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Recent Advances in Stability and Seepage Analysis of Earth Dams: A Review Leveraging Numerical Methods and Computational Intelligence

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Abstract

Ensuring the safety and long-term performance of earth dams is paramount due to their critical role in water management and the potential consequences of failure. Dams are susceptible to stability issues and internal erosion driven by complex hydraulic conditions, including seepage and fluctuating water levels. Traditional analytical methods often fall short in capturing the full complexity of these interactions and optimizing mitigation measures. This review fills a notable gap in the existing literature by holistically integrating numerical modeling (FEM, Limit Equilibrium) and artificial intelligence (ANN, GA) techniques to provide a comprehensive assessment of earth dam behavior. This review synthesizes recent research applying advanced computational techniques, including numerical methods like the Finite Element Method (FEM) and Limit Equilibrium methods, alongside computational intelligence approaches such as Artificial Neural Networks (ANN) and Genetic Algorithms (GA), to analyze the stability and seepage characteristics of earth dams and evaluate the effectiveness of seepage control measures. Drawing insights from several recent studies, this article examines the influence of rapid drawdown on dam slope stability, the impact of fissured soil orientation, and critically, the effectiveness of various seepage control measures (cutoff walls, horizontal drains, pipe drains, injections) and their optimal configurations, including combined approaches. It highlights the capabilities of numerical modeling for detailed analysis and optimization and the potential of AI and hybrid methods for improved prediction and parameter identification in complex, nonlinear scenarios. The findings underscore the importance of integrating diverse computational tools for robust design, risk assessment, and monitoring of earth dams.

Keywords: Earth dams; Stability assessment; Seepage mitigation; Finite Element Method; Neural networks; Genetic algorithms.

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1. Introduction

Earth dams are essential components of modern infrastructure, serving vital functions such as water supply, hydropower generation, and irrigation. However, their performance and stability are subject to complex interactions between soil mechanics and hydraulic conditions. Challenges such as internal erosion, piping, rapid water level changes (rapid drawdown), and the presence of heterogeneous or fissured materials pose significant risks to their structural integrity. Water seepage through the dam body and foundation is a primary concern, contributing to over 35% of earth dam accidents [6].

Historically, the analysis of dam stability and seepage relied primarily on simplified analytical or limit equilibrium methods [12]. While foundational, these approaches often fall short in capturing the nuanced, nonlinear behavior of geomaterials and the intricate geometries of dams and their foundations. The advent of high-performance computing has paved the way for sophisticated numerical methods, particularly the Finite Element Method (FEM) and various Limit Equilibrium techniques, which offer powerful tools for detailed simulation of stress-strain behavior, fluid flow, and potential failure mechanisms [1, 3, 4, 5, 7, 8, 12]. Software like GeoSlope (SEEP/W, SLOPE/W) and OptumG2 have become indispensable in this domain, enabling engineers to model complex scenarios and analyze critical parameters like factor of safety, displacement fields, and pore water pressures [1, 3, 7, 8]. More recently, computational intelligence techniques, notably Artificial Neural Networks (ANN) and Genetic Algorithms (GA), are emerging as valuable complements to traditional numerical methods. These data-driven approaches excel at identifying complex, often nonlinear, relationships within large datasets and show promise in areas like parameter estimation, prediction, and optimization, which can enhance the capabilities of physics-based models [5]. Despite the increasing application of numerical and AI methods in geotechnical research, there is a clear lack of comprehensive reviews that synthesize both perspectives in the context of dam seepage and stability assessment. This article aims to bridge this gap by critically examining and comparing recent work that leverages these complementary approaches. This review article consolidates findings from recent studies that leverage these advanced computational tools to address critical problems in the analysis of earth dams. By synthesizing insights from the provided set of research papers, it aims to highlight the current state of practice, identify key findings regarding dam behavior under challenging conditions, and underscore the synergistic potential of combining numerical modeling with computational intelligence for optimizing seepage control and enhancing stability.

2. Dam Stability and Seepage Analysis

Earth dams, as critical water impoundment structures, are particularly susceptible to stability issues driven by internal seepage and fluctuating water levels. Ensuring their stability requires thorough analysis under various operational scenarios.

2.1 Impact of Rapid Drawdown

Rapid drawdown of water from the reservoir is a particularly challenging condition for the upstream slope stability of earth dams. This phenomenon leads to a rapid reduction in the stabilizing external hydrostatic pressure on the upstream face, while the pore water pressure within the saturated embankment fill dissipates much more slowly due to limited permeability. This imbalance significantly reduces the effective stresses and, consequently, the shear strength of the soil, potentially leading to slope failure [1, 10].

Numerical studies, such as the case study of the Sidi Abdelli dam using Geo-SLOPE/W [1], and other FEM analyses [10, 11], confirm that the factor of safety (FS) of the upstream slope decreases significantly with the initiation of rapid drawdown. Berilgen (2007) highlighted that the rate of pore water fall has a significant impact on stability during drawdown, influencing the magnitude of displacement [9]. The analysis shows that pore water pressures near the toe of the dam are high before drawdown, decrease as elevation rises, and become very low at the toe after rapid drawdown initiates, only to increase as dissipation begins before decreasing again with elevation . Velocity vectors of seepage reverse direction during rapid drawdown, exiting from the upstream side, indicating a potential seepage face on the upstream slope . The Factor of Safety drops below 1.0 in the initial days of rapid drawdown, signifying an unsafe condition, but gradually increases above 1.0 after a certain period (e.g., 13 days in the Sidi Abdelli case), as pore water pressure dissipates and effective stresses recover [1]. This highlights the transient nature of the stability issue during rapid drawdown and the importance of considering the rate of pore pressure dissipation [1, 11].

2.2 Stability in Fissured Materials

The presence of fissures in dam foundation or embankment materials introduces planes of weakness that can significantly influence stability and seepage patterns. Unlike intact soil, fissured soil behavior depends not only on the inherent soil properties but also on the orientation, spacing, and properties of the fissures themselves [4]. Research by Davis (1980) and Zheng et al. (2000) has established failure criteria for fissured soil, providing a foundation for understanding their behavior [13, 14].

Numerical investigations using FEM software like OptumG2, which incorporate failure criteria accounting for fissured planes with varying orientations, demonstrate the substantial impact of fissure angles on dam stability. Studies analyzing different orientations (using angles α1 and α2, and their coupled effects) reveal that the factor of safety and resulting slope displacements vary significantly depending on the fissure angles . While intact soil exhibits a certain baseline FoS, the presence of fissures generally leads to lower FoS values. The critical failure surface location and type (circular, infinite, or plane slides) are also dictated by the fissure orientation. Notably, findings suggest that dams built on or with fissured materials where fissures are oriented closer to the vertical tend to exhibit higher stability compared to those with fissures oriented closer to the horizontal. Displacement patterns and magnitudes are also strongly influenced by fissure orientation, with maximum displacements often observed near the core and varying significantly with coupled fissure angles [4]. This underscores the necessity of detailed site investigation and analysis considering the specific characteristics and orientation of fissured planes in dam design and stability assessment.

2.3 Seepage Control Measures in Dams

Controlling seepage through the dam body and foundation is crucial for preventing internal erosion, reducing uplift pressures, and maintaining overall stability. Common measures include cutoff walls and drainage systems (horizontal drains, pipe drains, injection curtains) [3, 6, 7, 8]. Numerical modeling is extensively used to optimize the design parameters of these measures.

Studies on injection curtains and horizontal drains highlight the influence of various parameters on seepage characteristics like uplift pressure, discharge seepage, and exit gradient [3, 6]. For injection curtains, depth, permeability, position, inclination, number, and spacing are key factors [6]. Analysis shows that cutoff wall depth significantly impacts seepage, with maximum efficiency in reducing exit gradient and discharge seepage achieved when the penetration depth exceeds 75% of the foundation depth, especially with low permeability . Permeability of the cutoff wall is paramount; lower permeability dramatically reduces flow and changes seepage paths. Optimal configurations involving cutoff walls and horizontal drains are sought to minimize uplift pressure and exit gradient, parameters critical for preventing piping and ensuring stability [3].

A comparative analysis of horizontal and pipe drains reveals differences in their effectiveness. Numerical simulations show that pipe drains generally outperform horizontal drains in managing seepage and enhancing stability. Pipe drains, particularly those with larger diameters, lead to a more significant reduction in pore pressure compared to horizontal drains. Optimal placement of these drains is critical; studies indicate that for pipe drains, locations within a specific relative distance ($X/B=0.2$ to 0.4, where X is distance from toe and B is dam base width) from the dam toe result in maximum safety factors . While horizontal drains also contribute to seepage control, their impact on pore pressure reduction and overall stability appears less pronounced than that of optimally placed pipe drains. Analyzing statistical error metrics (RMS, MAE, MSE) confirms that pipe drains provide more consistent predictions of discharge seepage and exit gradient compared to horizontal drains, indicating better control over erosion risk [7].

Further investigation into combined countermeasures is crucial for comprehensive seepage control. A case study on the Krerish Dam in Algeria, utilizing SEEP/W, examined the combined effects of cutoff wall depth and position, and horizontal drain length on seepage characteristics including discharge seepage, exit gradient, and uplift pressure [8]. The study provides valuable quantitative insights into the performance of different combined configurations, as summarized in Table 1.

Table 1. Summary of Performance Improvements for Key Combined Seepage Control Configurations Adapted from Krerish Dam Study [8].

Configuration	Reduction in Discharge Seepage (%)	Reduction in Exit Gradient (%)	Reduction in Uplift Pressure (%)
Cutoff Wall Depth 1.0H (vs 0.5H)	35	28	*Decreases with depth*
Cutoff Wall Central Position (vs Downstream)	*Lower Q, i central vs downstream*	*Lower Q, i central vs downstream*	22 (Central lower)
Horizontal Drain Length 0.3X (vs 0.1X)	15	*Decreases with length.*	40
Optimal Combined: CW 1.0H Central + HD 0.3X	45	38	50

As shown in Table 1, increasing cutoff wall depth from 0.5H to 1.0H significantly decreased discharge seepage (by 35%) and outlet gradient (by 28%). The position of the cutoff wall also mattered; a central placement within the dam base was more effective than a downstream placement, reducing uplift pressure by 22% compared to the downstream position [8]. Horizontal drain length also played a critical role; increasing the length from 0.1X to 0.3X (where X is the dam width) led to a 40% reduction in uplift pressure and a 15% reduction in discharge seepage. The most effective configuration identified was a combination of a centrally located cutoff wall at a depth of 1.0H and a horizontal drain with a length of 0.3X. This optimal setup achieved substantial overall reductions: a 45% decrease in discharge seepage, a 38% decrease in exit gradient, and a 50% decrease in uplift pressure. Error analysis of different configurations using RMS, MAE, and MSE metrics further highlighted the importance of incorporating cutoff wall depth, particularly when combined with horizontal drains, for achieving more accurate predictions and better seepage control [8].

3. Integration of Advanced Computational Techniques

Beyond traditional numerical methods, the integration of computational intelligence techniques offers promising avenues for enhancing geotechnical analysis, particularly in dealing with data-driven prediction and complex nonlinear systems.

Artificial intelligence methods, such as Back Propagation Neural Networks (BPNN) and hybrid approaches combining BPNN with Genetic Algorithms (GA), are being explored for tasks like predicting piezometric levels in earth dams. These models learn complex, nonlinear relationships directly from monitoring data, complementing physics-based FEM models that rely on defined material properties and boundary conditions. A hybrid BPNN-GA model leverages GA for optimizing the initial weights and thresholds of the BPNN, potentially improving its training efficiency and predictive performance. Comparison studies evaluating these AI models against FEM and actual monitoring data show that AI models, especially standard BPNN in one studied case, can achieve a more precise alignment with observed piezometric level variations compared to FEM, which relies on idealized conditions. While FEM provides a useful reference based on theoretical assumptions, AI models demonstrate strong potential for predicting real-world behavior influenced by unmodeled environmental factors. The use of performance metrics like MSE, MAE, and MAPE quantifies the predictive accuracy and allows for comparison between different models, highlighting the benefits of AI in handling nonlinearity and learning from historical data [5].

Table 2. Comparison of Prediction Model Performance based on Error Metrics (Adapted from AI Prediction Study [5] for Piezometer P06)

Prediction Model	MSE	MAE	MAPE (%)
BPNN	0.0214	0.0164	4.03
BPNN-GA	0.0676	0.0590	14.63

As shown in Table 2, comparison studies evaluating these AI models against FEM and actual monitoring data show that AI models, especially standard BPNN in this case, can achieve a more precise alignment with observed piezometric level variations compared to FEM, which relies on idealized conditions. While FEM provides a useful reference based on theoretical assumptions, AI models demonstrate strong potential for predicting real-world behavior influenced by unmodeled environmental factors. The use of performance metrics like MSE, MAE, and MAPE quantifies the predictive accuracy and allows for comparison between different models, highlighting the benefits of AI in handling nonlinearity and learning from historical data. The lower error metrics for BPNN compared to BPNN-GA for this specific piezometer indicate its superior predictive accuracy in this context [5].

4. Discussion

The reviewed studies collectively demonstrate the significant advancements in geotechnical analysis of earth dams driven by the integration of numerical methods and computational intelligence. Numerical tools like FEM and Limit Equilibrium methods [2] provide the fundamental framework for simulating complex geotechnical processes (stress-strain, fluid flow, stability analysis, failure mechanisms) under various boundary conditions and material properties. This is evident in analyses of rapid drawdown [3,9,10, 11], fissured soil [6,12,13], and various seepage control designs [4,1,7,8]. These methods allow for detailed visualization of critical phenomena such as changing pore pressure fields, evolution of safety factors, formation of slip surfaces, and spatial distribution of displacements and internal forces.

The challenges posed by complex material behavior (fissured soil), transient conditions (rapid drawdown), and the need for optimizing mitigation measures highlight the need for sophisticated modeling capabilities. Parametrized numerical studies, such as the detailed analysis of combined cutoff walls and horizontal drains at the Krerish Dam [8], are invaluable for optimizing design choices, revealing optimal depths, solubilities, types (pipe vs. horizontal), positions, and lengths [4,1, 7, 8]. The Krerish Dam study specifically highlights the significant benefits of combining measures and optimizing their configuration for substantial reductions in discharge seepage, exit gradient, and uplift pressure [8], as quantitatively summarized in Table 1.

Furthermore, the integration of AI and hybrid techniques represents a promising avenue for enhancing geotechnical analysis, particularly in dealing with data-driven prediction and complex nonlinear systems [5]. As shown in the case of piezometric level prediction [5], and summarized by error metrics in Table 2, data-driven models can complement or even outperform traditional physics-based models in capturing real-world variability and nonlinearities, especially when validated against comprehensive monitoring data. AI offers potential for enhanced prediction, parameter identification (inverse problems), and optimization of design parameters.

Future research directions could involve more tightly coupled multi-physics simulations (e.g., integrating seepage, mechanical deformation, and thermal effects), developing more sophisticated constitutive models that explicitly account for complex features like anisotropy and evolving fissure networks, and further leveraging AI for real-time monitoring data interpretation, anomaly detection, and predictive maintenance of earth dams. Validating these advanced models with extensive field data remains crucial for ensuring their reliability and practical applicability.

5. Conclusion

This review, based on a set of recent research articles, illustrates the state-of-the-art in applying computational techniques to analyze the stability and seepage of earth dams. Numerical methods like FEM and Limit Equilibrium are established tools providing fundamental insights into structural behavior under challenging conditions such as rapid drawdown and the presence of fissured materials. Parametric numerical studies are essential for optimizing seepage control measures like cutoff walls and drainage systems, with findings highlighting the critical influence of design parameters like depth, permeability, drain type, location, and diameter on effectiveness and overall stability.

Specifically, detailed studies on the Krerish Dam demonstrate the significant benefits of combined countermeasures. Optimizing the depth and position of cutoff walls and the length of horizontal drains can achieve substantial reductions in discharge seepage, exit gradient, and uplift pressure, crucial for preventing internal erosion and maintaining stability. The analysis of error metrics further underscores the importance of integrating cutoff wall depth into seepage control designs for increased prediction accuracy and effectiveness. The review also highlights the growing capacity of engineers to leverage AI and hybrid techniques for predicting complex geotechnical variables like piezometric levels, offering improved accuracy and robustness compared to traditional methods in specific scenarios. Collectively, these papers underscore the importance of integrating and developing sophisticated computational tools for robust analysis, optimization, and prediction in the design and monitoring of earth dams. Continued validation with field data is key to ensuring the safety, reliability, and resilience of these critical structures.

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