

NUMERICAL ANALYSIS OF EMBANKMENT SLOPE FAILURE: A REVIEW ON SEEPAGE, STABILITY, AND EARTHQUAKE EFFECTS

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ABSTRACT

The embankment slopes on rivers, highways, and other flood protection structures are very susceptible to collapse either because of excessive rain or seismic loading. These failures should be prevented to ensure that infrastructure is designed in a safe and powerful way. In spite of the fact that field investigations and laboratory experiments are useful sources of information, they are often expensive, time-consuming, and even dangerous. Consequently, numerical modelling has gained popularity and become a viable method to assess slope stability in different environmental conditions as well as loading conditions. In fact, the research study examines 20 numerical studies (2014-2015) on Limit Equilibrium Method (LEM) and Finite Element Method (FEM) and coupled models, such as GeoStudio (SLOPEW, QUAKEW, SEEPW) and PLAXIS, to evaluate stability under the effects mentioned. Besides qualitative literature review, the study offers a comparative quantitative synthesis of reported safety factors of sampled numerical studies. The factor of safety reductions in seepage, seismic and combined hydro-seismic loading conditions are analyzed in percentages to examine their relative contribution to the stability of the slope of the embankment. The findings demonstrate that the overall effect of hydro-seismic is always the most severe stability decrease with the accentuation of the importance of complete coupling of numerical models in real-life assessment of embankment performance. Regardless of these improvements, the study has found major gaps in the analysis of embankment slope, such as the few fully-coupled hydro-seismic simulations, unsaturated soil behaviour modeling, the lack of 3D methods and use of simple seismic input. In a bid to address the challenges, it is suggested that a future researcher should come up with a fully integrated three-dimensional numerical model using sophisticated tools such as the FLAC3D to analyze the seepage caused by rainfall, the non-uniform seismic loading at the same time.

Keywords: *Embankment slope failure, Numerical analysis, Limit Equilibrium Method, Finite Element Modelling, Seismic effects.*

1. INTRODUCTION

The riverbanks, highways, reservoirs and flood protection systems are important structures that have embankment slopes as their key elements. But when subjected to a long seepage, heavy rainfall or forces in the form of earthquakes, they are very susceptible to failure. These sorts of failures may cause extreme structural destruction and become a threat to the local communities. Though field and laboratory studies have been in existence to learn more about the slope behavior, these investigations are time-consuming, expensive and in many cases fail to provide the detailed interaction of soil, water flow and seismic loads. Numerical modeling has thus been extensively embraced in geotechnical engineering since it offers a secure, speedy and more trustworthy platform on which slope responses can be assessed in different loading and environmental settings.

The effects of numerous constituents on the stability of an embankment are a subject that has been explored in recent studies. As an example, it was found that soil nails help to make slopes much more stable, as they enhance the factor of safety (Hossain and Islam, 2016). Experiments of water table rising and earthquake shaking indicate that saturated slopes experience much more stability reduction, especially when the seismic acceleration is high (Hossain, Mukit, and Kibria, 2016). Dynamic modeling of the Horan Dam was further evidence that well-designed embankments could resist the substantial ground motion (Mahmoud et al., 2024). Hydraulic impacts have been researched in many studies as well. Although the indicators of stability are safe, the regular variation of the water levels has been found to contribute to the risk of deformation (Jadid et al, 2019). Other effective drainage systems, such as horizontal drains, have reported a great deal of improvements in terms of safety (Al-Nedawi and Al-Hadidi, 2020). Rapid drawdown conditions are known to considerably decrease slope safety according to coupled seepage-stability analysis (Belew et al, 2022). Despite the high vulnerability of 3D models at the time of simultaneous heavy rains and seismic loads (Wang et al., 2024), some recent works have reported essential stability loss during the interaction of internal cavities and earthquakes (Hameed et al, 2025).

Although there has been a lot of improvement, the majority of studies are still individual assessments of the seepage and seismic effects. To contribute to making future embankment designs safer and resilient, this research undertaking underlines the need to have fully-integrated hydro-seismic numerical techniques.

2. METHODOLOGY

The review involves a systematic and open procedure in gathering, assessing and interpreting the recent research on numerical modelling of embankment slope failure due to seepage and earthquake influence. The general purpose consisted in making a clear, reproducible, and fair synthesis of the research papers that were the most relevant. In order to obtain this objective, the principles that directed the methodology resembled the PRISMA standards that have four primary phases, such as literature collection, the implementation of screening and eligibility, organization of studies by theme, and comparative assessment.

2.1 Literature Collection

The first stage involved major academic databases, high quality and well known databases, including Web of science, Science direct, springer link, and Google scholar were searched, as well as reliable geotechnical engineering repositories and university research archives. Primarily we used to search numerical analysis of embankment slope failure followed by synthesis of these works which contains such words as embankment slope failure, seepage modelling, earthquake induced slope instability. Articles that were published since 2014 and up to 2025 were preferred to reflect on the latest developments and new modelling practices. Other pertinent literature was found through reviewing the reference list of the identified papers, and this is why the influences that could be included in the search were not there in reference lists of particular papers.

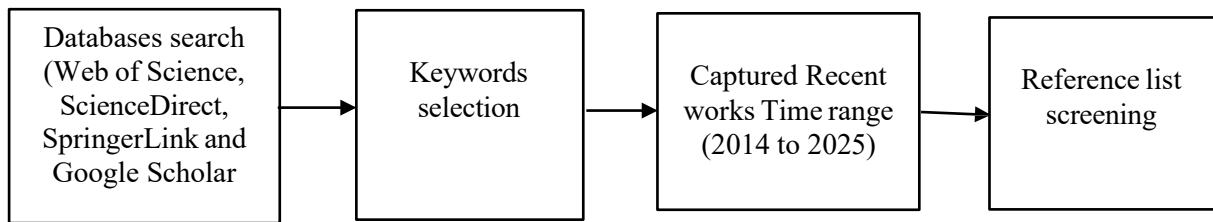


Figure 1: Flowchart of literature collection

2.2 Screening and Eligibility

Following the collection of the first set of 70 studies a two-step screening procedure was conducted in order to determine which research would fit into the objectives of our review most. Initially, we analyzed titles and abstracts so as to narrow down on the studies that are irrelevant to this study. The analysis of the entire text of the shortlisted studies was then done to facilitate proper review. Included in the studies were those concerned with numerical analysis of embankment or earth-dam slopes, and slope failure due to earthquakes, and properties such as seepage modelling, slope instability due to earthquakes, and quantifiable results such as factor of safety, change of pore water pressure, or slope deformation. Natural landslides were addressed when there was no relevance to embankment, or when non-clear methodology information was eliminated. Out of the preliminary search, 20 studies were eventually selected to be analysed in detail in order to form this review.

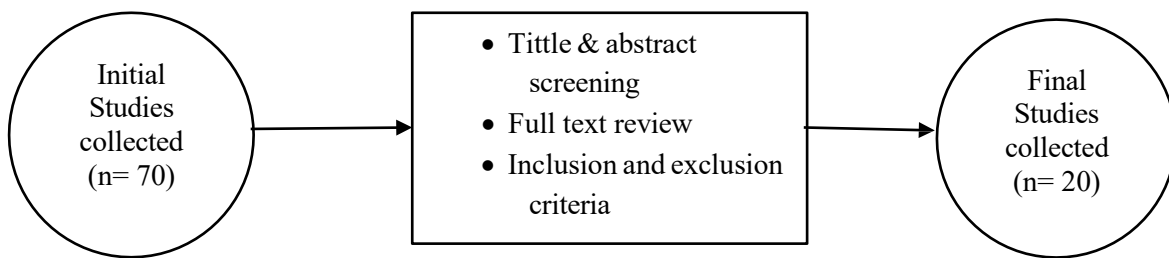


Figure 2: Flowchart of screening and eligibility

2.3 Thematic Categorization

Having identified the eligible studies, they were themed based on the overriding factors in slope behavior. The three dominant themes were studies on seepage and hydraulic loading, slope stability in a static condition or reinforced condition and earthquake and dynamic responses. This classification was easy to compare the mode of applying diverse modelling techniques in analyzing the impact of water movement, strength of soil, reinforcement methods and seismic forces on the performance of embankment. It was also helpful to bring out the studies that incorporate various effects especially hydro-seismic interactions, which are increasingly important in the assessment of embankment performance in the real world.

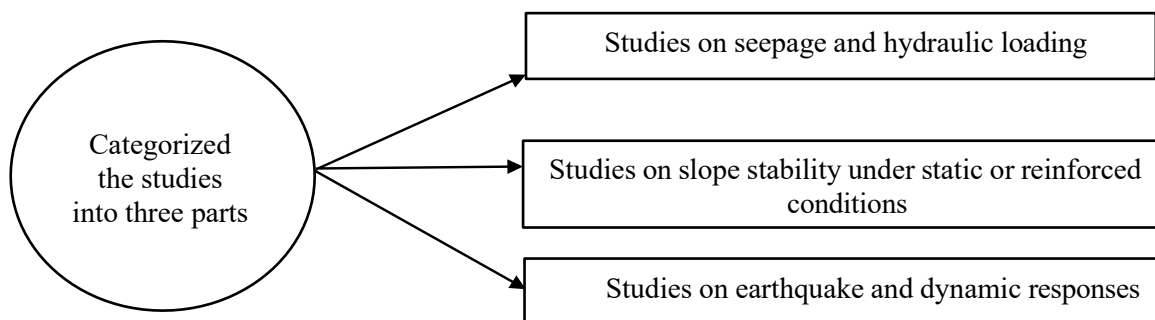


Figure 3: Flowchart of thematic categorization

2.4 Comparative Analysis and Researcher's Approach

In the chosen studies, the main information was collected regarding the methods of modelling, soil and hydraulic parameters, software, loading conditions, assumptions of analysis, and main details. This information was compared among the studies to find out similarities, differences and trends in numerical methods. The synthesis was directed to the extent of simulating seepage and earthquake effects by different models as well as the abilities of the models to predict the aspects of safety and deformation and also the limitations. Through this process, the review identifies the strengths as well as the gaps that still persist in this procedure including a lack of fully-coupled hydro-seismic analysis, a lack of consideration of unsaturated soil behavior, and dependence on simplified seismic inputs. The overall objective of this methodology is to provide a well-rounded, objective and informative explanation that spurs the development of research and modeling of embankment slope moving forward.

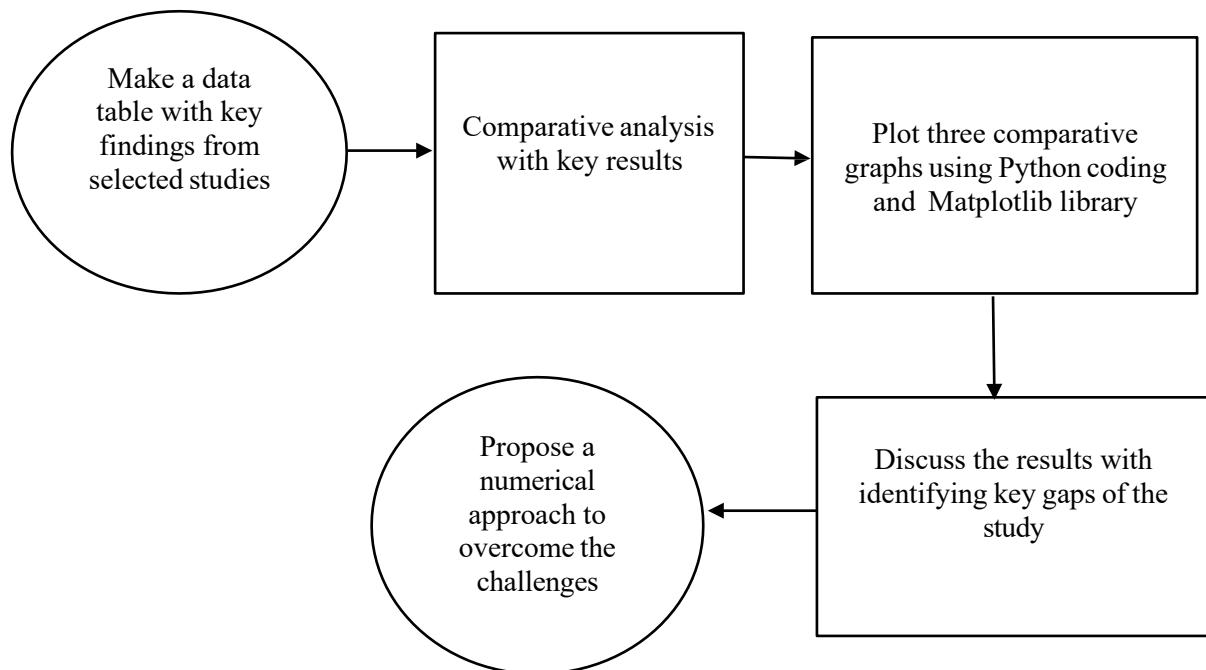


Figure 4: Flowchart of comparative analysis and researcher's approach

3 DATA TABLE

Table 1 gives a summary of major numerical investigations in area of embankment and earth-dam slope stability under seepage, rainfall and seismic loading conditions. The table identifies the methods applied, software, and key critical parameters of modeling applied, and key findings of each study. It gives a comparative account of how the variegated numerical methodologies measure the slope behavior and safety. The current summary helps identify the trends of research and the gaps in the integrated analysis of hydro-seismic.

Table 1: Overview of Compiled Studies

No.	Paper / Author	Year	Method	Software	Key Parameters	Results
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1	Hossain & Yin	2014	Direct shear tests on CDG soil–cement interface under saturated conditions	Not specified	Grouting pressure (0–250 kPa), Normal stress (50–300 kPa), Interface friction angle (31.5°), Adhesion intercept (16.4–41.8 kPa)	The strength of shear to grouting pressure is directly proportional; the suggested model is close to experimental results.
2	Hossain & Yin	2014	Direct shear tests & analytical modeling	Modified Direct Shear Apparatus (MDSA)	Matric suction (0–300 kPa), net normal stress (50–300 kPa), CDG soil, cement grout	Shear strength ↑ with suction & stress; dilatancy affects apparent friction angle; proposed model matches experimental data
3	Hossain & Yin	2015	Direct shear tests under suction & pressure	Modified Direct Shear Apparatus (MDSA)	Matric suction (0–300 kPa), net stress (50–300 kPa), grouting pressure (0–250 kPa)	Shear strength ↑ with suction & stress; pressure grouting improves strength at low suction but reduces it at high suction
4	Hossain & Islam	2016	Limit Equilibrium (Morganstern-Price)	GeoStudio (SLOPE/W)	Nail inclination (20°–45°), dry slope (45°), layered soil properties	FOS ↑ with nail; peak FOS at 30° inclination; beyond that, FOS decreases; 18% gain over unreinforced slope
5	Hossain et al.	2016	Limit Equilibrium (Morgenstern-Price), Pseudo-static analysis, Dynamic FEM	SLOPE/W, QUAKE/W	$\gamma = 16\text{--}19 \text{ kN/m}^3$; $c = 20\text{--}30 \text{ kPa}$; $\phi = 10\text{--}16^\circ$; Damping ratio = 0.1; Poisson's ratio = 0.33; $G_{\max} = 5000 \text{ kPa}$	FS decreases as k_h increases; slope unstable at $k_h > 0.30$ (dry) and $k_h > 0.25$ (wet); horizontal acceleration (k_h) is the dominant factor compared

						to k_v ; dry slope more stable than wet; maximum lateral displacement occurs at slope top, nearly zero at bottom.
6	Mahmoud et al.	2024	2D Finite Element Analysis for dynamic slope stability	GeoStudio (SEEP/W, SLOPE/W, QUAKE/W)	Pore-water pressure, effective stress, displacement, acceleration, factor of safety	Horan Dam H4 is stable under seismic conditions; factor of safety remains above critical limits even at max acceleration (0.163g); no liquefaction observed; settlement within safe limits
7	Jadid et al.	2019	Strain-based & traditional stability analysis	PLAXIS 2D, Slope/W	6 storm cycles, soil strain, hydraulic loading	Strain-based method showed rising failure risk; FS stayed nearly constant but underestimated actual damage
8	Al-Nedawi & Al-Hadidi	2020	Finite Element Seepage & Stability Analysis	GeoStudio (SEEP/W, SLOPE/W)	Water levels: 92m, 104.5m, 107.5m; Soil zones; Drain filter	Seepage risk increases at flood level; horizontal drain improves safety factor from 0.91 to 1.37
9	Belew et al.	2022	Coupled seepage & slope stability analysis	PLAXIS 2D	Mohr-Coulomb model; static/dynamic loading; rapid drawdown	Seepage rates within limits; FOS ranged 1.066–1.306; dam stable under all conditions
10	Hameed et al.	2025	Experimental + FEM (Seepage & Dynamic Analysis)	GeoStudio (SEEP/W, QUAKE/W)	Cavity location, shape, size; PGA: 0.1–0.47 g; soil damping; pore pressure sensors	Upstream & double cavities caused max deformation; dynamic FOS dropped below 0.6; validated by lab tests
11	Dhiman et al.	2024	FEM-based dynamic, seepage & slope stability analysis	GeoStudio (QUAKE/W, SEEP/W, SLOPE/W)	PGA = 0.8g; dam height = 18 m; clay core; silty sand casing; saturated/unsaturated flow	Dynamic analysis showed significant crest displacement; seepage vectors validated; slope stability improved with

						geosynthetics
12	Bayati et al.	2025	Analytical & numerical method comparison	ABAQUS, FLAC3D, FE/FD/BE	Pseudo-static, pseudo-dynamic, Newmark, SSR, LA, SPH, DEM, MPM	Stress-deformation and SSR methods offer high accuracy; method choice depends on project needs, data, and complexity
13	Hossain & Rahman	2025	Limit Equilibrium (Morgenstern-Price)	GeoStudio (SLOPE/W)	Nail inclination (5°–85°), length (8–16 m), spacing (1–2.5 m); slope angles 30°–90°	Optimal FOS at 25° (gentle), 20° (medium), 15° (steep); FOS ↑ with length, ↓ with spacing
14	Pandey et al	2023	LEM & Stress-Based FEM (Mohr-Coulomb)	GeoStudio (SEEP/W, SLOPE/W, SIGMA/W)	8h RDD; permeability variation; pore pressure; upstream filters; FOS threshold = 1.3	FOS = 1.28 (LEM), 1.27 (FEM) → unsafe; safe draw-down rate ≥ 20h; filters & permeability improve FOS but nonlinear FEM shows instability persists
15	Shi et al.	2025	Analytical + Numerical (Finite Difference Method + Perturbation Method)	FLAC3D	Slope geometry, seismic input type, epicentral distance, earthquake intensity, constitutive laws	Non-uniform input yields lower average safety factors; peak acceleration magnifies with elevation; elastoplastic models offer more conservative stability estimates
16	Khadka et al.	2025	LEM (Bishop/GLE) vs FEM-SSR under rainfall & seismic; PCPP protection concept	Slide2, RS2	Four coastal slopes; Mohr–Coulomb; Van Genuchten; transient rainfall; Rayleigh damping	Rainfall dominates stability loss; SRF drop up to ~31%; PCPP raises SRF ~16%
17	Jyothi & Singh	2023	Limit Equilibrium (Morgenstern-Price), Pseudo-static seismic analysis	GeoStudio 2022 (SLOPE/W, SEEP/W, QUAKE/W)	Mohr-Coulomb model, $k_h = 0.1–0.16$, FRL, 100-year life	FOS: Upstream 2.80, Downstream 1.70; Rapid drawdown FOS = 2.29 (min); Seepage loss: 5622.9 m ³ /yr (steady), 34,311.17 m ³ /yr (drawdown);

						Max displacement = 0.107 m; Post EQ FOS: 2.32 (U/S), 1.39 (D/S); Safe under static & seismic conditions
18	Salahudeen et al.	2023	Empirical & Numerical Modelling (Limit Equilibrium, Finite Element Method)	GeoStudio (SLOPE/W, SEEP/W)	$\gamma = 1.76\text{--}1.96$ Mg/m ³ ; $c = 3\text{--}13$ kN/m ² ; $\phi = 18\text{--}25^\circ$; water height = 7.6 m	FS = 2.302 (stable); FS = 1.416 under rapid drawdown (safe); seepage rate = 1.27E-04 m ³ /s; hydraulic velocity = 4.15E-04 m/s; need for low-permeability core and proper compaction.
19	Chandra et al	2016	Limit Equilibrium (Morgenstern-Price), Finite Element (Dynamic)	GeoStudio 2007 (SLOPE/W, QUAKE/W)	Dam height: 17 m; Slopes: 3H:1V (U/S), 2H:1V (D/S); Unit weight: 18–24 kN/m ³ ; Cohesion: 5–20 kPa; ϕ : 20–30°; Earthquake: 0.2–0.3g, 10s	FOS increases with cohesion & ϕ ; decreases with height; Seismic analysis: peak crest acceleration = 0.41g (base 0.2g), max displacement = 0.07 m; Safe performance; dynamic response significant at crest.
20	Wang et al	2024	3D Rigorous Limit Equilibrium Method (slice-free), Global analysis under combined seepage and seismic forces	Custom 3D Model (validated with Slide software)	Parameters: unit weight (19.2–21 kN/m ³), cohesion (13.5–29.3 kPa), $\phi = 20^\circ$; Seepage from rainfall; Seismic coefficients $k_h = 0.05\text{--}0.15$, $k_v = \pm 0.025$; Study area: Woshaxi landslide, Three Gorges Reservoir	Proposed a 3D method satisfying full equilibrium; Verified with classic examples (FOS \approx 2.05 vs. analytical 2.12); Case study shows rainfall + earthquake reduces FOS < 1.0 (unstable); Horizontal seismic effect > vertical; Porosity most influential under rainfall; Combined rainfall + horizontal EQ critical for failure

4 RESULTS

This part is a presentation of the synthesized findings as a result of the comparative analysis of the reviewed numerical studies and the derived graphical evaluations. The findings are devoted to methodological trends, loading-condition effects, loading conditions and the essential indicators of stability of embankments regarding their slope performance.

4.1 Distribution of Numerical Modeling Approaches

As Figure 1 demonstrates, more than half of the studied works involve LEM and FEM. Complex embankments are not common with 3D modeling and fully coupled hydro-seismic analysis. Even the majority of research works are based on simplified or half-coupled approaches.

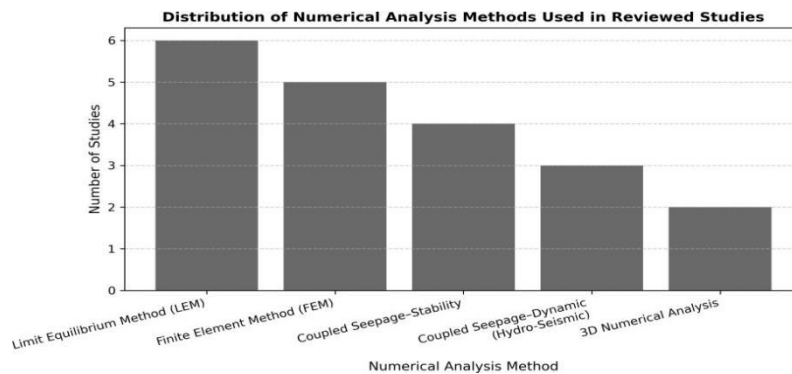


Figure 5: Distribution of numerical methods used in embankment slope studies

4.2 Effect of Loading Conditions on Slope Stability

As indicated in Figure 2, stability decreases in various loading circumstances. Seepage or saturation decreases Factor of Safety (FOS) by 10-25% whereas seismic loading decreases Factor of Safety (FOS) by 15-35%. When the two are combined, the worst effect is the probable decrease in FOS by more than 40. This can validate the fact that failure risk is grossly underestimated when the factors are analyzed separately.

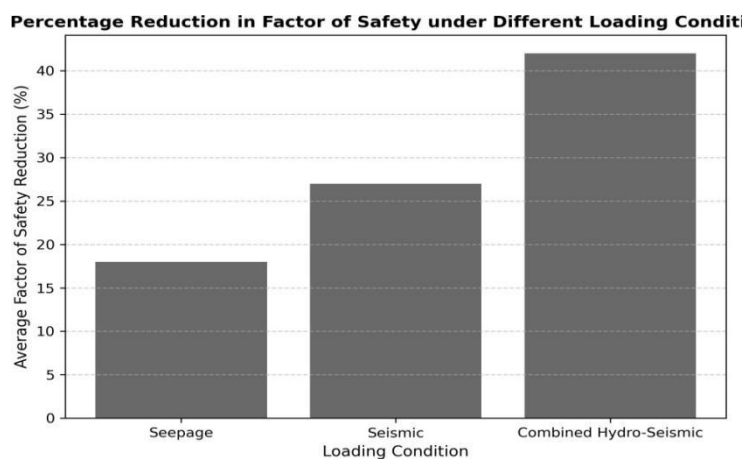


Figure 6: Factor of safety reduction under different loading conditions

4.3 Temporal Evolution of Research Focus

Figure 3 indicates the trends in research between the years 2014 and 2025. Although older literature concentrated on the study of seepage or seismic effects individually, combined hydro-seismic analysis has become popular since 2020. Nevertheless, full coupled studies are still uncommon and there is a major gap in general embankment slope investigation.

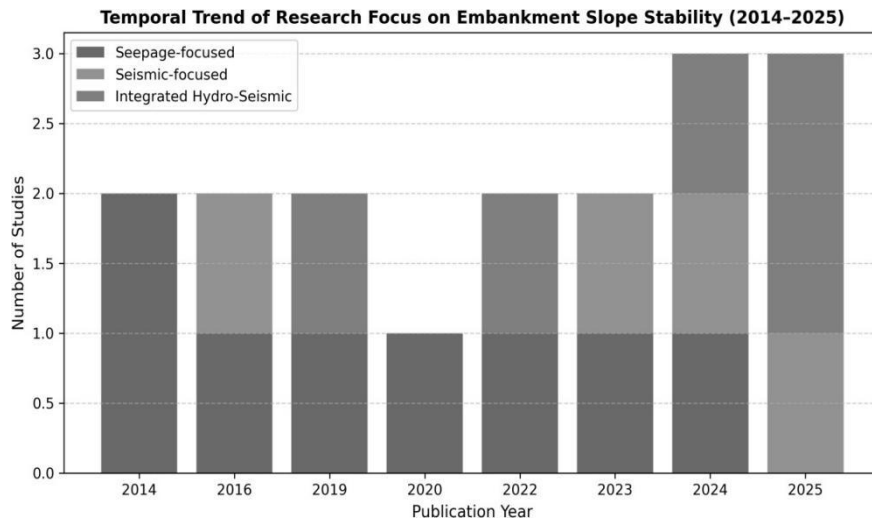


Figure 7: Research trend in embankment slope stability (2014–2025)

5 DISCUSSION

Embankment slope failure is a complicated process that depends on seepage, soil characteristics, and seismic loading that complicates the prediction of failures. Most of the existing literature which incorporates seepage and seismic effects separately, is even though slope stability analysis has been enhanced by the use of numerical techniques like the Finite Element Method (FEM) and Limit Equilibrium Method (LEM). Intense rainfall or quick drawdown seepage plays a major role in decreasing slope stability, whereas seismic loading also contributes to the risk of failure, especially in saturated soils.

The comparative findings of this review indicate that the stability of embankments is more adversely influenced when combined seepage and seismic loading take place and result in significantly more factor of safety degradation than when loading is done in isolation. Although recent three-dimensional models have tried to include both effects, there are yet to be a fully coupled hydro-seismic numerical analysis. Thus, it is evident that this paper indicates the necessity of combined numerical models that simultaneously simulate seepage movement and soil mechanics and seismic waves to enhance the prediction of failures and assist in designing embankments sustainably.

6 CONCLUSION

The paper has emphasized the usefulness of numerical modeling as an efficient instrument of determining the stability of embankment slopes during seepage and seismic loads.

- The comparative outcomes have shown that, under combined hydro-seismic loading, the seepage and earthquake effects have a major effect in decreasing the stability of embankment, with the most severe decrease being at the base of the embankment.
- The results indicate that when the problem of seepage and seismic effects is studied in isolation, the traditional numeric analysis could be misleading about the potential risk of embankment failure.

- Key gaps in research identified in the review are the fact that few fully coupled hydro-seismic models have been used, that the unsaturated soil behavior has not been fully considered, and that there is lack of three-dimensional analysis as well as simplified seismic inputs.
- The main contribution of this work is the realization that complete and intricate hydro-seismic numerical models are required that can concurrently consider the seepage movement, soil behavior, as well as seismic excitation.
- Further studies ought to be focused on the enhancement of more sophisticated three-dimensional coupled numerical models to help in safer, more resilient and sustainable embankment modeling under climate change and earthquake risks.

7 DECLARATION OF USE OF AI

AI tools were used to extract key data and points from 20 research papers for the comparison table. This technology assisted in the identification of certain parameters in the literature to save time. In total, AI was helpful in the preparation of the manuscripts. All the results were checked and verified and thus made sure that they were accurate.

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