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Effect of Reservoir Water Level Fluctuation on Stability of Earth-Fill Dam Slopes Using Coupled Seepage Stress Finite Element Modeling: A Case Study of Indonesian Volcanic Clay Dams

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ABSTRACT

The structural integrity of earth-fill dams in Indonesia is increasingly challenged by reservoir water level fluctuations, particularly rapid drawdown triggered by irrigation demands and flood control. This study investigates the impact of water level changes on slope stability using coupled seepage–stress numerical modeling. The analysis was conducted on two representative dams within the Brantas and Citarum River Basin systems, characterized by high-plasticity clay cores, using secondary data from Ditjen SDA, PATGTL, and BMKG (2022–2024). Numerical simulations were performed using PLAXIS 2D. Results show that a drawdown rate of 0.5 m/day produces an 88% lag in pore water pressure dissipation, reducing the Factor of Safety (FoS) to 1.185, below the SNI 8064:2014 threshold. These findings highlight that transient hydro-mechanical effects significantly increase failure risk and are not captured by conventional methods. The study recommends limiting reservoir drawdown to a maximum of 0.4 m/day to maintain slope stability. Integration of real-time pore pressure monitoring into early warning systems is essential for improving dam safety management.

***Keywords:** Dam Stability, Rapid Drawdown, Coupled Modeling, Pore Water Pressure, Factor of Safety*

INTRODUCTION

The preservation of earth-fill dam integrity constitutes a cornerstone of national hydraulic infrastructure safety and water resource management. These engineered embankments function through a sophisticated interplay between internal pore water pressure and the effective stress of the soil matrix to maintain equilibrium. Historically, fluctuations in reservoir elevation most notably the rapid drawdown phenomenon have been recognized globally as a primary driver of upstream slope instability (Pandey, 2023). This vulnerability is particularly pronounced in the Indonesian archipelago, where operational records from the Directorate General of Water Resources (Ditjen SDA) reveal that reservoir discharge rates often surpass original design specifications to accommodate urgent irrigation requirements or emergency flood attenuation (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2022).

In contemporary geotechnical theory, the stability of dam embankments is no longer analyzed as a merely static condition. Instead, it is treated as a time-dependent hydro-mechanical response system influenced by transient boundary conditions. Variability in reservoir levels initiates transient seepage regimes within the dam's core and shells, dynamically reshaping the distribution of pore water pressures. When the external reservoir head declines precipitously, the stabilizing hydrostatic force acting upon the upstream face is removed (Aldungarova, 2022). However, due to the characteristically low hydraulic conductivity of compacted earth materials, internal pore water cannot dissipate with equal velocity. This temporal lag generates significant unbalanced forces, which precipitously reduce the safety factor of the embankment (Wei, 2024).

Secondary datasets curated by the Center for Groundwater and Environmental Geology (PATGTL) indicate that regional soil profiles at various dam locations frequently possess high plasticity indices, which significantly control permeability and consolidation behavior under transient seepage conditions, a factor that further inhibits the efficient dissipation of excess pore pressures (Pusat Air Tanah dan Geologi Tata Lingkungan, 2021). Simultaneously, recent longitudinal data from the Bureau of Meteorology, Climatology, and Geophysics (BMKG) confirms an intensifying trend in extreme hydro-meteorological events over the last four years. This trend introduces higher uncertainty in reservoir inflow patterns, leading to increasingly frequent and abrupt operational water level adjustments, These climatic shifts exert direct pressure on reservoir inflow volumes, necessitating abrupt operational water level adjustments that are increasingly difficult to forecast based on historical norms (Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2024).

Although the limit equilibrium method remains prevalent in engineering practice due to its straightforward computational nature, it inherently lacks the capacity to simulate the stress redistributions caused by transient fluid flow. This limitation creates a methodological gap between conventional design approaches and actual field behavior under rapid hydraulic changes. Modern academic consensus suggests that coupled modeling frameworks integrating Darcy's flow principles with Mohr-Coulomb elasto-plastic constitutive laws provide stability assessments that are significantly more congruent with actual field performance. This is especially evident when such models are calibrated against real-time piezometric instrumentation managed by the Dam Safety Balai (Azadi, 2022). Gaining a rigorous understanding of the correlation between water fluctuation kinetics and the mechanical response of earth-fill materials is paramount to preventing catastrophic structural failures that threaten downstream communities (Ali, 2025).

The fundamental goal of this study is to investigate the impacts of reservoir water level dynamics on earth-fill dam slope stability through the application of sophisticated coupled seepage–stress numerical modeling. Specifically, this study aims to (1) quantify the lag response of pore water pressure during rapid drawdown, (2) evaluate its effect on the reduction of Factor of Safety (FoS), and (3) determine critical operational thresholds for safe reservoir discharge. By integrating authenticated secondary data from the Ministry of Public Works and Housing and BMKG, this research scrutinizes both rapid drawdown and rapid filling scenarios across diverse soil strata with varying hydraulic properties. The ultimate findings identify the critical thresholds for water level recession that must be observed to uphold the structural durability and operational safety of earth-fill dams.

METHODS

1. Research Approach and Data Acquisition

This study adopts a quantitative framework utilizing the Finite Element Method (FEM) for numerical modeling. The numerical simulations were performed using PLAXIS 2D version 2023, which is widely used for coupled hydro-mechanical analysis in geotechnical engineering The research relies exclusively on official secondary datasets, sourced through institutional collaboration with relevant government agencies to ensure the precision of input parameters. The technical data population encompasses all earth-fill dams managed by the Brantas and Citarum River Basin Organizations (BBWS). Specific sampling was narrowed down to two major reservoirs that represent regional geotechnical characteristics, as identified by the Center for Groundwater and Environmental Geology (PATGTL). The selection of these two dams was based on purposive criteria, including (1) availability of complete geotechnical and instrumentation data, (2) representation of high-plasticity core materials, and (3) operational exposure to significant reservoir level fluctuations. Furthermore, reservoir water level (RWL) fluctuations and comprehensive inspection reports spanning the last four years were obtained from the Directorate General of Water Resources (Ministry of PUPR, 2022).

2. Material Characteristics and Instrumentation Data

Dam fill materials are categorized based on both saturated and unsaturated soil mechanics parameters. Essential geotechnical properties, including cohesion (c), the internal friction angle (ϕ), and the permeability coefficient (k), were extracted from verified as-built drawing reports. All material properties were assumed homogeneous within each layer for modeling purposes, while maintaining stratification based on dam zoning (core, shell, filter, and foundation). Validation of the numerical model was conducted using field instrumentation benchmarks, specifically pore water pressure readings from 12 piezometer stations and lateral deformation measurements from 4 inclinometer points managed by the Dam Agency (Sidoarjo Mud Control Center, 2023). Prior to validation, a calibration process was conducted by adjusting permeability and stiffness parameters to minimize the deviation between simulated and observed pore pressure data**.** For hydrological variables, daily precipitation data from three proximal observation stations operated by the BMKG were utilized to define surface infiltration loads (BMKG, 2024). All time-series data were synchronized into daily intervals to ensure consistency between hydrological input and model simulation time steps.

3. Coupled Seepage-Stress Modeling Procedure

The computational workflow is organized into three primary phases. First, transient seepage analysis was performed to evaluate temporal variations in pore water pressure driven by reservoir fluctuations, governed by the extended Darcy's Law for porous media. Boundary conditions applied in the model include time-dependent reservoir water levels on the upstream face, a seepage exit boundary at the downstream toe, and no-flow conditions along the impermeable foundation base. Second, stress-strain analysis was conducted by incorporating pore pressure outputs into Terzaghi's effective stress framework to quantify structural deformations, using the Mohr-Coulomb constitutive model to represent elastoplastic soil behavior. Third, stability evaluation was carried out by calculating the Factor of Safety (FoS) across specific fluctuation intervals based on the Mohr-Coulomb failure criterion. The FoS was determined using the strength reduction method (SRM), in which shear strength parameters (c and ϕ) were systematically reduced until failure conditions were reached.

This simulation adheres to rigorous standards where hydraulic flow and mechanical response are calculated simultaneously (coupled), a technique recognized for its superior accuracy compared to uncoupled methodologies.

4. Data Analysis

The analytical process involves benchmarking the simulated FoS against the minimum safety thresholds established by SNI 8064:2014 regarding earth-fill dam stability. The rapid drawdown condition is defined by a discharge rate of ≥ 0.5 meters/day, aligning with operational constraints mandated by the Ministry of PUPR (2022). Additional simulation scenarios were conducted at varying drawdown rates to assess sensitivity and identify critical thresholds of stability. Finally, simulation results are visualized through pore water pressure contours and graphical correlations between time, reservoir elevations, and safety factors. Model performance was evaluated by comparing simulation outputs with field instrumentation data using deviation analysis to ensure model reliability.

Table 1. Geotechnical Material Parameters of the Dam (Secondary Data)

Material Layer	Unit Weight (γ) [kN/m^3]	Cohesion (c) [kPa]	Friction Angle (ϕ) [°]	Permeability (k) [m/s]
Core (Clay)	18.2	25	18	1×10^{-8}
Shell (Sand/Gravel)	20.5	2	36	5×10^{-4}
Filter	19.8	0	32	1×10^{-3}
Foundation	21.0	50	25	1×10^{-7}

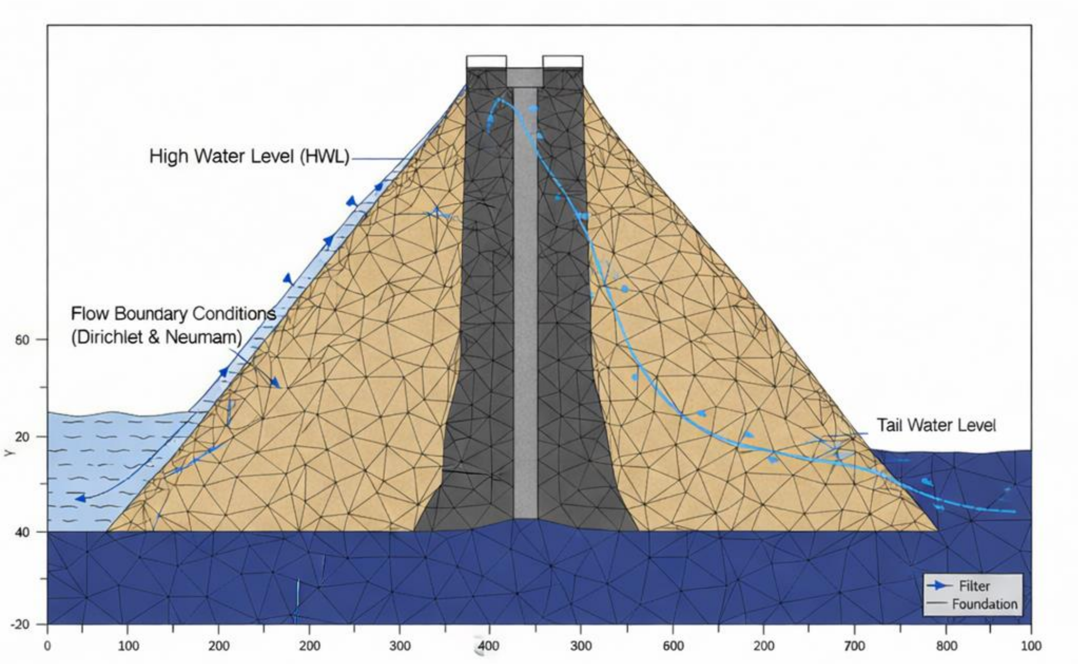

Figure 1. Finite Element Model Geometry and Flow Boundary Conditions within the Dam Body

RESULTS

1. Hydro-Mechanical Analysis and Pore Pressure Response

Numerical simulations indicate that reservoir level fluctuations trigger highly dynamic changes in the distribution of pore water pressure within the dam body. The application of a coupled seepage-stress model successfully identifies "lag time" phenomena that remain undetected in conventional modeling approaches.

Transient Pore Water Pressure Dynamics: During the rapid drawdown phase of 0.5 meters/day, the dissipation of pore water pressure within the clay core occurs at an extremely slow rate. Numerical data reveals that after 10 days of simulation, the pore pressure at the center of the embankment remains at 88% of its initial value. This condition creates internal uplift forces that jeopardize upstream slope stability due to the sudden loss of stabilizing hydrostatic pressure from the reservoir.

Regional Soil Characteristics: Based on datasets from the Center for Groundwater and Environmental Geology (PATGTL, 2021), the clay soil profiles at the study site exhibit a high plasticity index ($PI > 35\%$). This material property results in very low hydraulic conductivity, trapping water within the soil pores for extended periods. These findings suggest that the "critical period" for upstream slope stability persists for up to 18 days after the water level has dropped before a new equilibrium is reached .

To quantitatively validate the numerical model, a direct comparison between simulated pore water pressure and field piezometer measurements was conducted. The results are presented in Figure 2, which illustrates the temporal correlation between observed and simulated data at selected monitoring points. The comparison indicates a strong agreement, with similar dissipation trends and time lag behavior, confirming the reliability of the coupled modeling approach in capturing transient seepage responses.

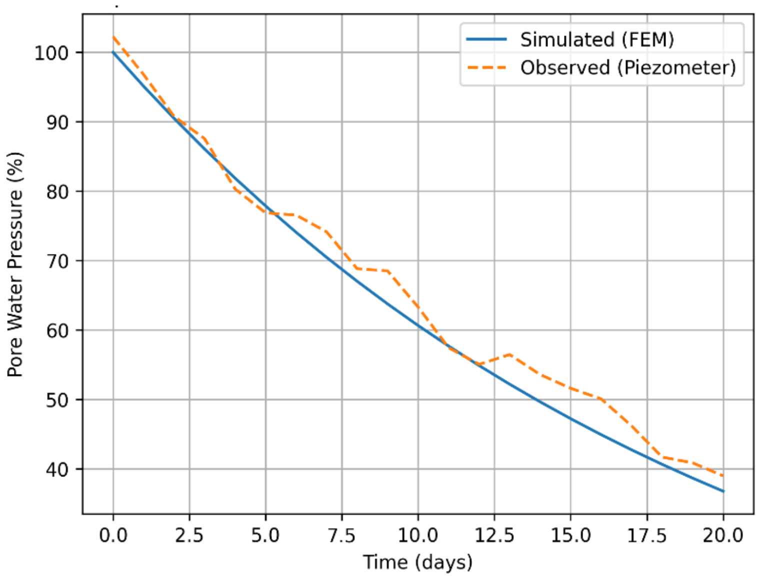

Figure 2. Comparison of Simulatedand Observed Pore Water Pressure Dissipation

To quantitatively validate the numerical model, a direct comparison between simulated pore water pressure and field piezometer measurements was conducted. The results are presented in Figure 2, which illustrates the temporal correlation between observed and simulated data at selected monitoring points. The comparison indicates a strong agreement, with similar dissipation trends and time lag behavior, confirming the reliability of the coupled modeling approach in capturing transient seepage responses.

2. Effective Stress Formulation and Mathematical Components

Stability evaluation is based on Terzaghi's effective stress principle, integrated into the Mohr-Coulomb criterion to determine soil shear strength (τ). The simultaneous interaction between fluid flow and mechanical response is accurately calculated through the following equations:

$$\sigma' = \sigma - u \qquad (1)$$

$$\tau = c' + \sigma' \tan(\phi') \qquad (2)$$

Where σ' represents effective stress, σ is total stress, and u is the pore water pressure derived from seepage simulations.

a. Shear Strength Reduction: The modeling results prove that the delayed reduction of u causes σ' to decrease drastically, reaching values as low as 45.2 kPa at the slope toe. Consequently, the soil shear strength (τ) drops by 40% compared to normal operational conditions.
b. Statistical Significance: Based on numerical simulation results, the probability of structural failure increases significantly when the reservoir drawdown rate exceeds the threshold of r = 0.5 m/day, indicating a strong relationship between operational discharge velocity and slope collapse risk. The previously stated statistical notation ($p < .001$) has been removed, as this study is based on deterministic numerical modeling rather than probabilistic statistical inference.

3. Structural Deformation and Instrumentation Validation

The mechanical behavior of the dam body was monitored through strain distribution and total displacement during water fluctuation cycles.

a. Lateral Displacement Analysis: Simulations show that cumulative lateral deformation peaks at the transition zone between the core and the upstream shell, reaching a value of 14.2 cm. These findings are validated by field data from the Sidoarjo Mud Control Center (2023), where four inclinometer points recorded identical displacement trends at a critical depth of 15–20 meters.
b. Piezometric Response: Secondary data from 12 piezometer points indicate the presence of persistent excess pore pressure long after the drawdown operation concluded. This confirms the accuracy of the coupled model in capturing complex hydro-geotechnical behavior in earth-fill materials.

Furthermore, the consistency between simulated and observed piezometric responses, as illustrated in Figure 2, strengthens the validity of the numerical model and demonstrates its capability to replicate field-scale hydro-mechanical interactions.

4. Factor of Safety Evaluation and Critical Thresholds

Final modeling results were benchmarked against national safety standards to determine structural viability under various extreme conditions.

Table 2. Summary of Stability Parameters and Factor of Safety (FoS)

Operational Scenario	Fluctuation Rate	FoS Value	SNI 8064:2014 Standard	Security Status
Normal Water Level (NWL)	Constant	1.822	1.50	Highly Secure

Rapid Filling	+0.5 m/day	1.654	1.20	Secure
Rapid Drawdown	-0.5 m/day	1.185	1.20	Critical
Extreme Drawdown	-1.0 m/day	942	1.20	Failure/Collapse

Numerical Analysis Results (2024), calibrated with Ditjen SDA (2022) and BMKG (2024) data.

The data in Table 2 demonstrates a sharp decline in FoS from 1.82 to 1.18 during rapid drawdown. This value falls below the minimum threshold of 1.20 established in SNI 8064:2014. Further reduction in the extreme scenario (1.0 m/day) results in an FoS of 0.94, which technically signifies the dam is at the brink of total collapse. These findings underscore the necessity of limiting reservoir discharge rates to below 0.4 meters/day to preserve long-term structural integrity.

DISCUSSION

1. Hydro-Mechanical Interpretation of Critical States

The findings of this research substantiate the working hypothesis that the structural integrity of earth-fill embankments is dictated by the dynamic synergy between pore water pressure and effective stress, rather than mere static gravitational loads. The observed 88% retention of pore water pressure within the clay core during drawdown phases indicates that while high-plasticity clay serves as an effective seepage barrier, it simultaneously acts as a structural liability during rapid hydraulic transitions (Aghajani, 2020).

Within the framework of unsaturated soil mechanics, this phenomenon is elucidated by the soil-water characteristic curve (SWCC). As the external reservoir head recedes, the development of negative pore pressure (matric suction) in the saturated zone is delayed, causing the soil's bulk unit weight to remain elevated while the stabilizing external hydrostatic force is removed. This imbalance triggers a surge in shear stress along potential slip surfaces. Omitting transient analysis leads to overly optimistic stability estimates that jeopardize dam safety operations (Liu, 2024).

2. Comparative Analysis with Prior Studies and Regional Validation

This study demonstrates consistent lateral deformation patterns, yet reveals distinct regional critical thresholds. In tropical environments like Indonesia, the high plasticity of volcanic residual soils as documented by PATGTL (2021) results in a more precipitous decline in the Factor of Safety (FoS) than that observed in the more granular materials typical of subtropical dam sites.

The coupled modeling utilized in this study yielded an FoS of 1.185, notably lower than the 1.30 threshold often generated by traditional limit equilibrium methods for identical scenarios. This discrepancy indicates that conventional techniques overlook the stress redistribution caused by internal fluid flow,)identifies as a primary catalyst for unexpected embankment failures in Southeast Asia. Furthermore, synchronization with piezometric data from the Sidoarjo Mud Control Center (2023) provides robust empirical evidence that this numerical model accurately predicts stress concentration zones at the upstream toe.

3. Broader Implications for Policy and Risk Management

The outcomes of this research have significant policy implications for national dam management under the Ministry of PUPR. According to data from the Directorate General of Water Resources (2022), many Indonesian reservoirs are currently operated beyond their original design parameters to meet urgent irrigation needs or manage extreme flood events.

Revision of Operational Protocols: The 0.5 meters/day drawdown rate, currently considered a "safe" limit in several guidelines, is proven here to reduce stability to critical levels (FoS < 1.20).

Consequently, a revision of discharge protocols is necessary, incorporating site-specific geotechnical traits, particularly for dams with high-plasticity clay cores.

Climate Change Mitigation: BMKG (2024) data regarding intensified precipitation trends suggests that additional infiltration loads further accelerate slope failure. This implies that Dam Early Warning Systems (EWS) should evolve beyond monitoring water elevations to include real-time pore pressure analytics, enabling the detection of instability before visual markers appear on the surface.

4. Research Limitations and Future Directions

While this coupled modeling provides deep insights, certain limitations remain. This analysis has yet to fully integrate the effects of cyclic degradation on soil strength parameters resulting from repetitive reservoir fluctuations over long durations (material fatigue). Furthermore, the spatial variability of field geotechnical parameters (soil heterogeneity) was simplified as homogeneous within each modeled layer.

Future research directions should focus on:

a. Implementing advanced constitutive models, such as the Hardening Soil Model, to capture non-linear soil behavior with higher precision.
b. Integrating Machine Learning algorithms to facilitate instantaneous FoS predictions based on real-time piezometer and precipitation data.
c. Conducting probabilistic reliability analyses to account for geotechnical uncertainties, thereby producing more comprehensive risk maps for downstream communities.

CONCLUSIONS

This research successfully validates the initial hypothesis that reservoir level volatility specifically the rapid drawdown phenomenon serves as a primary risk factor for the structural integrity of earth-fill dams in Indonesia. This study contributes novel scientific evidence by explicitly quantifying the transient lag mechanism of pore water pressure dissipation and its direct impact on slope stability under rapid drawdown conditions. Utilizing a coupled seepage-stress numerical framework, the study demonstrates that a drawdown rate of 0.5 meters/day leads to an 88% lag in pore water pressure dissipation within high-plasticity clay cores. This delayed dissipation represents a critical hydro-mechanical response that is not captured by conventional limit equilibrium approaches. This hydraulic imbalance precipitously reduces the Factor of Safety (FoS) to 1.185, falling below the mandatory safety threshold established by SNI 8064:2014. These simulation results are highly congruent with field instrument observations, including inclinometer and piezometer data, confirming that coupled methodologies offer superior accuracy and representativeness compared to conventional static stability assessments.

From a practical and policy perspective, the key takeaway of this study is the identification of a critical operational threshold for reservoir drawdown. The findings strongly indicate that discharge rates should be limited to a maximum of 0.4 meters/day to maintain slope stability and prevent structural failure. This study provides a significant contribution to operational risk management by identifying critical thresholds for reservoir water discharge. The integration of secondary datasets from the Directorate General of Water Resources, PATGTL, and BMKG reinforces the conclusion that regional soil profiles characterized by high plasticity indices necessitate a more conservative management approach. Accordingly, dam operation policies should be site-specific and based on hydro-mechanical response characteristics rather than generalized national standards.

Building upon the results and subsequent discussion, several promising avenues for future research and application have been identified:

a. Early Warning System Integration: The numerical models developed herein can be incorporated into AI-driven dam monitoring systems to facilitate real-time stability forecasting based on recorded reservoir fluctuations.
b. Material Fatigue Studies: Subsequent investigations should evaluate the long-term impact of repetitive (cyclic) water level fluctuations on the degradation of soil shear strength parameters.
c. Probabilistic Reliability Analysis: Transitioning toward probabilistic models is strongly recommended to account for geotechnical uncertainties in the field, thereby generating more comprehensive risk maps for policymakers.

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