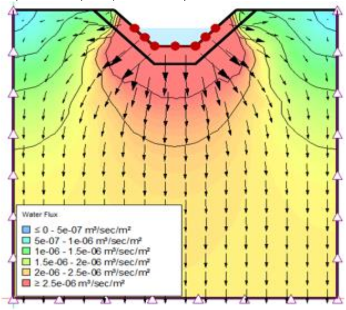
No lining (b/h=3)



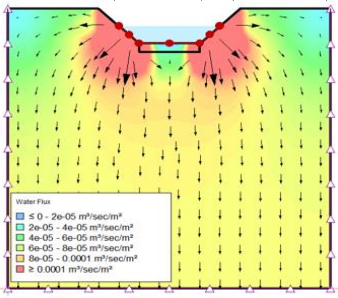
Compact earth lining side only (t/h=1), (b/h=4)



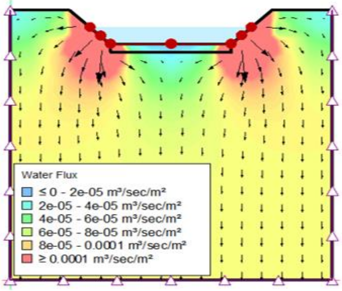
Compact earth lining bad and side (t/h=0.5), (b/h=0.6)



Compact earth lining bad and side (t/h=0.5), (b/h=1)



Compact earth lining bad only (t/h=0.5), (b/h=1)



Compact earth lining bad and side (t/h=0.5), (b/h=1)

Figure 4. Several cases of SEEP/W model results for the study

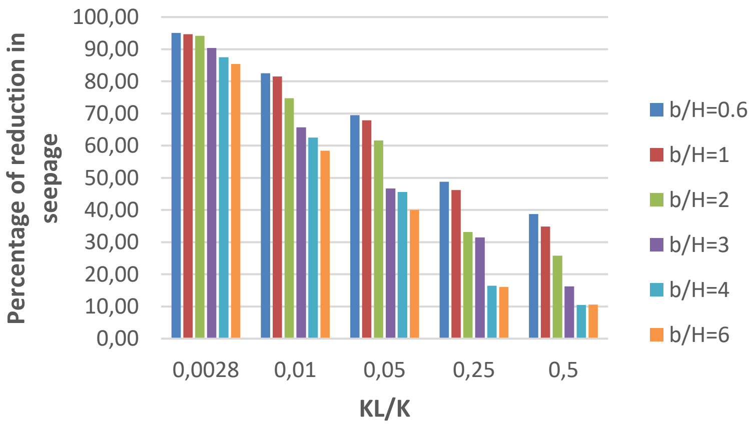


Figure 5. Influence of permeability on seepage with different (b/H)

4.2 Influence of the ratio of lining thickness to height of water TL/H

The thickness of the geopolymer lining is a crucial aspect of canal design. The effect of geopolymer-reinforced lining thickness was investigated at a permeability ratio (KL/K) of 0.0028, equivalent to the addition of 25% selected fine ash. Further decreasing this ratio (KL/K) did not significantly alter the seepage rate, as discussed in the previous section. As expected, the study revealed a strong inverse relationship between lining thickness and seepage rate.

For thin linings (TL/H = 0.2), the seepage rate in wider canals (b/H = 6) results in only an 80–90% reduction compared to the unlined condition. At TL/H = 0.5, the seepage rate is reduced by 90–95%, which is still insufficient for wider canals. Increasing the layer thickness to TL/H = 1.0 significantly improves performance, reducing the seepage rate and achieving reductions exceeding 98% for most canal shapes. At TL/H = 1.5, the seepage rate is extremely low (<0.5 KH), achieving near-perfect loss control across all b/H ratios. These results, illustrated in Figure 6, indicate that at TL/H = 1.0, the effect of water height in the canal diminishes. This may be explained by two factors: first, the hydrostatic pressure of the water increases with height; second, a thicker material creates longer closed soil paths with geopolymer.

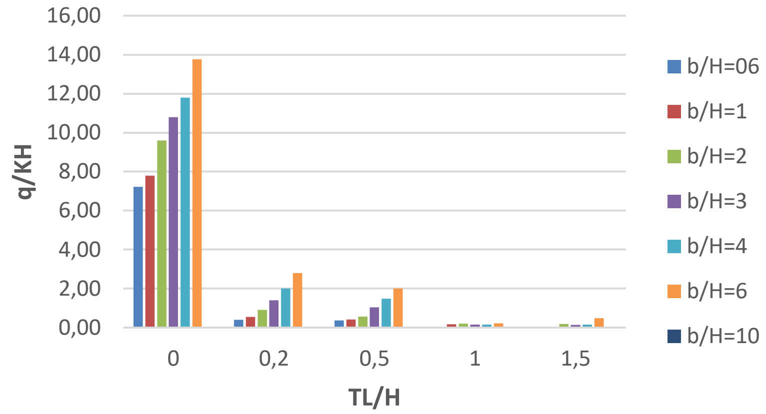


Figure 6. Influence of (TL/H) on the seepage for (KL/K= 0.0028)

4.3 Influence of lining orientation on seepage

Controlling the location of the lining is a simple method for controlling seepage. The effect of three types of canal lining (bottom lining only, sidewall lining only, and full bottom and sidewall lining) on seepage was investigated compared to the absence of lining, as illustrated in Figure 7.

The results clearly show that full lining achieves the highest efficiency, reducing seepage losses by 98–100% when the lining thickness reaches TL/H = 1.0–1.5, owing to its ability to block both vertical and horizontal seepage pathways simultaneously. With partial lining, performance varies considerably depending on whether the canal bottom or sidewalls are lined. Bottom lining alone is significantly more effective, achieving a seepage reduction of approximately 60–70%. Most seepage occurs vertically through the canal bottom. Blocking this pathway greatly reduces water loss. In contrast, lining only the sidewalls offers less benefit, typically reducing seepage by 35–50%, because it restricts only lateral flow while allowing significant vertical flow through the bottom. Despite these improvements, neither partial lining method matches the performance of full lining, which can achieve reductions exceeding 90%, even at moderate thickness levels (thickness-to-height ratio ≥ 0.5). Therefore, in cases where full lining is not economically or technically feasible, lining the bottom of the canal may be recommended as a more reliable and cost-effective alternative to lining only the sidewalls.

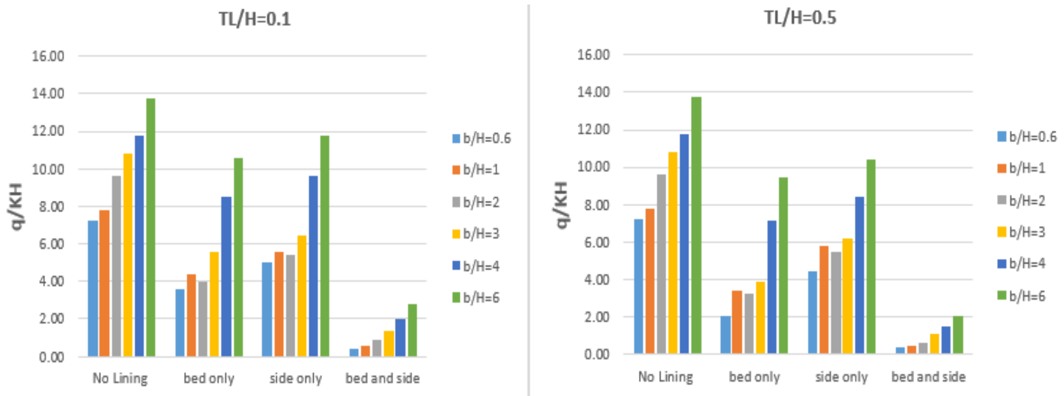


Figure 7a. Influence of lining orientation on seepage

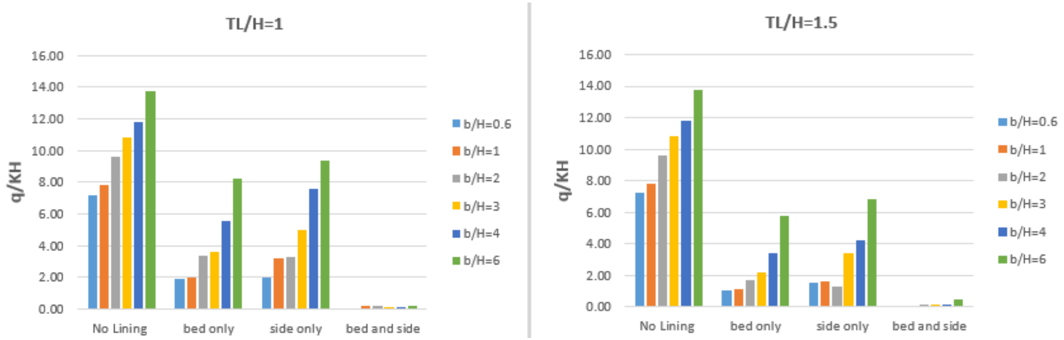


Figure 7b. Influence of lining orientation on seepage

4.4 Influence of water level on seepage

The findings of this study indicate that the seepage rate in earthen canals is strongly affected by both the canal water level and the canal lining condition. As shown in Figure 8, for unlined canals, a clear positive relationship was observed between the water level and the dimensionless seepage rate (q/KH). As the water depth increased, the hydraulic pressure gradient on the canal bottom and sidewalls increased, promoting seepage. For example, when b/H = 6, the seepage rate q/KH increased from approximately 11.1 at a water depth of 0.2 m to approximately 17.8 at a depth of 1.0 m. Wider canals exhibited higher seepage rates due to the increased contact area with the soil, providing additional pathways for seepage. As shown in Figure 9, the use of a 0.25 m-thick geopolymer-reinforced soil lining significantly reduced seepage across all tested scenarios. Seepage losses were reduced by approximately 70–90% compared to the unlined canal, demonstrating the effectiveness of geopolymer lining in reducing soil permeability and water loss. However, despite this significant improvement, the positive relationship between water depth and seepage rate persisted. Greater water depths continued to generate higher seepage rates, although these rates were considerably lower than those observed in the unlined canal.

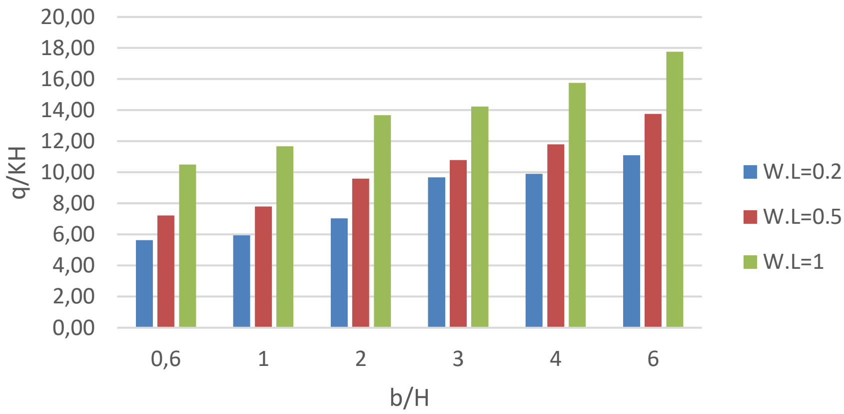


Figure 8. Influence of water levels on the seepage for (KL/K= 0.0028)

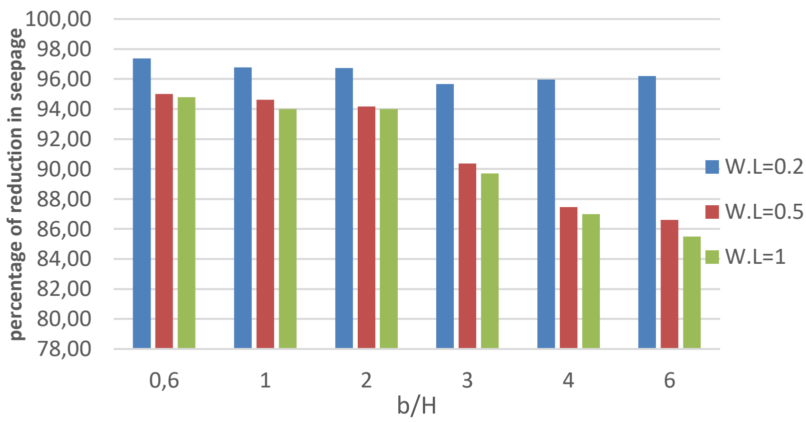


Figure 9. Percentage of reduction in seepage for different water levels

5. Results verification

To verify the results obtained from the numerical analysis, the water discharge values obtained under selected conditions were compared with values computed using the analytical expression shown in Equation 2, proposed by Vedernikov [22], which is a widely accepted method for estimating seepage losses in earthen canals.

$$q=K\ (B+AH) \quad (2)$$

where:

q: seepage rate ($m^3/s/m$)

K: permeability coefficient (m/s)

B: canal width (m)

H: water depth (m)

A: cross-sectional shape-dependent coefficient (unitless)

Table 3 summarizes the verification results. It shows close agreement between the findings from the numerical analysis and those computed using Equation 2. Figure 5 illustrates the comparison.

Table 3. Comparison between the numerical model and Vedernikov's equation

K, m/s	m	H, m	b, m	B, m	A	b/H	q (Vedernikov) (m3/s/m')	q (model) (m3/s/m)	q/KH (Vedernikov)	q/KH (model)
1× 10-4	1	0.5	0.3	2.3	2.9	0.6	3.75×10-4	3.61×10-4	7.5	7.22
1× 10-4	1	0.5	0.5	2.5	3	1	4×10-4	3.9×10-4	8	7.8
1× 10-4	1	0.5	1	3	3.2	2	4.6×10-4	4.8×10-4	9.2	9.6
1× 10-4	1	0.5	1.5	3.5	3.32	3	5.2×10-4	5.4×10-4	10.4	10.8
1× 10-4	1	0.5	2	4	3.45	4	5.73×10-4	5.9×10-4	11.5	11.8
1× 10-4	1	0.5	3	5	3.62	6	6.81×10-4	6.88×10-4	13.6	13.8

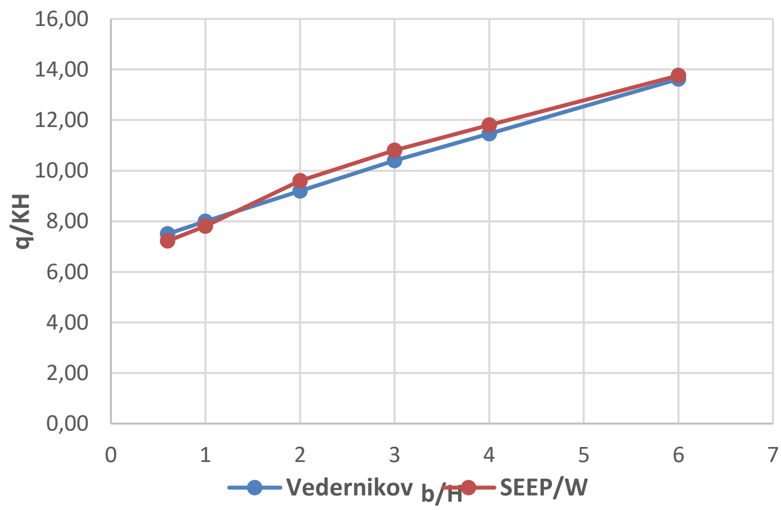


Figure 10. Graphical comparison between the numerical model and Vedernikov's equation

6. Conclusions

This study presented a comprehensive numerical investigation of seepage control, considering four parameters: the permeability coefficient, the lining layer thickness, the lining orientation, and the water level. Using SEEP/W finite element modelling, verified by comparison with analytical solutions, several key findings emerged:

1. The ratio of lining permeability to that of the original soil (KL/K) significantly affects seepage rates. Ratios with KL/K ≤ 0.05 achieved seepage reductions exceeding 85–95%, while extremely low values (KL/K ≤ 0.0028) resulted in near-complete elimination of seepage loss (>99%).
2. Increasing the liner thickness significantly improved channel performance. Thin linings (thickness-to-height ratio = 0.2–0.5) showed a limited reduction in seepage (less than 95%), particularly in wide channels, while thicker linings (thickness-to-height ratio ≥ 1.0) achieved near-complete seepage control in all channel shapes.
3. Full lining of the channel bottom and sidewalls was the most effective configuration, reducing seepage by 98–100% at thickness-to-height ratios between 1.0 and 1.5. Partial lining showed lower efficiency, with lining only the bottom (60–70%) outperforming lining only the sidewalls (35–50%), confirming that vertical seepage through the channel bottom is the primary loss mechanism.
4. Seepage rates increased with rising water levels due to the increased hydraulic gradient, particularly in unlined and wide channels (bottom-to-height ratio = 6). These geopolymer liners reduced water loss by 70–90%, although a positive relationship between water level and seepage remained evident.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

Author contributions

The contribution to the paper is as follows: Amer Hasan Taher: conceptualization, methodology, investigation, data curation, writing, original draft; Mustafa Ahmed Yousif: methodology, formal analysis, investigation, validation, writing, review and editing; Lubna Abdulrahman: experimental design support, laboratory testing and sample preparation, data curation, visualization, writing, review and editing; Ahmed Mancy Mosa: supervision, project administration, resources, software and numerical modelling, funding acquisition, writing, review and editing. All authors approved the final version of the manuscript.

Acknowledgments

The authors would like to express their gratitude to Mustansiriyah University, College of Engineering, Civil Engineering Department and Highway and Transportation Engineering Department, for their assistance and support in completing this project.

References

[1] UN-Water and Food and Agriculture Organization of the United Nations (FAO), *Progress on Change in Water-Use Efficiency: Global Status and Acceleration Needs for SDG Indicator 6.4.1, 2021*. Rome, Italy: FAO, 2021. https://doi.org/10.4060/cb6413en

[2] United Nations Children's Fund (UNICEF) and World Health Organization (WHO), *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2022: Special Focus on Gender*. New York, NY, USA: UNICEF and WHO, 2023.

[3] Food and Agriculture Organization of the United Nations (FAO), *The State of Food and Agriculture 2020: Overcoming Water Challenges in Agriculture*. Rome, Italy: FAO, 2020. https://doi.org/10.4060/cb1447en

[4] E. Koncagül and R. Connor, *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water; Facts, Figures and Action Examples*. Paris, France: UNESCO, 2023.

[5] World Bank, *High and Dry: Climate Change, Water, and the Economy*. Washington, DC, USA: World Bank, 2016. https://doi.org/10.1596/23665

[6] M. G. Eltarabily, H. F. Abd-Elhamid, M. Zeleňáková, M. K. Elshaarawy, M. Elkiki, and T. Selim, "Predicting seepage losses from lined irrigation canals using machine learning models," *Frontiers in Water*, vol. 5, Art. no. 1287357, 2023. https://doi.org/10.3389/frwa.2023.1287357

[7] K. Bakhodir, B. Masharif, and Y. Quvochbek, "Filtration reliability of the channel with concrete lining," *E3S Web of Conferences*, vol. 410, Art. no. 05024, 2023. https://doi.org/10.1051/e3sconf/202341005024

[8] M. Singh, O. Jangid, P. Llinas, and B. Breul, "Bituminous geomembrane: Successful alternative of distressed concrete canal lining built over expansive clays," in *Geosynthetics: Leading the Way to a Resilient Planet*, London, UK: CRC Press, 2023, pp. 1999–2006. https://doi.org/10.1201/9781003386889-268

[9] R. Kumar and S. Kumari, "Geotechnical properties of materials used in landfill clay liner: A critical review," *Sādhanā*, vol. 48, Art. no. 64, 2023. https://doi.org/10.1007/s12046-023-02124-0

[10] K. Ding and L. Gao, "Development in canal lining technology in China," *Irrigation and Drainage*, vol. 69, no. S2, pp. 36–40, 2020. https://doi.org/10.1002/ird.2438

[11] S. Barkhordari and S. M. H. Shahdany, "A systematic approach for estimating water losses in irrigation canals," *Water Science and Engineering*, vol. 15, no. 2, pp. 161–169, 2022. https://doi.org/10.1016/j.wse.2022.02.004

[12] H. Ahmed, M. Gaber, H. Mohamed, and W. El Sadek, "Quantifying seepage and evaporation loss reductions through canal lining: A field study from Nakada, Egypt," *Journal of Engineering Sciences*, vol. 53, no. 5, pp. 199–214, 2025. https://doi.org/10.21608/jesaun.2025.378449.1489

[13] A. Mohammadi, A. P. Rizi, and N. Abbasi, "Field measurement and analysis of water losses at the main and tertiary levels of irrigation canals: Varamin irrigation scheme, Iran," *Global Ecology and Conservation*, vol. 18, Art. no. e00646, 2019. https://doi.org/10.1016/j.gecco.2019.e00646

[14] W. Mao, Y. Zhu, S. Huang, X. Han, G. Sun, M. Ye, and J. Yang, "Assessment of spatial and temporal seepage losses in large canal systems under current and future water-saving conditions: A case study in the Hetao Irrigation District, China," *Agricultural Water Management*, vol. 291, Art. no. 108615, 2024. https://doi.org/10.1016/j.agwat.2023.108615

[15] G. Zakir-Hassan, M. A. Kahlown, J. F. Punthakey, G. Shabir, M. Aziz, M. Sultan, H. Ashraf, Q. U. A. Nawaz, and F. Majeed, "Evaluation of hydraulic efficiency of lined irrigation channels: A case study from Punjab, Pakistan," *Hydrology Research*, vol. 54, no. 4, pp. 523–546, 2023. https://doi.org/10.2166/NH.2023.105

[16] M. M. Ahmed, M. A. Yousif, and A. H. Tahe, "Fly ash-based geopolymerization for enhancing clayey soils in canal linings: An experimental and numerical analysis using SEEP/W," *Engineering, Technology & Applied Science Research*, vol. 16, no. 1, pp. 31145–31151, 2026. https://doi.org/10.48084/etasr.13480

[17] N. Yaseen, M. Irfan-ul-Hassan, A.-u.-R. Saeed, S. A. Rizwan, and M. Afzal, "Sustainable development and performance assessment of clay-based geopolymer bricks incorporating fly ash and sugarcane bagasse ash," *Journal of Materials in Civil Engineering*, vol. 34, no. 4, Art. no. 04022036, 2022. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004159

[18] S. R. Abdila *et al*., "Evaluation on the mechanical properties of ground granulated blast slag (GGBS) and fly ash stabilized soil via geopolymer process," *Materials*, vol. 14, no. 11, Art. no. 2833, 2021. https://doi.org/10.3390/ma14112833

[19] H. Castillo, H. Collado, T. Droguett, M. Vesely, P. Garrido, and S. Palma, "State of the art of geopolymers: A review," *e-Polymers*, vol. 22, no. 1, pp. 108–124, 2022. https://doi.org/10.1515/epoly-2022-0015

[20] A. M. Mustafa Al Bakri, H. Kamarudin, M. Bnhussain, I. K. Nizar, and W. I. W. Mastura, "Mechanism and chemical reaction of fly ash geopolymer cement—A review," *Journal of Asian Scientific Research*, vol. 1, no. 5, pp. 247–253, 2011.

[21] B. Shinde, A. Sangale, M. Pranita, J. Sanagle, and C. Roham, “Utilization of waste materials for soil stabilization: A comprehensive review,” *Progress in Engineering Science*, vol. 1, no. 2–3, Art. no. 100009, 2024. https://doi.org/10.1016/j.pes.2024.100009

[22] M. E. Harr, *Groundwater and Seepage*. Mineola, NY, USA: Dover Publications, 1991.