



Article info

Type of article:

Original research paper

DOI:

<https://doi.org/10.58845/jstt.utt.2026.en.6.2.297-314>

***Corresponding author:**

Email address:

tamhs.cttl@tlu.edu.vn

Received: 18/12/2025

Received in Revised Form:

29/03/2026

Accepted: 14/04/2026

Degradation mechanism in dispersive-soil earthen dams under climatic conditions: A case study from Song Sat reservoir, Khanh Hoa, Vietnam

Vung Van Tran¹, Quan Duy Tran², Viet Trung Nguyen³, Phien Vu Dinh⁴
Tam Sy Ho^{5*}

¹Institute of Education and Applied Sciences, Central Vietnam (IEAS), Thuyloi University, Hanoi, Vietnam

²Faculty of Chemistry and Environment, Thuyloi University, Hanoi, Vietnam.

³Thuyloi University, Hanoi, Vietnam

⁴Advanced Materials and Intelligent Systems for Infrastructure and High-Speed Rail (AMIS-HSR) research group, University of Transport Technology, Hanoi, Vietnam

⁵Faculty of Civil Engineering, Thuyloi University, Hanoi, Vietnam

Abstract: The safety of earthen dams remains a critical global concern, particularly in the context of climate change and the increasing frequency of extreme weather events. Highly dispersive soils and climate stress in South Central Vietnam are causing dam degradation and downstream slope failure. The combined approach, which involves both field observations and laboratory experiments, is employed to provide a comprehensive understanding of the underlying mechanism. The statistical results elucidate the annual progression in the number and size of sinkholes, thereby revealing patterns of erosion development over time and in relation to climatic conditions. In which the number of sinkholes on the downstream slope increased from 20 in 2014 to 626 in 2023, a rise of more than 30-fold, including a sharp seasonal escalation of over 70% during the 2020–2023 rainy periods alone. In parallel, laboratory tests-including Pinhole, Crumb, and Exchangeable Sodium Percentage (ESP) tests-were conducted to confirm the strong dispersivity of the dam fill soil, with ESP values ranging from 16% to 31%, and Pinhole and Crumb tests consistently classifying the soil as dispersive. The results show that the soil in this region has a high and is highly prone to structural breakdown upon contact with water. This research provides both scientific and practical foundations for proposing appropriate engineering solutions, and application of automated monitoring technologies, thereby contributing to improved dam-safety management under increasingly extreme climatic conditions.

Keywords: Earthen dam erosion; Song Sat Reservoir; Dispersive soil; Internal erosion; Climate change.

1. Introduction

Soil erosion and dispersion in earthen dams

have long been recognized as major threats to dam safety, and these risks are becoming increasingly

severe under more frequent and intense climate-driven hydrological extremes [1], [2]. Prolonged drought followed by short-duration, high-intensity rainfall accelerates cracking, rapid wetting, internal erosion, and structural degradation in compacted soils are conditions that have contributed to numerous dam incidents worldwide. Foundational studies have established the vulnerability of dispersive soils to hydraulic and climatic disturbances. Sherard et al. [3] demonstrated that dispersive clays are highly susceptible to internal erosion; Blight [4] showed that desiccation cracking during drought predisposes slopes to rapid failure upon sudden wetting; A study in 1999 [5] highlighted instability in embankments subjected to abrupt moisture fluctuations; and Weng et al [6] documented sinkhole formation in Chinese dams after intense rainfall following dry periods. Collectively, these studies emphasize that dispersive soils, especially in fine-grained embankments, are prone to structural breakdown under variable moisture conditions. Recent research has revisited dam-safety challenges in the context of climate change, with the finding of more extreme rainfall and infiltration patterns significantly increase failure probability in soil slopes and earthfill dams [7], [8]. Parallel advances in reliability-based analysis and seepage modelling [9] have improved prediction of internal erosion and piping hazards. Meanwhile, new frameworks for identifying and stabilizing dispersive soils, ranging from geochemical–hydraulic indices to material improvement techniques, have been proposed [10]. Despite these advances, most recent studies remain laboratory- or model-focused and lack integration with long-term field observations.

In Vietnam, several research on embankment erosion have been conducted [11], [12], [13], [14], but they largely focused on surface erosion and slope instability under heavy rainfall [15], [16], while the influence of dispersive or slaking soils has received limited attention. Existing studies on soil improvement using lime, gypsum, or

polymers remain small-scale and have not been tested under rainfall simulation or dry-wet cycles typical of the South-Central region. This area witnesses prolonged dry seasons, causing severe surface cracking and structural degradation of soils, followed by short-duration but high-intensity rainfalls that lead to rapid infiltration, increased pore water pressure, internal erosion, soil dispersion, and ground subsidence. Current assessments are mostly descriptive and lack quantitative evaluation linking soil disintegration characteristics to the observed erosion processes, and little research has been devoted to clarifying the mechanism of soil dispersion under the effect of “drought followed by sudden heavy rainfall.”

This study addresses those gaps by adopting a dual-approach framework in which laboratory experimental results are systematically cross-validated with long-term field monitoring data to clarify the relationship between climatic extremes and the physico-chemical behavior of embankment soils, in the case study of the Song Sat Reservoir in Khanh Hoa Province (Fig. 1). The Song Sat Reservoir is an earth-fill dam with a maximum height of 34 m, located in a transitional semi-mountainous area of Khanh Hoa Province. The embankment materials are mainly derived from weathered acidic rocks, rich in clay minerals and highly sensitive to moisture and seepage conditions. Combined with prolonged dry seasons and intense rainfall events, these conditions increase the susceptibility to soil dispersibility, erosion, and downstream slope instability. The reservoir serves irrigation, water supply, and flood control purposes, providing irrigation for approximately 3,800 ha of agricultural land, with a total storage capacity of $69.33 \times 10^6 \text{ m}^3$. The downstream earthen dam slope of the reservoir, where hundreds of sinkholes and erosion gullies have been recorded since 2014, reflects a significant and progressive loss of slope stability.

The approach aims to achieve three main objectives: (i) To evaluate the dispersibility and

erosion resistance of the embankment soil at Song Sat Reservoir; (ii) To analyze the erosion mechanisms through Pinhole, Crumb, and

Chemical Tests; (iii) To propose appropriate technical measures to enhance downstream slope stability under extreme climatic conditions.

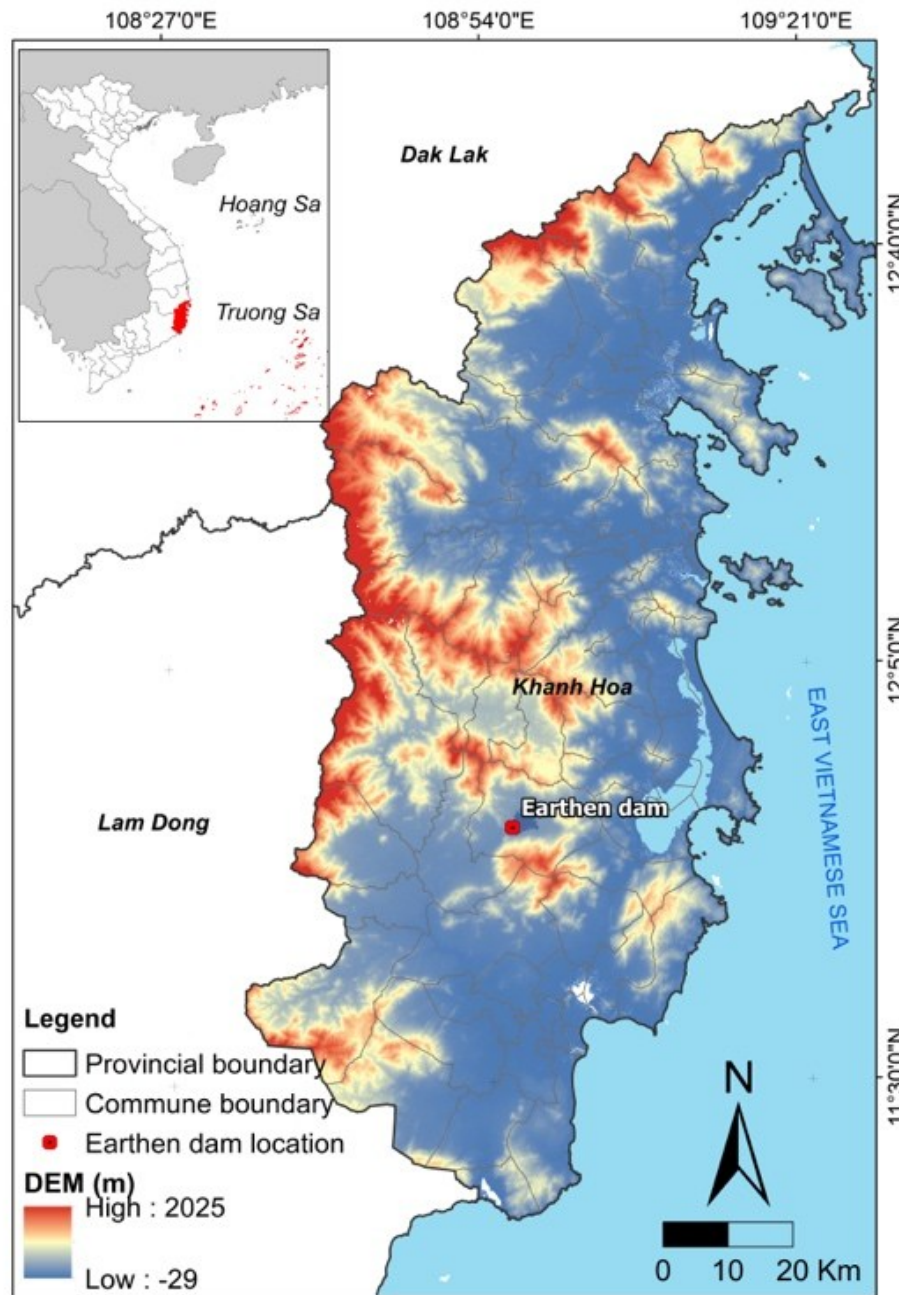


Fig. 1. Case study and Song Sat dam location

2. Data collection and Methodology

A total of 11 soil samples were collected in 2024 by the research team from Thuyloi University using standard field sampling procedures, under the national research project entitled “Study on the dispersive characteristics and erosion mechanisms of embankment dam soils in the South Central region and proposal of technological

solutions” (Project Code: ĐTDL.CN-50/22) by the Ministry of Science and Technology. Laboratory testing and statistical analysis were conducted in accordance with relevant standards. All data were verified, processed, and archived by the research team, and are available for research purposes and carefully preserved for laboratory testing. Besides, periodic field investigations combined with

topographic surveys using total stations and GPS equipment have been conducted from 2014 to 2025 to monitor the progression of erosion gullies, sinkholes, and terrain deformation over time.

Prior to specific dispersibility evaluations, fundamental geotechnical properties of the soil were determined, including particle size distribution, Atterberg limits, and Standard Proctor compaction tests, to establish the baseline physical characteristics and structural vulnerability of the embankment materials following TCVN 8719:2012 (reference: Vietnamese Standards: TCVN 8719:2012. Soils for hydraulic engineering construction - Laboratory test method for determination of expansion characteristics of soil (2012))

The laboratory assessment was then conducted with three experiments, starting with Pinhole Test to evaluate internal erosion potential and the rate of structural breakdown under hydraulic flow. This test is in accordance with ASTM D4647-93. In which soils are categorized into three levels of dispersibility: dispersive, slightly dispersive, and non-dispersive, based on visual observation of water turbidity, flow rate through the pinhole, and the degree of enlargement of the pinhole.

Crumb Test is then conducted to enhance the reliability of the study in accordance with ASTM D6572-00 to assess the degree of soil dispersion upon contact with water. Finally, Chemical Test (ESP) to determine the Exchangeable Sodium Percentage, an indicator of soil structural stability. Since the 1960s, researchers have recognized that the presence of exchangeable sodium ions (Na^+) is a key chemical factor contributing to the dispersibility of clay soils. The chemical test is considered a highly accurate method and is widely applied in both research and practice to assess the dispersive characteristics of soils. All laboratory tests were performed using equipment installed in accordance with American Society for Testing and Materials (ASTM) standards, simulating realistic

seepage conditions within the dam body.

In parallel, the laboratory results were cross-referenced with field monitoring data to elucidate the correlation between climatic factors (i.e., prolonged drought followed by intense rainfall) and the physical–chemical behavior of the embankment soil. This dual approach-integrating modeling and empirical evidence-provides a robust foundation for assessing erosion risk and formulating appropriate technical solutions.

3. Results

3.1. Erosion Development Over Time

The analysis of downstream-slope erosion over the past decade was derived directly from the long-term field monitoring program outlined in Section 2, which included annual surveys, GPS-based mapping and sinkhole inventory datasets collected from 2014 to 2023. Table 1 and Fig. 2 summarize the number and average sizes of erosion pits in the period of from 2014 to 2023.

Period 2014–2017: This period recorded the initial signs of slope erosion, particularly after the heavy rainfall season in 2016, during which recorded rainfall reached up to 96 mm in a single event [14]. Numerous small surface cracks and shallow erosion gullies were observed, along with the formation of initial sinkholes ranging from 0.2 to 0.5 meters in diameter, typically located along natural drainage paths (Fig. 3). This can be explained by prolonged drought, the surface layer of the downstream slope experienced significant desiccation and cracking, leading to a reduction in shear strength and increased infiltration potential. When intense rainfall occurred abruptly, water rapidly penetrated through the cracks, generating elevated pore water pressure, which in turn triggered soil disintegration and localized erosion—especially in the central and lower portions of the downstream slope. Despite of limited scale, these signs served as an early warning for more severe erosion stages in subsequent years. This phenomenon aligns with similar observations reported in Australia, where desiccated clay soils

quickly eroded when exposed to heavy rainfall [4].

Period from 2018 to 2020: Since late 2018, erosion on the downstream slope of the dam has become increasingly severe, with significant expansion in both scope and scale. The primary cause stems from mentioned climate condition, combined with an ineffective drainage system and heterogeneous geological conditions. Concentrated surface runoff and internal erosion weakened the soil structure, leading to the

formation of deep gullies and large sinkholes (diameters ranging from 0.5–1.0 m), mainly in the middle and lower parts of the slope (Fig. 4). Field monitoring documented the interconnection of sinkholes, forming continuous erosion networks and significantly compromising the protective soil layers. Similar phenomena have been reported in China, where heavy rains following droughts caused internal voids and sinkholes in many earthen dams [17].

Table 1. Development of Erosion Pits (2014 - 2023)

Year	Number of Erosion Pits (sinkhole)	Average Diameter (m)	Average Depth (m)
2014	20	0.10	0.20
2015	25	0.20	0.30
2016	30	0.25	0.35
2017	45	0.40	0.40
2018	50	0.55	0.45
2019	70	0.60	0.55
2020	150	0.70	0.80
2021	200	0.80	1.00
2022	250	1.00	1.20
2023	626	1.50	2.50

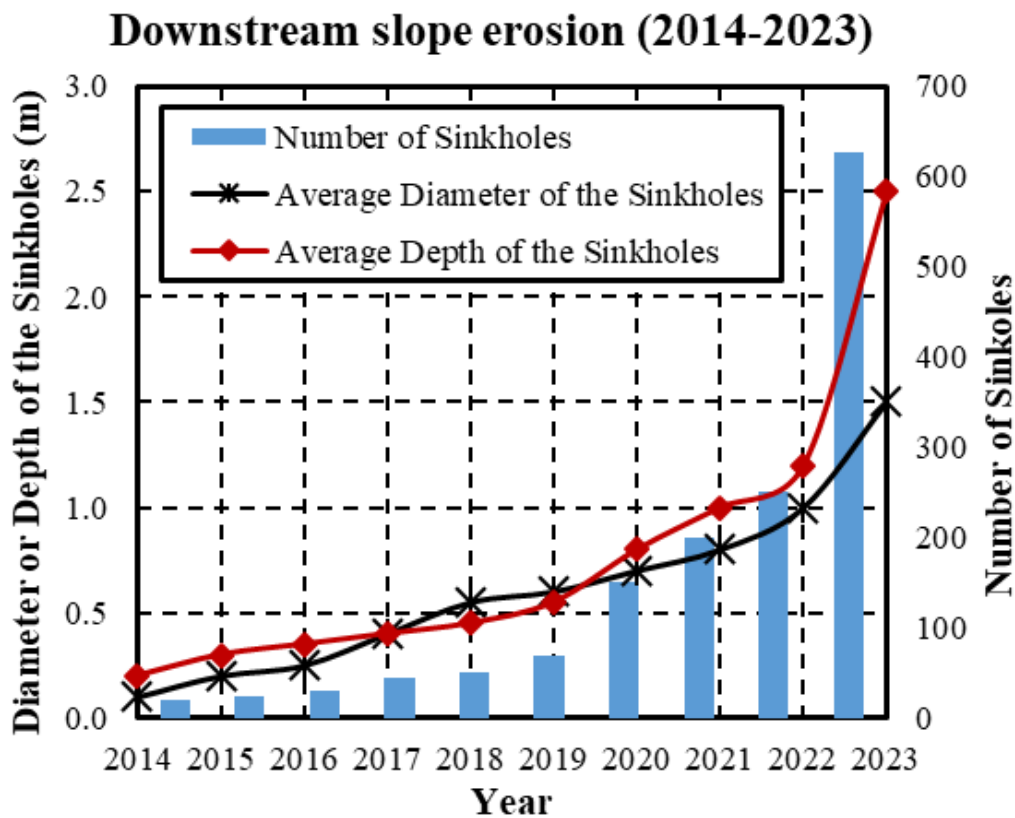


Fig. 2. Variation in the number of sinkholes from 2014 to 2023



Fig. 3. Sinkhole formation on the downstream slope of the dam during 2014–2017



Fig. 4. Sinkhole formation on the downstream slope of the dam during 2018–2020

Period from 2020 to 2023: Within this timeframe, the province was affected by approximately 14-17 tropical storms and depressions, including both storms making direct landfall in the South Central region and storms whose circulation systems induced heavy rainfall and strong winds over the province [18]. Significant events include Sinlaku, Linfa, Nangka; Conson Dianmu. The inadequate drainage system, combined with soil strength degradation caused by years of disintegration, led to waterlogging, increased pore water pressure, and deep percolation that triggered severe internal erosion. Numerous large sinkholes (with diameters ranging

from 0.5–3.5 m and depths up to 2.5 m) were recorded across the downstream slope (Fig. 5). These sinkholes were not isolated but increasingly interconnected, forming a subsurface void network that compromised the dam's structural integrity and significantly elevated the risk of large-scale slope failure. Several areas experienced sudden collapses and massive slumping, putting the entire structure at extreme risk. By November 2023, a total of 626 sinkholes had been documented, including 67 with diameters exceeding 1 meter (Fig. 6). Despite emergency backfilling and temporary reinforcement efforts costing nearly VND 1 billion, the solutions proved unsustainable,

particularly in untreated or substandardly reinforced areas. Similar events were reported in Spain and Italy, where flash floods following droughts caused severe collapses due to internal erosion and loss of soil cohesion [5].

Period from December 2024 to Present: In the nearest period, the implementation of temporary reinforcement measures, erosion intensity has shown signs of reduction in some treated areas. However, sinkhole formation has continued to develop in untreated zones or at the boundaries between reinforced and unreinforced sections. Field observations up to early 2025 recorded 390 active and expanding sinkholes, many of which measured 0.5–1.0 m in diameter and up to 1.5 m in depth, indicating a persistently high risk of erosion (Fig. 7, Fig. 8 & Table 2). These findings confirm that the current interventions are only temporary in nature and insufficient to fully control the problem without a more comprehensive and sustainable approach moving forward.

Most of the previously identified sinkholes were backfilled and temporarily stabilized at the

end of 2023 as part of emergency mitigation measures. However, in 2024, approximately 390 new sinkholes were observed to re-form on the downstream slope.

The erosion process at the Song Sat earthen dam has shown a complex evolution from 2014 to the present, both in terms of the increasing number and severity of sinkholes. Field monitoring data collected over this period strongly affirm the necessity for systematic and sustainable mitigation solutions to ensure the long-term safety and integrity of the structure.

3.2. Laboratory Test Results for Soil Dispersibility Evaluation

A series of laboratory tests were conducted to evaluate the dispersibility of soils, thereby assessing their erosion resistance and structural stability under the conditions observed at the downstream slope of the Song Sat reservoir earthen dam. Soil samples were collected from multiple locations across the dam's downstream slope and subjected to the following key tests:

3.2.1. Geotechnical Properties



Fig. 5. Sinkhole formation on the downstream slope of the dam during 2020–2023

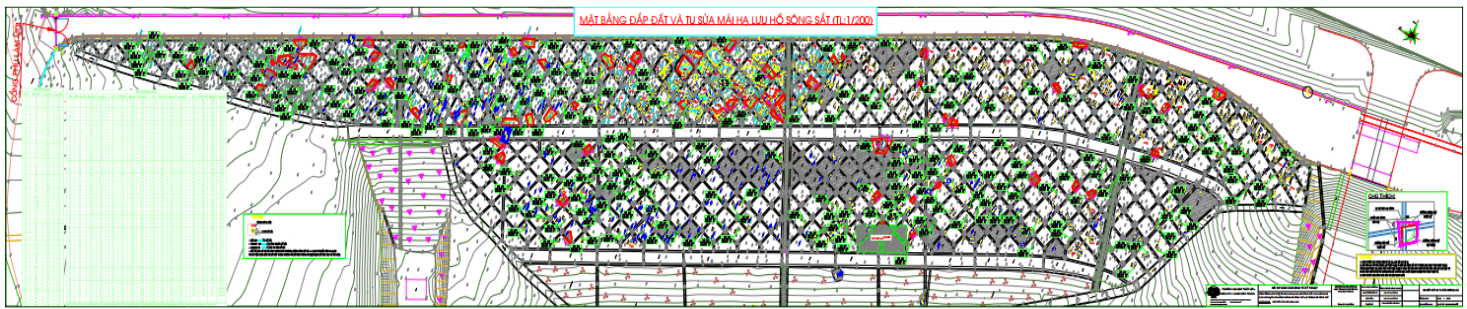


Fig. 6. Locations of 626 sinkholes (red cross) identified on the downstream slope of the earthen dam in 2023

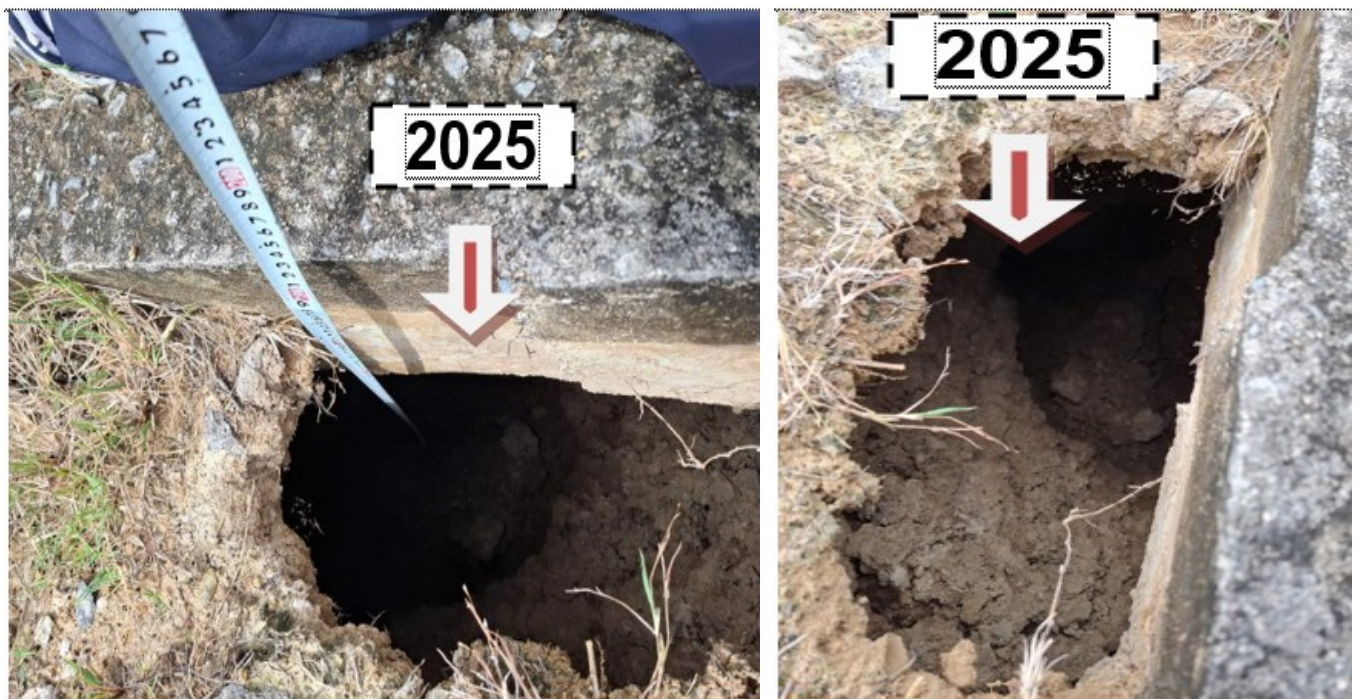


Fig. 7. Photographs of sinkholes on the downstream slope of the dam in 2025

Table 2. Development of erosion sinkholes from 2024 to 2025

Year	Number of Erosion Pits (sinkhole)	Average Diameter (m)	Average Depth (m)
1-2024	0	0.00	0.00
2-2024	0	0.00	0.00
3-2024	0	0.00	0.00
4-2024	0	0.00	0.00
5-2024	0	0.00	0.00
6-2024	50	0.60	0.50
7-2024	89	0.80	0.70
8-2024	135	0.90	0.85
9-2024	214	1.05	1.10
10-2024	245	1.10	1.15
11-2024	311	1.15	1.20
12-2024	352	1.20	1.25
1-2025	378	1.20	1.25
2-2025	390	1.20	1.25

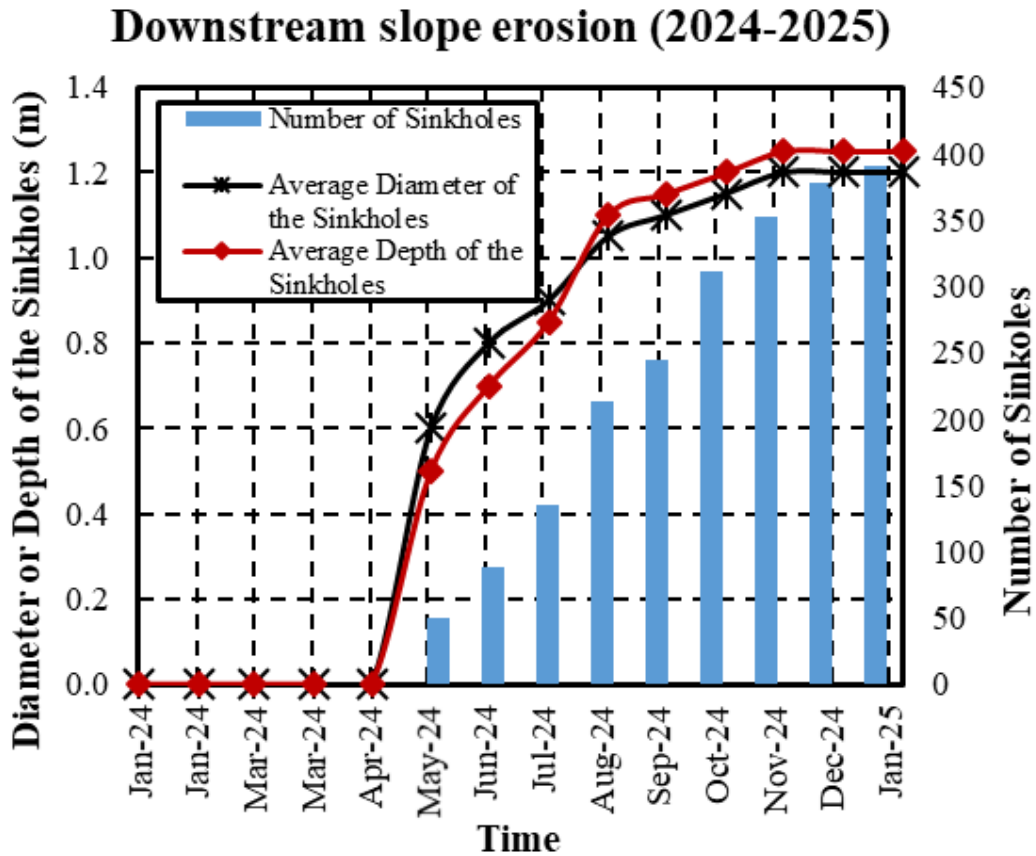


Fig. 8. Evolution of Sinkhole Quantity from Jan 2024 to Feb 2025 of the earthen dam in 2025

From the Atterberg limits, and Standard Proctor compaction tests, the soil exhibits a multi-graded structure consisting of 3–4% gravel, 20–25% sand, 10–13% silt, and 8–12% clay, classifying it primarily as clayey sand or sandy clay. While the coarser sand and gravel provide a skeletal framework, the relatively significant proportion of fines (silt and clay) dictates behaviour of soil. In the context of dispersion, the clay particles are highly susceptible to detachment, while the silt is easily washed away once the soil matrix is compromised. The embankment fill is characterized by low plasticity, with a natural moisture content ranging from 10.7% to 12.2%. This low plasticity indicates that the physicochemical bonds between the clay particles are relatively weak.

Compaction tests revealed a maximum dry unit weight of 1.65–1.71 g/cm³ (with specific samples measuring 1.678–1.710 g/cm³). These values indicate that the fill was compacted

relatively well, achieving a design compaction degree of approximately $K \approx 0.97$, which similar with result of Truong et. al [19]. However, the data highlights that high compaction alone is insufficient to prevent dispersion in slaking soils.

3.2.2. Pinhole Test

Four soil samples of the earthen dam materials at Song Sat Reservoir were applied Pinhole Test. The test progression was summarized using the results shown in Fig. 9 and Table 3.

The erosion time (t) increases monotonically with flow volume (V) for all samples, indicating progressive pinhole enlargement under sustained seepage. Sample S3 exhibits the shortest erosion times and the highest turbidity (398 NTU), reflecting the strongest soil dispersion and internal erosion susceptibility, whereas S1 and S4 show relatively lower erosion intensity. The consistent relationship between shorter erosion time and higher turbidity confirms that particle dispersion

governs the rate of internal erosion development. Consequently, all tested soils are classified as

dispersive (D), with varying degrees of erosion severity.

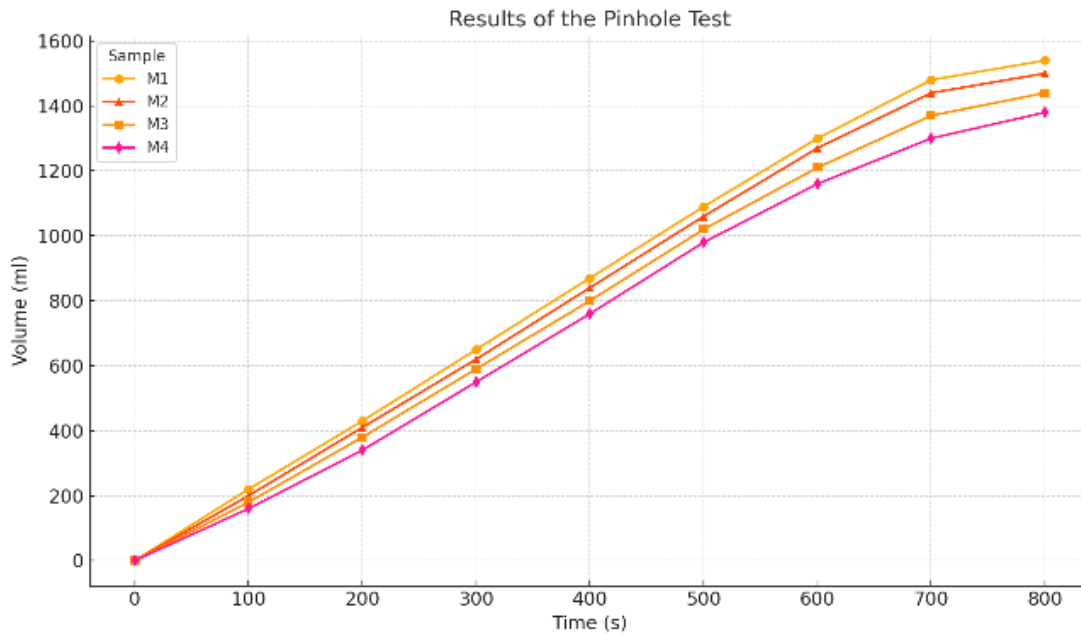


Fig. 9. Variation of Water Volume Through the Pinhole Over Testing Time

Table 3. Summary of Pinhole Test Results

TT	V	S1 t	S2 t	S3 t	S4 t
1	0	0	0	0	0
2	100	31	29	26	36
3	200	75	69	63	87
4	300	118	107	96	140
5	400	157	143	128	185
6	500	201	184	166	235
7	600	237	216	194	280
8	700	281	256	231	331
9	800	327	296	265	389
10	900	370	336	301	439
11	1000	420	378	336	503
12	1100	461	415	369	553
13	1200	506	452	397	615
14	1300	552	492	432	671
15	1400	595	532	469	721
16	1500	639	571	502	775
	NTU	265	321	398	315
	Conclusion	D	D	D	D

The enlargement of the pinhole could not be observed due to sample disintegration upon saturation and removal from the apparatus. Based on the two observable criteria-water turbidity and discharge rate through the pinhole-all four samples were classified as dispersive soils, indicating a high

vulnerability of the embankment materials at Song Sat Dam to internal erosion.

3.3.3. Crumb Test

According to ASTM D6572-00, soil aggregates are placed into a clear glass beaker containing distilled water. The dispersibility of the

soil is then evaluated based on visual observation of water turbidity, the shape and size of the cloudy zone, and the integrity of the soil fragment. Based

on these criteria, the soil is classified into three categories: dispersive, slightly dispersive, and non-dispersive.

Table 4. Summary of Crumb Test Results


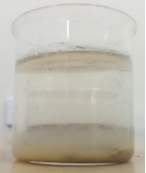
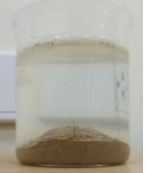
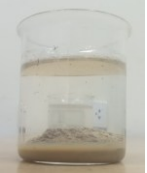




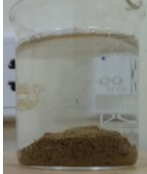
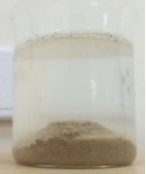


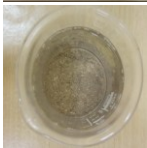




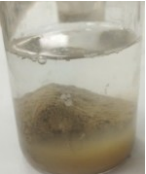
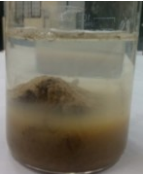


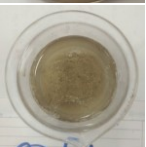
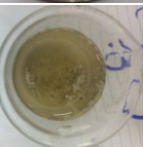
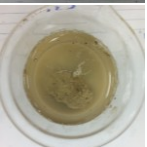




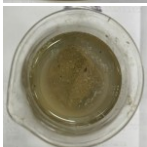
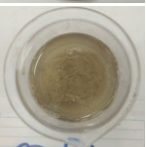
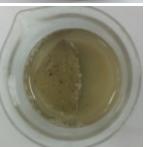
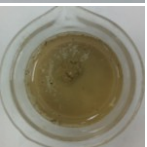
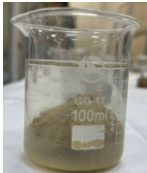



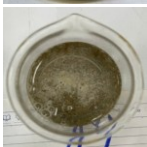
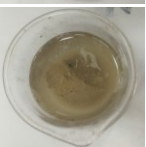

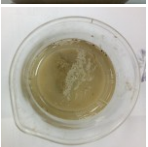
Samples	5'	1h	6h	24h	Classification
S1					D
					
S2					D
					
S3					D
					
S4					D
					
S5					D
					

Table 5. Summary of chemical test results and soil dispersibility classification

No.	Indicator	S1	S2
1	pH	6.08	5.72
2	CEC (cmolc/100g soil)	21	9
3	Ca ²⁺ (mg/100g soil)	2.2	2.2
4	Mg ²⁺ (mg/100g soil)	0.8	3.3
5	Na ⁺ (mg/100g soil)	3.4	2.8
6	K ⁺ (mg/100g soil)	4.3	—
7	EC (μS/cm)	514	162.2
8	SAR	27.76	16.88
9	ESP	16.19	31.11
10	Salt content (%)	0.029	0.009
11	Classification	D	D

The visual outcomes of the tested soil samples are shown in Table 4. The classification results indicate that the tested soils generally fall within the range of slightly dispersive to dispersive, highlighting a moderate to high susceptibility of the materials to structural breakdown upon contact with water.

3.3.4. Chemical Test

The most commonly used method is the Exchangeable Sodium Percentage (ESP) test, in which soil is classified based on ESP values as follows: ESP > 10% indicates dispersive soil; 7% < ESP ≤ 10% indicates moderately dispersive soil; and ESP < 7% indicates non-dispersive soil [20]. Based on this classification, the research team conducted chemical analysis on two representative soil samples collected from the downstream slope of the Song Sat dam embankment during the 2024 field campaign were analyzed. These samples correspond to the same sampling locations used in the Pinhole and Crumb tests to ensure consistency in evaluating the soil's dispersive behavior. The test results revealed that both samples had high ESP values (Table 5), classifying them as dispersive soils.

3.3.5. Evaluation and Analysis of Laboratory Test Results

The laboratory tests indicate that the dispersibility of the soil at the Song Sat dam is significantly high, especially for soil types with a large proportion of fine particles. Increased seepage pressure is the primary factor contributing to strong internal erosion, leading to a reduction in the soil's erosion resistance [21], [22]. Low-compaction soils with a high content of fine particles, such as silty clay, are easily disintegrated when exposed to concentrated water flow.

It is therefore essential to implement soil stabilization measures using additives such as lime or polymer, which enhance cohesion and reduce dispersibility. In parallel, the construction of an efficient drainage system is required to reduce internal water pressure within the dam body. Regular monitoring and inspection should also be strengthened to detect early signs of erosion and allow for timely remedial actions.

3.3. Influence of Climatic and Environmental

Although the laboratory samples were not collected in pre–post rainy-season pairs, the 2024 samples represent the soil condition after several years of severe drought–rainfall cycles (2020–2023). The prolonged dry seasons typically extend from December to June, with minimal rainfall and intense desiccation of the downstream slope

surface, followed by short but intense rainy seasons. The rapid increase in sinkholes, more than 30-fold between 2014 and 2023, with >70% growth during recent rainy seasons, indicates strong climatic control on soil degradation. Future sampling campaigns targeting both dry- and wet-season soil conditions would enable direct quantification of these climatic effects.

The combination of extreme climatic conditions and highly dispersive soil properties has created a severe erosion feedback loop. The soil in the Song Sat reservoir area undergoes severe moisture loss during dry season, resulting in desiccation cracks and reduced cohesion among soil particles. Surface cracking occurs due to the natural shrinkage of clay soils under extended drought conditions. As the soil becomes hardened and fractured, the bearing capacity and structural stability of the dam slope are significantly reduced. These cracks act as preferential pathways for rainwater infiltration during the wet season. When intense rainfall happens, the soil structure rapidly deteriorates, promoting rapid development of gullies and sinkholes, as observed in Fig. 8. The climate stress significantly increases hydraulic stress on the dam's surface, accelerating erosion, and subsidence, highlighting the urgent need for effective preventive and control measures to ensure the long-term safety of the dam structure.

4. Discussion

4.1. Mechanism of erosion due to dispersive

The erosion mechanism at the downstream slope of the Song Sat earthen dam is the result of a complex interaction between the physical–chemical characteristics of the embankment soil and the extreme climatic conditions typical of the South Central Coast of Vietnam. Erosion occurs in a closed-loop cycle. During the dry season, high temperatures and low humidity accelerate water evaporation, causing the soil to lose moisture severely. Clay particles shrink, leading to surface cracking and a significant reduction in internal cohesion.

When the rainy season arrives, intense rainfall within a short time infiltrates rapidly into the pre-existing cracks. This uneven infiltration causes localized increases in pore water pressure and disrupts the soil's stress equilibrium, particularly in the fine-grained, weak soil layers. Highly dispersive soils tend to lose structure rapidly upon water exposure, becoming vulnerable to surface runoff and seepage flows. Laboratory tests (Pinhole and Crumb) confirmed the strong dispersibility of the soil, while high ESP values (above 10%) indicated low chemical stability due to excessive exchangeable sodium content.

Erosion at the site not only occur at the surface but also progresses in depth through internal erosion, forming gullies and large sinkholes. In many cases, these features interconnect into subterranean tunnels that critically undermine the structural integrity of the dam. The erosion mechanism is thus not merely mechanical but represents a synthesis of climatic impacts, physical disintegration, and unfavorable geochemical properties. Understanding this mechanism is essential for developing effective mitigation strategies and ensuring long-term dam safety under changing climatic conditions.

4.2. Linkage Between Climate and Soil Structural Degradation

Fig. 10 illustrates the overarching annual variations in average temperature and rainfall from 2014 to 2023, further illustrating the impact of climate conditions on the structural degradation of the embankment. Within each recorded year, the region experiences a harsh and prolonged dry season spanning 6 to 8 months (normally January to August) [23], and the average temperature increased significantly, even reaching 37% in 2023, leading to intense moisture loss and deep vertical cracking in the clayey-sandy soil of the downstream slope.

At the onset of the rainy season, intense rainfall (200–300 mm over several days) infiltrates rapidly through these cracks, resulting in abrupt

moisture differentials between surface and subsurface layers. This sudden imbalance fractures the soil structure and triggers the formation of sinkholes and erosion gullies.

Similar phenomena have been reported internationally. Blight [4] in South Africa and Foster et al. [24] in the USA identified the “long-drought–heavy-rain” cycle as a major factor causing earthen dam instability in semi-arid zones. However, Song Sat dam exhibits several distinct conditions: the embankment soil has a high content of fine particles (>40%) and elevated ESP levels (15–30%), which significantly increase dispersibility and shorten the timeline for sinkhole development. Compared to Wang & Zhang’s findings in China [17], erosion at Song Sat occurs more rapidly and

intensively-particularly during 2014–2020, when the drainage system was incomplete. These results emphasize that for earthen dams constructed with dispersive materials, under harsh climatic conditions, the risk of instability remains high regardless of dam size unless appropriate preventive measures are implemented. Therefore, while our Pinhole and Crumb data represent a specific, cumulatively degraded local state, they highlight a broader mechanism: earthen dams constructed with highly dispersive materials under extreme tropical wet-dry cycles face a uniquely rapid risk of instability. Future studies expanding this methodology to multiple earthen dams across diverse climate zones will be essential to further refine these comparative erosion models.

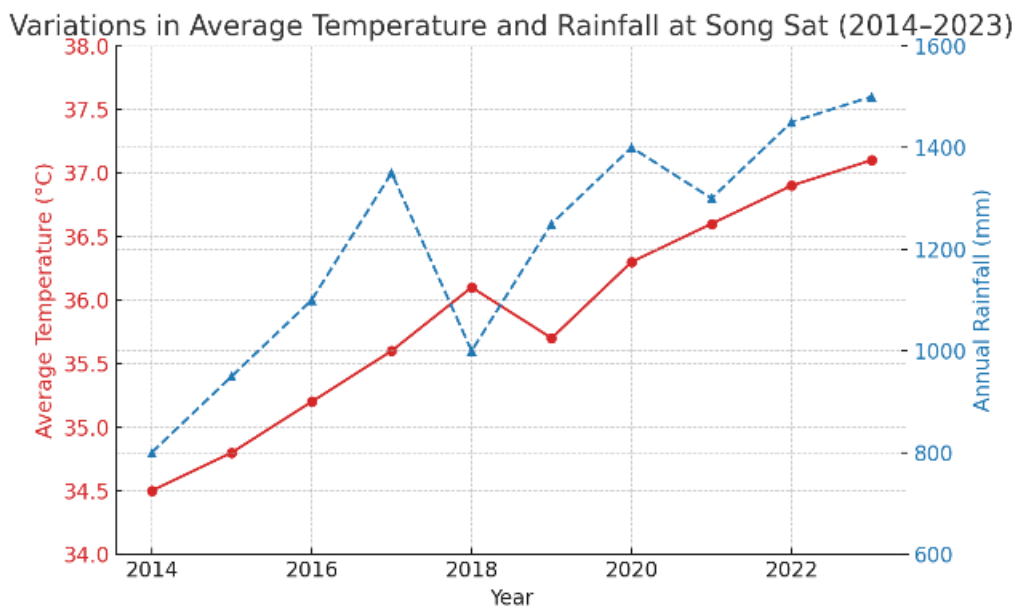


Fig. 10. Variations in average temperature and rainfall at Song Sat (2014–2023)

4.3. Evaluation of the Effectiveness of Existing Reinforcement Measures

In recent years, to mitigate downstream slope erosion, the management unit of the Song Sat reservoir has implemented several reinforcement measures, mainly in the form of localized and temporary interventions. Commonly applied methods include backfilling the sinkholes, installing steel mesh, using soil sacks or bamboo piles for temporary stabilization, and upgrading the surface drainage system with open channels and

fishbone-shaped ditches.

The Dam Safety Enhancement Project (WB8), with a budget exceeding 10 billion VND and launched in 2019, has contributed to partial improvements in the drainage system and slope reinforcement using geotextiles. However, these measures remain passive. The monitoring system is not automated, and sinkhole detection still relies on periodic manual inspections, limiting the ability to respond promptly to emerging erosion threats. The areas that have undergone treatment continue

to experience new sinkholes after each rainy season. Therefore, current measures have not yielded sustainable effectiveness.

These findings highlight that the current measures are still ineffective due to a lack of early warning capabilities, absence of a comprehensive treatment approach, and failure to incorporate soil improvement using anti-dispersive materials—considered the root cause of slope instability. This underscores the urgent need to research and implement more sustainable and integrated technological solutions in the next phase.

4.4. Technical Recommendations

Based on the research findings and the progression of downstream slope erosion at the Song Sat earthen dam, the authors propose a set of comprehensive technical solutions to enhance erosion resistance and long-term structural stability under extreme climatic conditions:

Soil improvement using anti-dispersive materials: Studies by Sherard et al. [3], Little [25], [26] have demonstrated that blending soil with additives such as lime, polymers, or fly ash significantly enhances resistance to dispersion and internal erosion. Experimental results obtained from both laboratory-scale rainfall simulation (flume tests) and field-scale monitoring at the Song Sat reservoir demonstrate that lime stabilization significantly enhances the resistance of soils with dispersive characteristics to disintegration and erosion. In the flume experiments, soil samples treated with lime at dosages of 3–5% exhibited a marked reduction in erosion depth, delayed initiation of rill formation, and decreased sediment yield compared to untreated soils under identical rainfall conditions. These findings are consistent with field observations, where treated sections showed improved surface stability and significantly lower erosion rates over multiple wet–dry cycles. The improvement is attributed to enhanced interparticle bonding and the reduction of soil dispersibility induced by lime treatment., enhances Pinhole and Crumb test indices, and reduces the

level of soil dispersion. Therefore, it is recommended to use 3–5% lime or polymer when stabilizing sinkholes or in newly filled areas.

Surface and toe slope reinforcement with durable structures: According to Foster et al. [24], the application of geotextiles, shotcrete, or wire mesh has proven effective in preventing surface erosion at earthen dams in semi-arid regions. For Song Sat dam, reinforcement is recommended at locations with concentrated surface runoff, or where recurring erosion gullies or cracks have formed, in order to prevent structural degradation and minimize deep infiltration.

The critical role of an efficient drainage system in reducing internal erosion risks has been emphasized [17]. It is proposed to redesign the slope drainage network, supplement with deep drainage pipes, and install pressure relief wells at the dam toe to manage groundwater levels and prevent excessive pore water pressure that could destabilize the dam.

Thus, based on the evaluation, application of modern monitoring technologies is an appropriate choice. Fell et al. [27] advocated for the use of automated monitoring systems equipped with moisture sensors, piezometers, and UAV (drone) surveillance to detect even minor deformations on the dam surface. This study recommends the adoption of real-time automated monitoring models combined with data analytics for early warning and proactive maintenance strategies.

As highlighted by IPCC [2], incorporating climate forecasting into reservoir operations is also essential. It is recommended to implement hydrometeorological forecasting models, especially during transitional periods between dry and rainy seasons, to adjust reservoir operation regimes and safeguard downstream slopes against extreme rainfall events.

5. Conclusions

The South Central Coast region of Vietnam, particularly the Khanh Hoa Province, is characterized by a harsh climate with two distinct

seasons: a prolonged dry season and a short rainy season with high-intensity rainfall. The stark contrast between these seasons significantly contributes to the erosion process on the downstream slope of the Song Sat reservoir's earthen dam.

This study adopted a dual-methodology to integrate long-term field monitoring with laboratory evaluation of soil dispersivity in order to clarify the mechanisms driving downstream-slope erosion at the Song Sat earthen dam. Using a dataset comprising more than 10 years of sinkhole inventories and five representative laboratory samples tested through Pinhole, Crumb, and ESP analyses, the study demonstrated that the number of sinkholes increased over 30-fold between 2014 and 2023, while all soil specimens were consistently classified as dispersive, with ESP values ranging from 16% to 31%. These combined results confirm that the repeated cycle of prolonged drought followed by intense rainfall has progressively weakened the soil structure, accelerated internal erosion, and is the dominant factor controlling the degradation of the downstream slope.

One of the limitations is that a comparative analysis was not conducted due to the focus on a single case study. Laboratory testing (Pinhole, Crumb, ESP) focused primarily on sandy clay soil types, excluding other fill materials such as gravelly soils or heavy clays. Meteorological and hydrological data were obtained from a nearby weather station, without integration of full-scale hydrodynamic modeling for the reservoir catchment. Secondly, the laboratory samples were not collected in pre- and post-rainy-season pairs, the study cannot directly capture the immediate structural breakdown occurring within a single seasonal transition. Future real time sampling campaigns targeting both dry- and wet-season soil conditions are necessary to provide control data and enable the direct quantification of these real-time climatic effects. Next, although annual

sinkhole progression and general meteorological data were documented, the study lacks a comprehensive quantitative analysis using statistical methods—such as regression, correlation, or trend analysis—to mathematically define the relationships between rainfall intensity, specific climatic variables, and the rate of sinkhole development

Further studies should extend the monitoring framework and long-term statistical analysis to include multiple earthen dams across diverse climate zones. Broader coverage of soil types in laboratory analysis is also necessary to refine classification and erosion risk prediction models. Integration of hydrodynamic simulations with remote sensing and automated monitoring systems would enhance early warning capabilities and support the development of a comprehensive dam safety database adaptable to climate change.

Funding Statement

The research and publication of their article were funded by the Ministry of Science and Technology, Vietnam.

Acknowledgments

The contents of this article are based on the results of the scientific research "Study on the disintegration characteristics and erosion mechanism of the downstream slope of the earthdam in the South Central region and propose scientific technological solutions for treatment", code number ĐTĐL.CN-50/22. The authors would like to thank the Ministry of Science and Technology for funding this research.

References

- [1] R. Fell, P. MacGregor, D. Stapledon, G. Bell, and M. Foster. (2014). *Geotechnical Engineering of Dams*, 2nd ed. *CRC Press*. doi: [10.1201/b17800](https://doi.org/10.1201/b17800)
- [2] Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on*

- Climate Change. *Cambridge University Press*. <https://doi.org/10.1017/9781009157896>
- [3] J.L. Sherard, L.P. Dunnigan, and R.S. Decker. (1976). Identification and Nature of Dispersive Soils. *Journal of the Geotechnical Engineering Division*, 102(4), 287–301. doi: 10.1061/AJGEB6.0000256
- [4] G.E. Blight. (2012). Origin and formation of residual soils. *Mechanics of Residual Soils*, 2nd ed. *CRC Press*. DOI:10.1201/B12014-6
- [5] D.V. Griffiths and P.A. Lane. (1999). Slope stability analysis by finite elements. *Geotechnique*, 49(3), 387–403. doi: 10.1680/geot.1999.49.3.387
- [6] X. Weng, J. Zhu, D. Wang, H. Chen, S. Wang, and Y. Qing. (2024). Exploring the relationship between drought-flood abrupt alternation and soil erosion over Guangdong, China through a convection-permitting model. *Geomatics, Natural Hazards and Risk*, 15(1), 2383779. doi: 10.1080/19475705.2024.2383779
- [7] J. Fluixá-Sanmartín, A. Morales-Torres, I. Escuder-Bueno, and J. Paredes-Arquiola. (2019). Quantification of climate change impact on dam failure risk under hydrological scenarios: a case study from a Spanish dam. *Natural Hazards and Earth System Sciences*, 19, 2117–2139. doi: 10.5194/nhess-19-2117-2019
- [8] P.N. Psarropoulos, N. Makrakis, and Y. Tsompanakis. (2024). Climate Change Impact on the Stability of Soil Slopes from a Hydrological and Geotechnical Perspective. *GeoHazards*, 5(4), 1190–1206. doi: 10.3390/geohazards5040056
- [9] W.N.H. Wan Ariffin, L. Mohd Sidek, H. Basri, A. M. Torres, A.N. Ahmed, and N.I. Ahmad Bukhari. (2025). Strengthening Dam Safety Under Climate Change: A Risk-Informed Overtopping Assessment. *Water*, 17(19), 2856. doi: 10.3390/w17192856
- [10] A.H. Vakili, A. Khajeh, M. Salimi, J.P.O. Patiño, and S. Yaghoubi. (2024). Investigating the efficacy of nanoclay particles in controlling the contact erosion behavior of dispersive clays. *Bulletin of Engineering Geology and the Environment*, 83, 384. doi: 10.1007/s10064-024-03881-w
- [11] N.T. Pham. (2024). An overview of riverbank erosion prediction techniques applied to the Mekong Delta, Vietnam. *E3S Web of Conferences*, 535, 01020. doi: 10.1051/e3sconf/202453501020
- [12] T.S. Ho et al. (2025). Machine Learning-Based Assessment of Soil Dispersibility and Erosion Types in Earthfill Dam: A Case Study from South Central Vietnam. *International Journal of Civil Engineering*, 12(9), 120–128. doi: 10.14445/23488352/IJCE-V12I9P111
- [13] T.V. Tran, B.T. Vu, M.V. Pham, D.Q. Nguyen, and D.C. Phan. (2023). Understanding downstream slope failure in earth dams: causes and remedies - a case study of Trieu Thuong no.2 dam, Quang Tri, Vietnam. *GEOMATE Journal*, 25(108), 163–171.
- [14] T.H. Thai, H.A. Huy, N.D. Mau, H.V. Dai. (2018). Indicators of Climate Change Across the Southcentral Region. *Vietnam Journal of Hydrometeorology*, 1, 1-10.
- [15] L.N. Luu et al. (2021). Attribution of typhoon-induced torrential precipitation in Central Vietnam, October 2020. *Climatic Change*, 169, 24. doi: 10.1007/s10584-021-03261-3
- [16] T.Q. Nguyen, H.C. Vu, L.T. Pham, L.T. Nguyen and V.H. Nguyen. (2024). Research on calculation of slope failures considering unstable transient surface due to rain. *The University of Danang - Journal of Science and Technology (UD-JST)*, 22(11C), 89–96. DOI: 10.31130/ud-jst.2024.564E
- [17] Z. Wang and F. Han. (2017). Metacognitive knowledge and metacognitive control of writing strategy between high- and low-performing Chinese EFL writers. *Theory and Practice in Language Studies*, 7(7), 523-532. doi:

- 10.17507/tpis.0707.04
- [18] NOAA Office for Coastal Management. Historical Hurricane Tracks. [Online]. Available: <https://coast.noaa.gov/hurricanes/#map=4/32/-80>. (accessed December 18, 2025).
- [19] Q.T. Truong, P.T. Le, and T.N.Q. Nguyen. (2018). Change of expansion characteristics of compacted soils used for dams in central Vietnam. *MATEC Web Conf.*, 193, 02003. International Scientific Conference Environmental Science for Construction Industry – ESCI 2018. doi: 10.1051/mateconf/201819302003
- [20] F.A. Gerber and H.J. Harmse. (1987). Proposed procedure for identification of dispersive soils by chemical testing. *Civil Engineer in South Africa*, 29(10), 397–399.
- [21] M. Ouyang and A. Takahashi. (2016). Influence of initial fines content on fabric of soils subjected to internal erosion. *Canadian Geotechnical Journal*, 53(2), 299–313. doi: 10.1139/cgj-2014-0344
- [22] B. Wang, L. Chen, and Z. Niu. (2022). Critical hydraulic gradient and fine particle migration of sand under upward seepage flow. *Scientific Reports*, 12, 14440. doi: 10.1038/s41598-022-18720-9
- [23] N.T. Thuy, L.T. Trung, V.T. Thuy, D.H. Nhung, and N.N. Das. (2025). Remote sensing - based water demand index mapping: Insights from Khanh Hoa Province, Viet Nam. *Journal of Climate Change Science*, 35, 41–50. doi: 10.55659/2525-2496/35.120222
- [24] M. Foster, R. Fell, and M. Spannagle. (2000). A method for assessing the relative likelihood of failure of embankment dams by piping. *Canadian Geotechnical Journal*, 37(5), 1025–1061. doi: 10.1139/t00-029
- [25] D.N. Little. (1995). Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime. *Kendall/Hunt Publishing Company*.
- [26] M. Mirzababaei, A. Arulrajah, and M. Ouston. (2017). Polymers for Stabilization of Soft Clay Soils. *Procedia Engineering*, 189, 25–32. doi: 10.1016/j.proeng.2017.05.005
- [27] R. Fell and J.-J. Fry. (2007). Internal Erosion of Dams and Their Foundations: Selected and Reviewed Papers from the Workshop on Internal Erosion and Piping of Dams and their Foundations, Aussois, France, 25–27 April 2005. *CRC Press*.