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SEEPAGE-INDUCED FAILURE AND DOWNSTREAM IMPACT ASSESSMENT OF GORONYO DAM, NIGERIA

Mukhtar Ibrahim Adamu[1], Gambo Haruna Yunusa[1*]

[1]*Department of Civil Engineering, Bayero University Kano: PMB 3011, Kano, Nigeria*
**ghyunusa.civ@buk.edu.ng*

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Abstract: *Seepage and slope instability are major causes of embankment dam failure, often leading to loss of life, property damage, and socio-economic disruption. The Goronyo Dam, commissioned in 1984 on River Rima in Sokoto State, Nigeria, has a storage capacity of 942 × 10^6 m^3 and serves over 80,000 ha of irrigated land. However, persistent water loss has raised concerns about seepage-induced deterioration and structural safety. This study investigated seepage behaviour, identified possible failure mechanisms, and assessed potential downstream impacts. Soil samples from failed and unfailed embankment sections were tested for particle size distribution, Atterberg limits, compaction, permeability, and shear strength. Results show predominantly fine-grained soils classified as low- to medium-plasticity clay (CL). The average liquid limit, plastic limit, and plasticity index were 31.8%, 19.5%, and 12.3%, respectively. Failed sections exhibited higher optimum moisture content (22.81%) and lower maximum dry density (1.67 Mg/m^3) compared to unfailed sections (17.05% and 1.73 Mg/m^3). Permeability values were 8.42 × 10^{-6} m/s and 5.30 × 10^{-6} m/s, respectively. Shear strength parameters indicated cohesion of 24.73 kPa and friction angle of 28° for failed sections, and 18.97 kPa and 37° for unfailed sections. Seepage and slope stability analyses using GeoSlope, 2007 yielded seepage discharges between 2.87–3.29 m^3/day/km (failed) and 1.35–3.15 m^3/day/km (unfailed). Factors of safety for upstream slopes were 2.50 and 3.08, and for downstream slopes 1.97 and 2.39, respectively. A survey of 100 downstream households revealed significant socio-economic impacts, with 87% reporting high flood intensity, loss of livelihoods, reduced irrigation, and decline in fishing activities. Pearson correlation analysis ($r < 0.5$, $p < 0.01$) confirmed a significant relationship between dam failure and socio-economic variables. The study highlights seepage as a key factor in embankment performance and underscores the need for improved seepage control and monitoring to ensure long-term dam safety.*

Key words: Seepage analysis; Embankment dam; Slope stability; Earthfill dam failure; Goronyo Dam

1 Introduction

Dams are critical hydraulic structures constructed across rivers or streams to obstruct, divert, or regulate water flow, thereby creating reservoirs for irrigation, water supply, flood control, hydropower generation, and socio-economic development (Wang et al., 2021, Pessoa et al., 2025). Earthfill embankment dams remain prevalent worldwide due to their adaptability to foundation variability and the widespread availability of construction materials (Temtime et al., 2023). However, seepage—the movement of water through the body and foundation of a dam—continues to be a critical concern in the safety and performance of earthfill dams. Uncontrolled seepage can increase pore water pressures, erode internal soil structure, and significantly contribute to embankment instability or failure (Al-Janabi et al., 2025).

The safety of an embankment dam is closely linked to subsurface hydrogeological conditions and material properties. Variations in soil permeability, stratification, and geological formations near the foundation and dam core influence seepage distribution and affect the development of the phreatic surface (Zheng et al., 2024). Thus, the performance and safety of a dam reservoir are governed not only by its geometric and structural design but also by the hydrogeological characteristics of the foundation and embankment materials. Seepage losses through the dam body and foundation depends largely on soil permeability, stratification, presence of fissures, and geological formations underlying the reservoir (Fell et al., 2005). Highly permeable or soluble formations, such as limestone, are particularly susceptible to excessive seepage due to cavity formation, making them unfavorable for dam foundations.

Seepage through embankment dams is a fundamental concern in geotechnical engineering because it directly influences slope stability, piping potential, and overall structural safety. Water flow may occur through the dam body, beneath the foundation, or along preferential seepage paths, leading to increased pore water pressures and reduction in effective stress within the soil mass (USACE, 2004).

The phreatic surface plays a crucial role in the stability of earthfill dams. If the phreatic line intersects or approaches the downstream slope, the soil may experience softening, sloughing, or internal erosion due to high exit gradients, potentially resulting in piping failure (Talukdar and Dey, 2019). To mitigate these risks, drainage measures such as horizontal drainage blankets and filters are commonly incorporated to control seepage (Narita, 2000).

Recent studies have demonstrated that integrating geotechnical investigations with advanced numerical modeling provides improved understanding of seepage paths and exit gradients, which are critical indicators of potential piping and slope instability.

Statistics indicate that seepage-related mechanisms account for approximately 25% of embankment dam failures worldwide (Kumar & Sharma, 2013). This highlights the need for detailed seepage assessment and continuous monitoring, especially for aging dams in developing countries.

Several studies have investigated seepage behaviour and slope stability of embankment dams using laboratory testing and numerical modelling techniques. However, most previous studies focused primarily on hydraulic performance or structural stability independently, with limited integration of downstream socio-economic consequences, particularly for aging embankment dams in Nigeria and Sub-Saharan Africa. Furthermore, limited published studies exist on the seepage performance and internal erosion risk of Goronyo Dam despite persistent reports of excessive water loss and embankment distress. The Dam was commissioned in 1984 across River Rima in Sokoto State, Nigeria. Therefore, this study integrates geotechnical characterization, numerical seepage-stability modelling, and socio-economic impact assessment to provide a comprehensive evaluation of seepage-induced risks associated with Goronyo Dam.

2 Material and Methods

The material and methods used in this research are explained herein.

2.1 Dam Characteristics

The Goronyo Dam is a homogeneous earthfill embankment structure located on the Rima River in Sokoto State, Nigeria. The Dam is located at 13°27'11"N, 5°40'35"E and 13°45'30"N, 5°67'63"E about 25 km East of Goronyo town and 90 km away from Sokoto city. It has a maximum height of approximately 21 m, a crest width of 8.5 m, and a total embankment length of about 12.5 km, consisting of a 7.1 km main embankment and a 5.4 km saddle embankment. The dam incorporates an ogee spillway fitted with radial gates for flood regulation, while seepage is monitored through a system of toe drains and piezometers. The embankment is designed with an upstream slope of 1V:3.5H and a downstream slope of 1V:2H. However, publicly accessible sources do not provide detailed information regarding the internal drainage and filter zoning of the embankment.

Goronyo dam is a multi-purpose storage dam designed to store nine hundred and forty-two million cubic meters (942 x 10^6 m^3) of water for irrigation and development of downstream areas from Goronyo to Argungu, covering an area of over seventeen thousand hectares (17,000 ha). The dam was also designed to control flood and to provide an annual regulated flow of four hundred and twenty-five million cubic meters (425 x 10^6 m^3) in order to double the rice cultivation in that area (i.e from forty thousand hectares (40,000 ha) to eighty thousand hectares (80,000 ha)). It also supplies over eighty thousand million cubic meters (80 x 10^6 m^3) of water annually to Sokoto, Argungu and Birnin-Kebbi water supply schemes (Sokoto Rima River Basin Development Authority, 2010).

2.2 Sampling Location

The failed sections of the dam refer to portions of the embankment that have already experienced structural failure, as illustrated in Plate 1. Soil Samples 1, 3, and 5 were obtained from these failed sections. In contrast, the unfailed sections comprise portions of the dam that remain structurally stable and undamaged. Soil Samples 2, 4, and 6 were collected from these intact sections, as shown in Plate 1.

2.3 Materials

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The materials used in this study are the soil samples and the water used in preparing the soil samples for the laboratory testing. A total of six (6) disturbed soil samples were collected at 1.5 m depth. Three (3) samples were collected from the failed sections and another three (3) samples from the unfailed sections of the embankment as shown in Table 1.

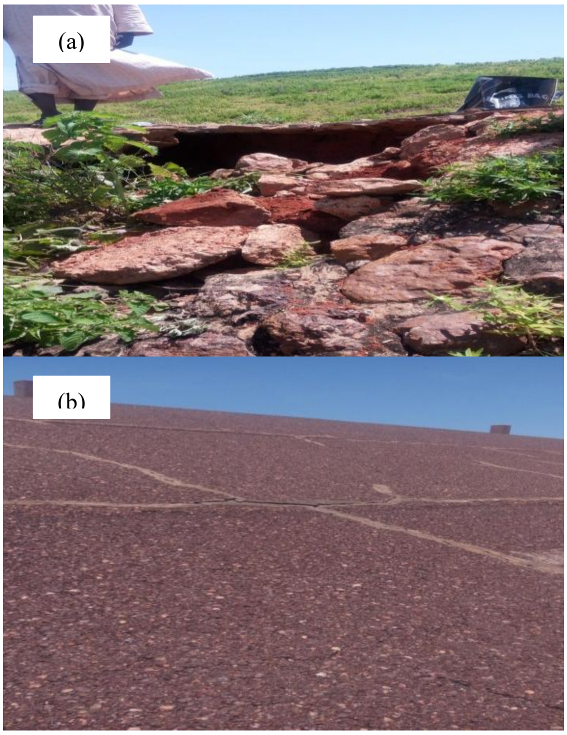

Plate 1: *(a) Failed section at the downstream toe (b) Unfailed section at the upstream of the dam.*

Table 1: *Sampling point locations*

Sample	Location	Latitude	Longitude
1	Failed	13°31'44"N	5°53'02"E
3	Failed	13°30'45"N	5°53'03"E
5	Failed	13°30'17"N	5°52'58"E
2	Unfailed	13°30'54"N	5°53'01"E
4	Unfailed	13°30'56"N	5°52'53"E
6	Unfailed	13°31'58"N	5°53'00"E

The collected soil samples were transported to Civil Engineering Department laboratory, Bayero University, Kano and tested for sieve analysis, Atterberg limits, compaction, permeability and direct shear in accordance with the standard procedure outlined in BS1377(1990).

2.4 Methods

The sieve analysis and the Atterberg limits are the soil index properties. The Atterberg limits was conducted using Casagrande apparatus. Both tests were conducted in accordance with BS 1377(1990).

The moisture-density relationship was determined through compaction test conducted in accordance with BS 1377 (1990). BSL compactive effort, which is easily achieved in the field (Etim, et al. 2017) was employed and it involved the use of a 2.5 kg rammer falling from a height of 300 mm onto a prepared soil samples (in three layers) in a 1000 cm^3 British Standard mould, each receiving twenty-seven (27) blows.

The permeability tests were carried out to determine the coefficient of permeability (k) of the embankment soil. A cylindrical core cutters were driven into the soil, the filled core cutters were dug out and wrapped. The samples were saturated and tested through falling head test in accordance with BS1377 (1990).

The shear strength tests were carried out using shear box machine and were used to evaluate the strength properties of soil. In the shear box machine; one portion of soil is made to slide along another by the action of a steadily increasing horizontal shearing force, where a constant load is applied normal to the plane of relative movement. These conditions are achieved by placing the soil in a rigid metal box (60 mm × 60 mm) in plan, consisting of two halves. During the shearing process, the relative displacement of the two portions of the specimen and the applied shearing force are both measured and a load - displacement curves were drawn. The tests were carried out in accordance with BS1377(1990).

The seepage and slope stability analyses were carried out using SEEP/W and SLOPE/W, respectively (GeoSlope International Ltd., 2007).

The embankment slope was evaluated for predicting the seepage flow i.e. to establish the condition of porewater pressure in the embankment using SEEP/W (GeoSlope International Ltd., 2007). The porewater pressure generated from the SEEP/W were exported to SLOPE/W for the slope stability analysis. When developing the numerical model using SEEP/W, the geometry of the dam (Figure 1) was used, and the materials properties obtained from the laboratory tests of the embankment soil samples (shear strength parameters and coefficient of permeability values) serves as key in parameters. The boundary conditions were assigned, and then the finite mesh was reviewed and fine-tuned to give a best model of the embankment slope.

The finite element mesh of the idealized Goronyo dam model consist of quadrilateral elements (i.e. 1 m × 1 m) in order to reduce the total number of nodes and invariably the time required to solve each simulation. In general, the finite elements mesh of the idealized slope model consists a structured quadrilateral mesh with approximately 5,000 nodes and 4,800 quadrilateral elements. A constant total head boundary equal to the reservoir head was assigned at the upstream side of the reservoir face, a seepage face (atmospheric or constant head) was assigned in the downstream slope. Moreover, No-flow Boundary ($q = 0$) was assigned at the bottom formation.

3 Results and Discussion

3.1 Laboratory Test Results of the Soil Samples

The results obtained from the laboratory tests conducted on the soil samples from the failed and unfailed sections of the Goronyo dam are presented in this section. The particle size distribution curves of the soil samples from the failed and unfailed sections are presented in Figure 2 and the summary of the properties of these soil samples are shown in Table 2. The particle size distribution results presented in Figure 2 indicate that the embankment materials are predominantly fine-grained soils, with fines content ranging from approximately 32 to 69%. Failed sections exhibit an average fines content of 52.92%, while unfailed sections show a comparable value of 53.61%. This similarity suggests that grain size distribution alone is not the primary cause of failure. However, the relatively high fines content implies reduced permeability and may increase susceptibility to internal erosion (piping) under seepage gradients.

As shown in Table 2, the failed sections exhibit low plasticity index with PI values ranging between 4 to 9%. This low plasticity value is an indication of poor cohesion retention under seepage and higher susceptibility to erosion and cracking (Fell et al., 2005). The unfailed sections exhibit wider variability, with some higher PI values up to 31%. The soil sample are classified mainly as CL (low plasticity clay) and ML (low plasticity silt).

The compaction results show that the OMC of the soils ranges between 10.96 to 24.96%, while the MDD ranges between 1.51 to 1.89 Mg/m³.

Although these values fall within typical ranges for fine-grained soils, variability between samples suggests inconsistent field compaction practices. The failed sections exhibit slightly lower average dry densities which indicate higher void ratios, promoting seepage flow and internal erosion (Fell et al., 2005).

The coefficient of permeability (k) of the soil ranges from 3.55×10^{-6} m/s to 8.70×10^{-6} m/s. These values are consistent with fine-grained soils and are generally acceptable for homogeneous earth dams.

The failed sections show higher average permeability (8.42×10^{-6} m/s) compared to unfailed sections (5.30×10^{-6} m/s). This difference, although moderate, becomes critical under hydraulic gradients, and it may increase seepage velocity and may enhance the likelihood of piping and internal erosion (Xu & Zhang, 2013).

The obtained shear strength parameters are also consistent with values reported in previous studies on earthfill dam materials. For example, compacted lateritic and silty clay embankment soils have been reported to possess cohesion values ranging from 10 to 40 kPa and friction angles between 25° and 40°, depending on density and moisture conditions (Soroush and Shorrieh, 2019). Similarly, the measured friction angles compare favorably with the ranges recommended by the USACE (2003) and Duncan et al., 2014) for well-compacted embankment soils. Therefore, the observed failure cannot be attributed solely to insufficient shear strength parameters, as the measured values are comparable to those reported for stable embankments. Consequently, both the failed and unfailed sections satisfy commonly accepted design criteria for embankment materials, indicating that inadequate shear strength is unlikely to be the primary cause of the observed slope failures. Instead, the failures are more likely associated with other contributing factors such as seepage-induced pore water pressure, localized saturation, inadequate drainage, or construction-related heterogeneities (El-Molla & Kilit, 2026; Liu et al., 2017).

3.2 Seepage Behaviour and Hydraulic Response

The seepage analysis carried out on Goronyo dam reveals critical insights into the embankment performance.

3.2.1 Seepage Quantities

The computed seepage discharges obtained through seepage analysis using SEEP/W (GeoSlope, 2007) is presented in Figure 3.

From this Figure, the estimated seepage discharges ranges from 2.87–3.29 m³/day/km for failed sections and 1.35–3.15 m³/day/km for unfailed sections. The summary of the seepages discharges for the failed and unfailed sections was presented in Table 3. These values were significantly lower than the observed field seepage (73.04 m³/day/km). Thus, a noticeable discrepancy was observed between the seepage quantities predicted by the numerical model and those measured in the field. Such differences are common in embankment dam studies because numerical seepage models are developed under idealized assumptions, including homogeneous material properties, continuous soil layers, and steady-state hydraulic conditions. In contrast, actual field conditions are often heterogeneous and influenced by several physical and environmental factors that are difficult to incorporate fully into numerical simulations. These findings are in agreement with that of Jia et al. (2022) and Tan, et al. (2017). Moreover, numerical modelling

results are approximation results rather than exact predictions.
The excessive seepage suggests the development of internal erosion (piping), progressive enlargement of flow channels and loss of fines through seepage flow (Figure 4). Therefore, seepage is identified as the dominant failure mechanism (Al-Janabi et al., 2025; Foster, et al., 2000).

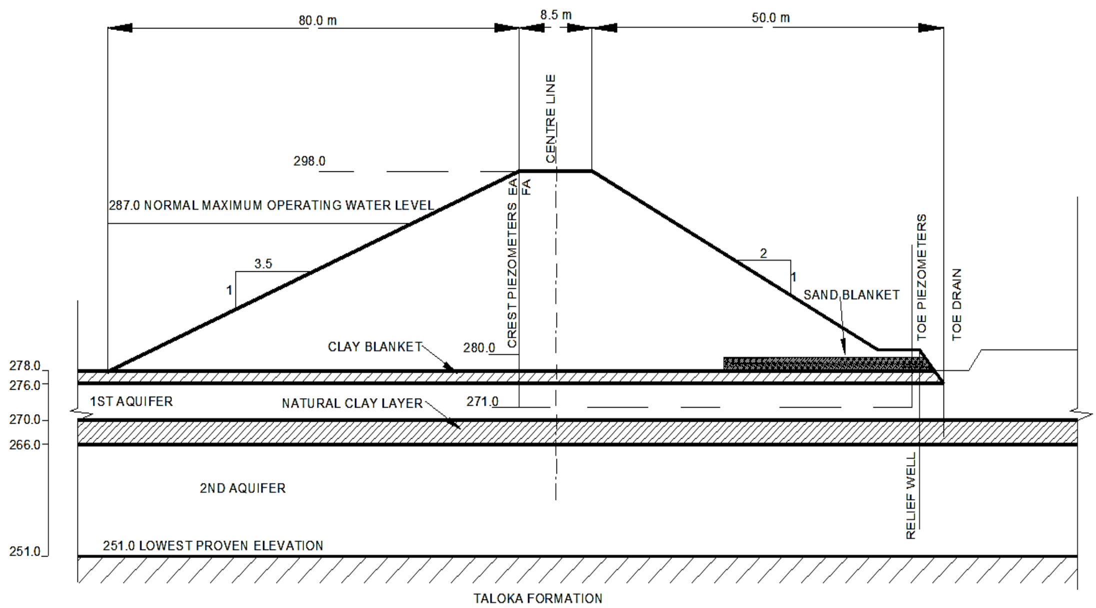

Figure 1: *Goronyo dam schematic cross section*

Table 2: *Summary of the laboratory test Results*

Property	Failed Sections				Unfailed sections			
	Sample 1	Sample 3	Sample 5	Average	Sample 2	Sample 4	Sample 6	Average
. Particle Size Distribution								
% Gravel	0	49	0	16	31	0	1	11
% Sand	37	18	37	31	42	31	33	36
% Fines	63	33	63	53	26	69	66	54
2. Atterberg limits								
Liquid limit (%)	34	28	24	29	48	33	24	35
Plastic limit(%)	28	19	20	22	17	16	17	17
Plasticity Index	6	9	4	7	31	17	7	18
Classification								
USCS	ML	CL	CL		CL	CL	CL	
4. Compaction test								
OMC (%)	24.96	18.65	24.83	22.81	22.5	10.96	17.69	17.05
MDD (Mg/m^3)	1.69	1.51	1.8	1.67	1.58	1.89	1.71	1.73
5.Permeability								
k (m/sec) x 10^{-6}	8.7	8.24	8.32	8.42	4.8	3.55	7.54	5.3
6.Shear strength								
Unit weight(kN/m^3)	16.53	17.44	18.72	17.56	18.17	18.36	15.76	17.43
Cohesion, c (kPa)	35.3	9.7	29.2	24.73	37.2	4.2	15.5	18.97

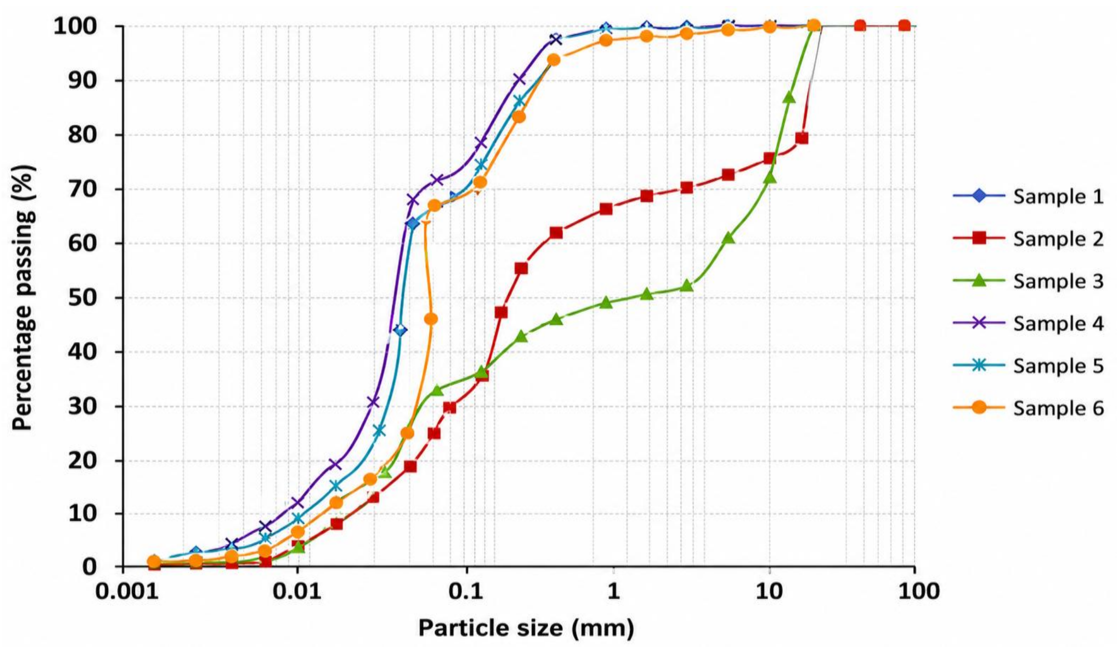

Figure 2: *Particle size distribution curves of the soil (samples 1, 3 & 5 – failed section, while 2, 4 & 6 – unfailed section)*

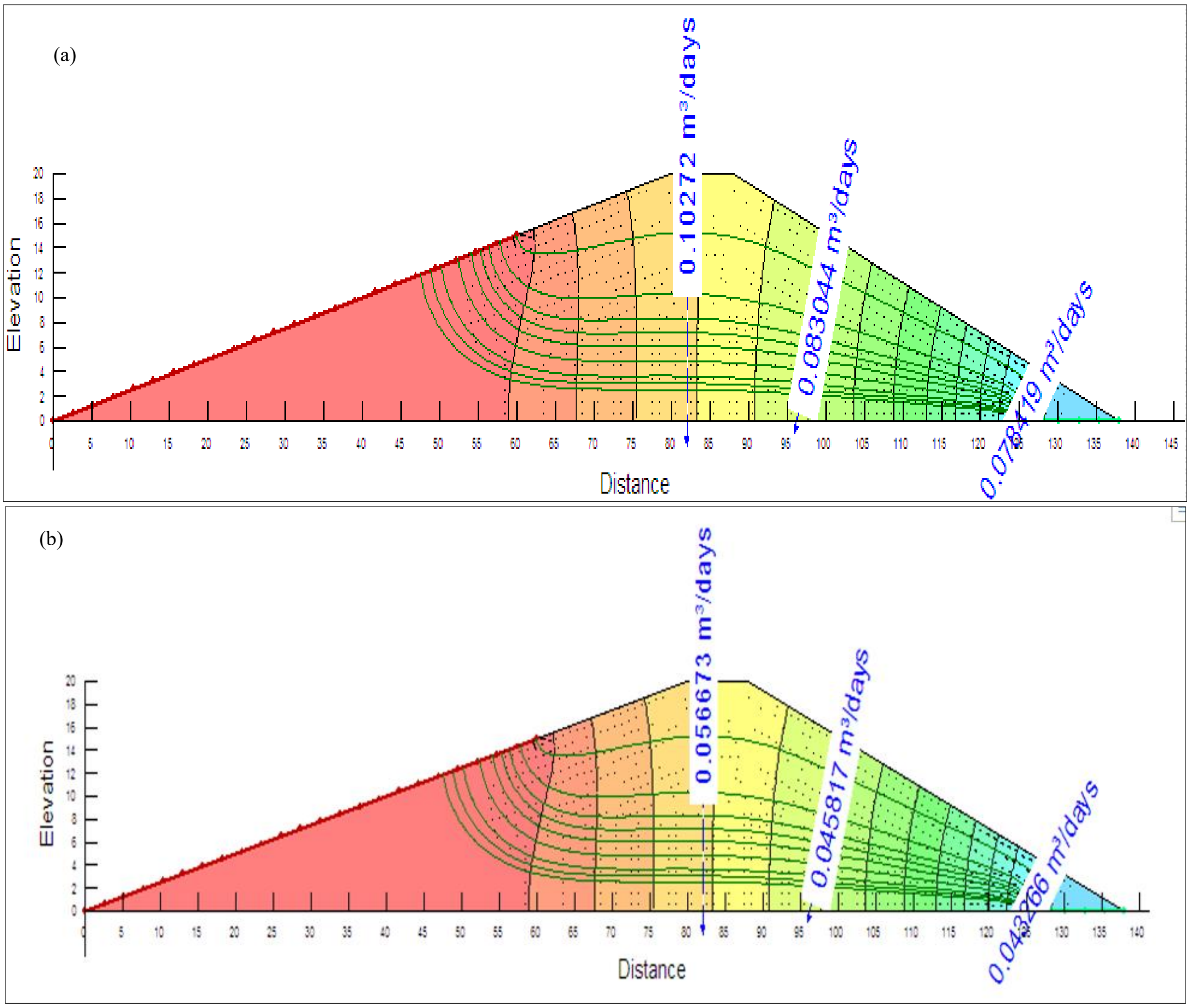

Figure 3: *Seepage model and quantities (a) Failed section (b) Unfailed section*

Table 3: Summary of the seepages discharges from SEEP/W

Sample	Flux 1 (m^3/day/km)	Flux 2 (m^3/day/km)	Flux 3 (m^3/day/km)	Total flux (m^3/day/km)
		Failed Sections		
1	0.103	0.083	0.078	0.264
3	0.097	0.079	0.074	0.250
5	0.089	0.072	0.068	0.230
Average	0.096	0.078	0.074	0.248
		Unfailed Sections		
2	0.567	0.046	0.043	0.146
4	0.042	0.034	0.032	0.108
6	0.098	0.079	0.075	0.253
Average	0.236	0.053	0.050	0.169

Figure 4: *Seepage flow containing eroded material from the dam*

3.3 Slope Stability Assessment

The slope stability analysis was performed using SLOPE/W (Geoslope, 2007) based on the porewater pressure generated from SEEP/W and the results are presented in Figure 5. The summary of the factor of safety (FoS) for the downstream and upstream slopes are presented in Tables 5 and 6, respectively.

Table 4: *Summary of the Factors of Safety of the downstream slope*

Failed Sections		Unfailed Sections	
Sample	FoS	Sample	FoS
1	2.16	2	2.46
3	1.90	4	1.79
5	1.86	6	2.93
Average	1.97		2.39

From Table 4, the FoS ranges between 1.86 – 2.16 for the failed sections and 1.79 - 2.93 for the unfailed sections of the downstream slope. The average FoS of the downstream slope are 1.97 and 2.39 for the failed and unfailed sections, respectively.
For the upstream slope, the FoS varies between 2.25 – 2.79 for the failed sections and 2.28 - 3.78 for the unfailed sections of the upstream slope of the dam.

The average FoS for the failed and unfailed sections of the upstream slope are 2.50 and 3.08, respectively. The computed factors of safety (FOS) for the investigated sections were all greater than 1.5. According to USACE EM 1110-2-1902, a minimum FOS of 1.5 is recommended for the long-term stability of the downstream slope of earth and rock-fill dams under steady-seepage conditions.

Table 5: *Summary of the Factors of Safety of the upstream slope*

Failed Sections		Unfailed Sections	
Sample	FoS	Sample	FoS
1	2.79	2	3.19
3	2.45	4	2.28
5	2.25	6	3.78
Average	2.50		3.08

The computed values therefore indicate satisfactory global slope stability for the analysed conditions (USACE, 2003). Consequently, conventional global rotational slope instability is unlikely to have been the primary mechanism responsible for the observed failure. However, an acceptable global FOS does not preclude localized failure mechanisms. The observed distress may instead be associated with localized seepage, elevated pore-water pressures, inadequate drainage, preferential seepage paths, internal erosion, or spatial variability in embankment materials. These finding are in agreement with that of Duncan et al., (2014).

3.4 Socio-Economic Impact of Dam Failure

The analysis of the socio-economic consequences of the Goronyo dam failure was performed through questionnaires. About 100 questionnaires were distributed to the downstream community. The findings demonstrate that the environmental impacts associated with flooding and changing reservoir conditions extend beyond direct physical effects to affect the livelihoods and economic activities of

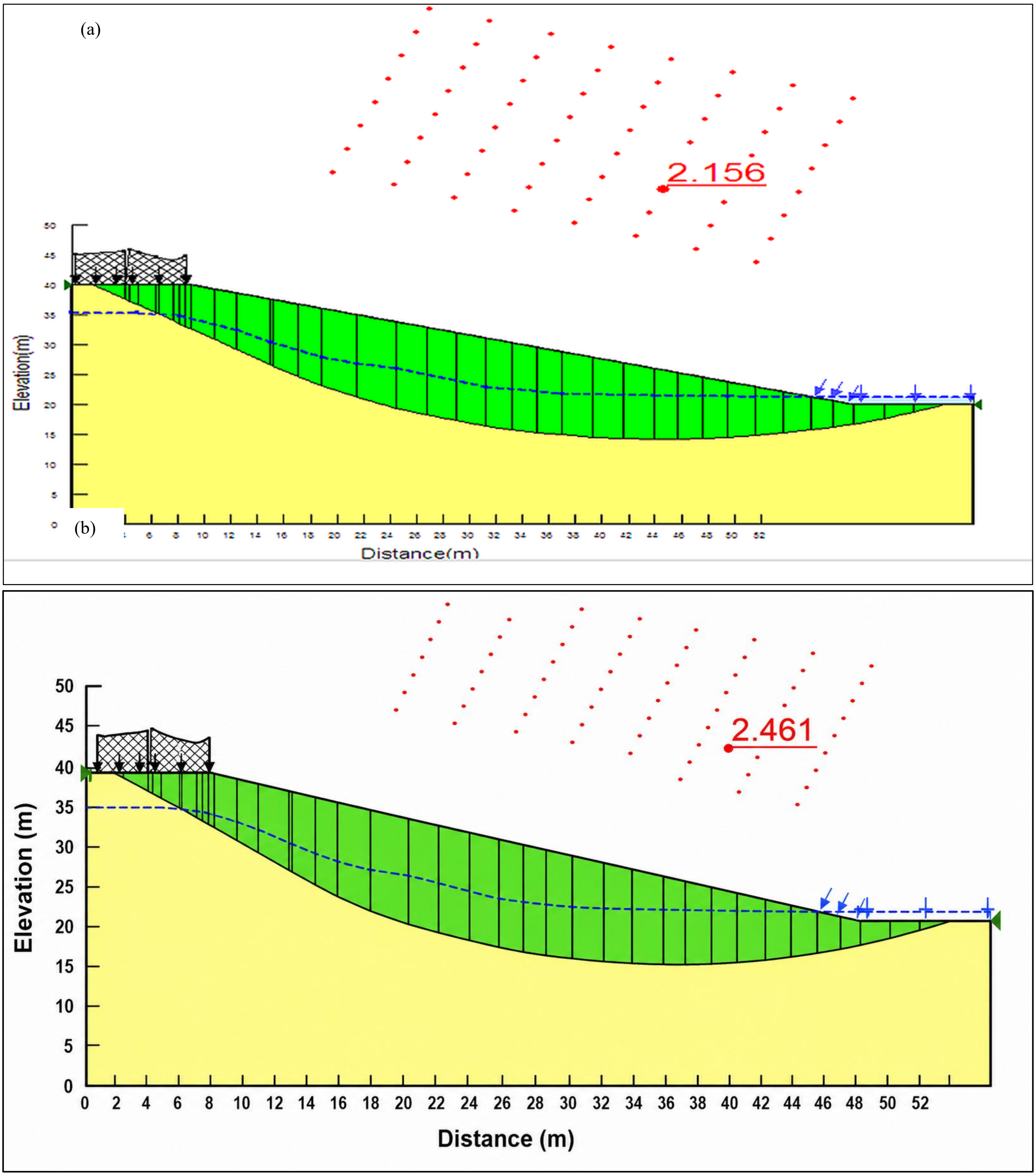

Figure 5: *Sample of FoS for the upstream slope (a) the failed section, (b) the unfailed section*

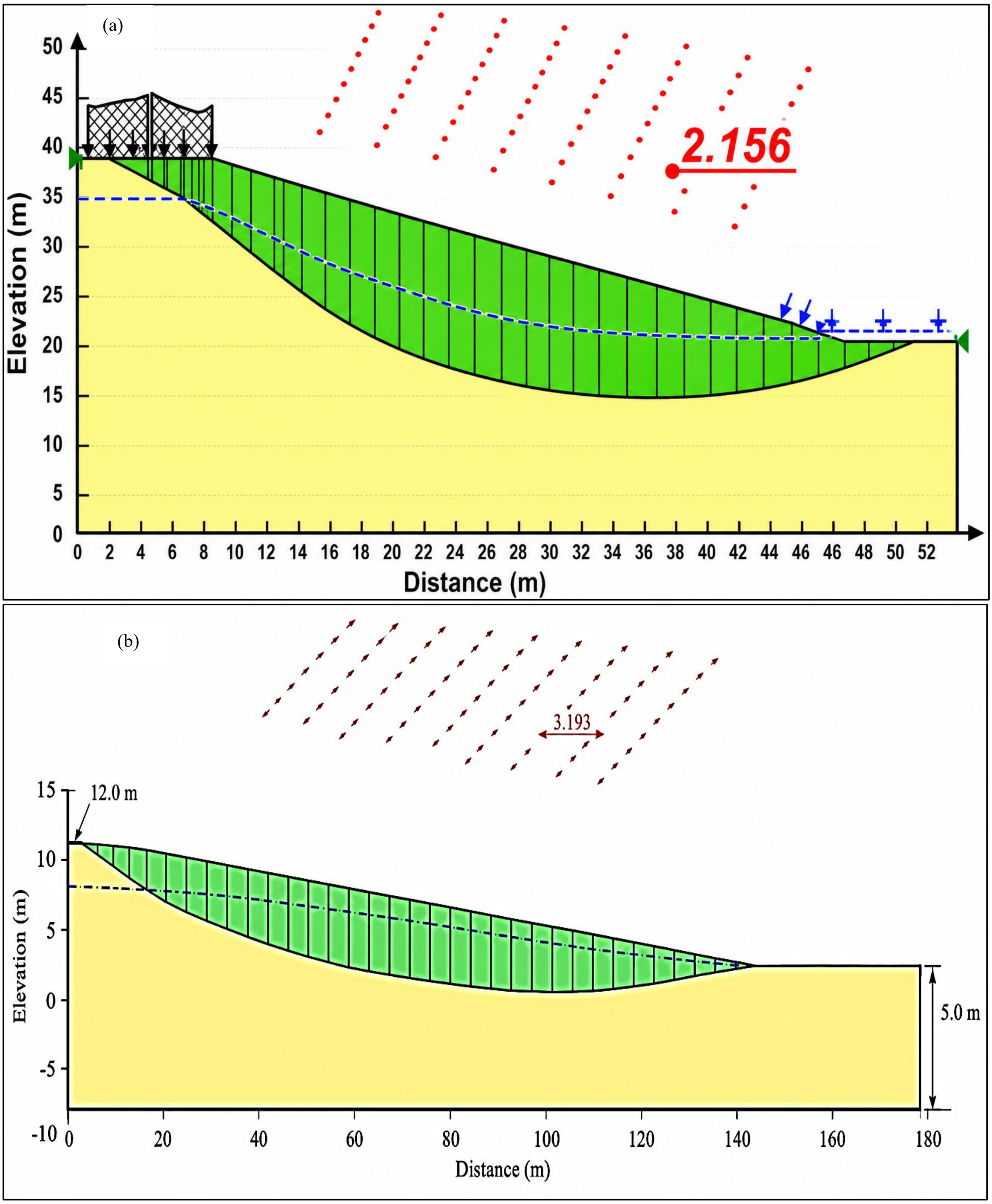

Figure 6: *Sample of FoS for the downstream slope (a) the failed section, (b) the unfailed section*

communities in the study area. Flooding was widely experienced by respondents, with 95% reporting recent flood experience, while 77% indicated that people had been displaced or relocated. With respect to livelihoods, 77% of respondents perceived a reduction in irrigation-water supply from the dam, while 68% reported a decline in their present income compared with previous years. Similarly, 77% perceived a reduction in fish abundance and 70% reported reduced fishing activities. These changes were accompanied by perceived reductions in fishermen's income and market supply of agricultural and fish products. Overall, the results suggest that changes in flooding conditions, water availability, agricultural production and fisheries may have broader implications for household livelihoods and local economic activity in Goronyo and surrounding communities.

A Pearson correlation analysis shows statistically significant relationships between dam failure and socio-economic variables as presented in Table 6.

Table 6: *Pearson correlation analysis result*

Indices	r – value	p-value
Flood casualty	0.322	<0.01
Irrigation	0.34	<0.01
Fishing	0.325	<0.01
Trading	0.399	<0.01

Table 6 presents the Pearson correlation coefficients (*r*) between dam failure impacts and selected socio-economic variables, including flood casualty, irrigation, fishing, and trading. All variables show positive correlation coefficients ranging from 0.322 to 0.399, with p-values < 0.01, indicating that the relationships are statistically significant at the 1% level of significant (Cleophas & Zwinderman, 2018). The results suggest a moderate positive relationship between dam failure events and adverse socio-economic outcomes. Trading exhibits the highest correlation (r = 0.399), implying that commercial activities are the most affected, this could be due to market disruptions, infrastructure damage, and reduced accessibility during flooding. Irrigation (r = 0.340) and fishing (r = 0.325) also show notable positive correlations, reflecting the dependence of local livelihoods on water resources, which are negatively impacted by uncontrolled seepage and flooding. Flood casualty shows the lowest correlation (r = 0.322), though still significant, indicating that while loss of life and injury occur, the socio-economic disruptions are more strongly expressed through livelihood impacts.

Overall, the statistically significant correlations confirm that dam failure has measurable and meaningful impacts on downstream socio-economic conditions**.** The moderate strength nature of the relationships suggests that, although dam failure is a key contributing factor, other environmental and socio-economic variables may also influence these outcomes. These findings reinforce the need for effective dam monitoring, seepage control, and risk mitigation strategies to reduce both human and economic vulnerabilities.

4. Conclusions

This study evaluated the causes and impacts of embankment failure through geotechnical testing, seepage and stability analyses, and socio-economic assessment. Based on the results obtained it can be concluded that:

i. The embankment soils are predominantly fine-grained and meets standard requirements.

ii. Shear strength and slope stability conditions are adequate.

iii. Seepage behaviour is excessive and uncontrolled and attributed primarily to internal erosion (piping), defective construction practices and inadequate seepage control measures.

iv. The study further establishes that dam failure has significant adverse effects on flood occurrence, agricultural productivity, fishing activities and local economic conditions.

v. Seepage monitoring instrumentation, filter/drain rehabilitation, periodic geotechnical inspection, grouting/remediation measures should be put in place to improve the dam’s stability.

References

Al-Janabi, A. M. S., Dibs, H., Sammen, S. S., Yusuf, B., Ikram, R. M. A., Alzuhairy, S. H., & Kisi, O. (2025). Comparison analysis of seepage through homogenous embankment dams using physical, mathematical and numerical models. *Arabian Journal for Science and Engineering*, *50*(11), 8143-8152.

BS 1377 (1990). *Methods of test for soils for civil engineering purposes* – Parts 1-8. BSI London.

Cleophas, T. J., & Zwinderman, A. H. (2018). Bayesian Pearson correlation analysis.

In *Modern Bayesian statistics in clinical research* (pp. 111-118). Cham: Springer International Publishing.

Duncan, J. M., Wright, S. G., & Brandon, T. L. (2014). *Soil strength and slope stability*. John Wiley & Sons.

EL-Molla, D. A., & Kilit, M. (2026). Seepage control, detection, and treatment in embankment dams: a state-of-the-art review. *Arabian Journal for Science and Engineering*, *51*(4), 3823-3849.

Etim, R. K., Eberemu, A. O., & Osinubi, K. J. (2017). Stabilization of black cotton soil with lime and iron ore tailings admixture. *Transportation Geotechnics*, *10*, 85-95.

Fell, R., MacGregor, P., Stapledon, D. & Bell, G., Foster, M. (2005). Geotechnical engineering of dams. (2nd ed.), CRC Press/Balkema, EH Leiden, The Netherlands.

Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. *Canadian geotechnical journal*, *37*(5), 1000-1024.

GeoSlope International Ltd. (2007): *SLOPE/W User's Guide for Slope Stability Analysis*, GEOSLOPE International Ltd, Calgary, Alta.

GeoStudio International Ltd. (2007): *SEEP/W User's Guide for Finite Element Seepage Analysis*, GEOSLOPE International Ltd, Calgary, Alta.

Jia, Y., Ding, Y., Wang, X., Zhang, J., & Chen, X. (2022). A numerical analysis of the leakage characteristics of an embankment dam slope with internal erosion. *Frontiers in Earth Science, 10*, 866238.

Kumar, J., & Sharma, K. M. (2013). Government of India Geological Survey of India. *world*, *4*, 089.

Liu, K., Vardon, P. J., Hicks, M. A., & Arnold, P. (2017). Combined effect of hysteresis and heterogeneity on the stability of an embankment under transient seepage. *Engineering Geology*, *219*, 140-150.

Narita, K. (2000). Design and construction of embankment dams. *Dept. of Civil Eng., Aichi Institute of Technology*.

Pessoa, E. G., Feitosa, L. M., Pereira, A. G., & e Padua, V. P. (2025). Designing an earth dam. Region- Water Conservancy, 2025, Vol. 8, Issue 1.

Soroush, A., & Shourijeh, P. T. (2019). Measures to prevent internal erosion in embankment dams. In *Sustainable and Safe Dams Around the World/Un monde de barrages durables et sécuritaires* (pp. 854-867). CRC Press.

Tan, X., Wang, X., Khoshnevisan, S., Hou, X., & Zha, F. (2017). Seepage analysis of earth dams considering spatial variability of hydraulic parameters. *Engineering Geology*, *228*, 260-269.

Talukdar, P., & Dey, A. (2019). Hydraulic failures of earthen dams and embankments. *Innovative Infrastructure Solutions*, *4*(1), 42.

Temtime, G. S., Eshete, A. S., & Abera, F. F. (2023). Seepage analysis in embankment dam under static condition using numerical model (case study: Legemera Earthen dam). *Abyssinia Journal of Engineering and Computing*, *3*(2), 1-13.

U.S. Army Corps of Engineers (2003). Engineering Manual. Engineering and Design-Slope stability. *US Army corps of engineering*.

U.S. Army Corps of Engineers (2004). General design and construction considerations for earth and Rock-fill Dams. *Engineer Manual*, *130*.

Wang, Y., Tian, Y., & Cao, Y. (2021). Dam siting: a review. *Water*, *13*(15), 2080.

Xu, T., & Zhang, L. (2013). Simulation of piping in earth dams due to concentrated leak erosion. In *Geo-Congress 2013: Stability and Performance of Slopes and Embankments III* (pp. 1091-1099).

Zheng, X., Yan, B., Wang, W., Du, K., & Fang, Y. (2024). Seepage–Deformation Coupling Analysis of a Core Wall Rockfill Dam Subject to Rapid Fluctuations in the Reservoir Water Level. *Water*, *16*(11), 1621.