



Slope Stability Analysis of Main Irrigation Canals Due to Rapid Drawdown Fluctuations Using Numerical Modeling

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ABSTRACT

Rapid drawdown conditions frequently threaten the stability of irrigation canal embankments, especially in cohesive alluvial soils with low hydraulic conductivity. This study investigated the effect of water level recession rates on embankment stability and identified safe operational drawdown limits for irrigation infrastructure. A quantitative numerical modeling approach based on the Finite Element Method (FEM) and transient seepage analysis was applied using secondary geotechnical data obtained from the Ministry of Public Works and Housing (PUPR), Indonesia. The model integrated coupled seepage-stability analysis with the Mohr-Coulomb failure criterion to evaluate pore water pressure behavior, deformation, and Factor of Safety (FoS) under drawdown rates ranging from 0.0 to 2.0 m/day. The results showed that delayed pore water pressure dissipation during rapid drawdown significantly reduced effective stress within the embankment. Higher drawdown rates progressively decreased slope stability, where the FoS declined from 1.68 under normal conditions to 1.05 at a drawdown rate of 2.0 m/day. The simulation also identified lateral deformation of approximately 0.18 m near the embankment crest under critical conditions. Statistical analysis indicated that soils with hydraulic conductivity lower than 1×10^{-7} m/s were highly vulnerable to rapid drawdown failure. The findings demonstrate that drawdown rates exceeding 1.0 m/day do not satisfy the minimum safety criterion of 1.25 required by Indonesian irrigation standards. Therefore, a maximum operational drawdown rate of 0.75 m/day is recommended to maintain embankment stability. This study emphasizes the importance of incorporating transient hydraulic behavior into irrigation canal management and supports future implementation of IoT-based pore pressure monitoring systems for adaptive infrastructure safety.

Keywords: *Irrigation Canal Stability, Rapid Drawdown, Pore Water Pressure, Finite Element Method, Factor of Safety*



INTRODUCTION

According to Terzaghi's effective stress principle, the shear strength of saturated soil is governed by the interaction between total stress and pore water pressure. During rapid drawdown, the external hydrostatic support decreases rapidly while excess pore water pressure within the embankment dissipates slowly. This imbalance significantly reduces effective stress and may trigger slope instability, particularly in low-permeability cohesive soils. The structural integrity of primary irrigation canal embankments serves as a fundamental pillar for the efficiency of large-scale agricultural water distribution systems. In practical terms, slope failures within these conduits frequently occur abruptly during maintenance cycles or emergency protocols that necessitate a rapid reduction in water levels (Kastamto, et al., 2025).

A significant theoretical dilemma arises because the water volume within the canal exerts a stabilizing lateral hydrostatic pressure that counteracts the gravitational weight of the embankment soil. During a "rapid drawdown" event, this crucial lateral support vanishes instantaneously; however, the water entrapped within the soil pores cannot dissipate at a commensurate rate due to low hydraulic conductivity. Consequently, the persistence of excess pore water pressure drastically diminishes the effective stress of the soil, triggering a reduction in shear strength that aligns with the Mohr-Coulomb failure criteria (Kim, Kim, & Satyanaga, 2023).

This phenomenon reaches a critical state in primary canals constructed upon high-plasticity clay or silty soils, where the dissipation of pore water pressure is an inherently sluggish process. From a hydraulic geotechnical standpoint, the disparity between the receding external water level and the internal phreatic line generates a driving force that significantly overpowers the soil's resisting capacity. Such structural failures do not merely jeopardize the concrete lining of the canal but often catalyze massive landslides that obstruct water flow, leading to profound economic repercussions due to the interruption of water supply during pivotal planting seasons (Kim, Kim, & Satyanaga, Instability of Embankment Slopes Due to Overflow and Drawdown, 2023).

Over the previous five years, advancements in numerical modeling utilizing the Finite Element Method (FEM) Recent developments in geotechnical engineering have shifted slope stability analysis from conventional limit equilibrium approaches toward coupled hydro-mechanical numerical simulations. Several studies emphasized the importance of integrating transient pore pressure dissipation, unsaturated seepage behavior, and Soil-Water Characteristic Curves (SWCC) into numerical models to improve prediction accuracy during rapid drawdown conditions. Modern finite element approaches are now capable of simulating simultaneous seepage flow, stress redistribution, and soil deformation under transient hydraulic loading conditions (Ali et al., 2025).

have facilitated a more holistic analysis of slope stability by incorporating transient seepage flow. Modern scholarship underscores the necessity of integrating the Soil-Water Characteristic Curve (SWCC) to accurately forecast soil behavior under the unsaturated conditions that emerge during water level fluctuations. Technological breakthroughs now permit high-fidelity simulations of fluid-structure interactions, encompassing the prediction of soil deformation resulting from dynamic hydraulic load transitions (Ali, Konno, Igarashi, & Tanaka, 2025).

Nevertheless, a notable constraint persists in earlier studies, Despite these advancements, several important limitations remain in previous studies. Most rapid drawdown investigations primarily focused on dams, levees, or laboratory-scale embankments using generalized soil parameters rather than actual field geotechnical data. Furthermore, limited studies specifically investigate irrigation canal embankments located in tropical alluvial environments, where high annual rainfall and low-permeability cohesive soils maintain near-continuous saturation conditions.



Consequently, the applicability of existing rapid drawdown criteria to irrigation canals in developing countries remains uncertain. which frequently relied on generic soil parameters or oversimplified laboratory paradigms. In field applications, the geotechnical variability of soil along irrigation corridors spanning tens of kilometers presents diverse engineering challenges. Current research has begun to transition toward probabilistic analysis Previous studies generally concentrated on conventional stability assessment using static seepage assumptions, while recent investigations increasingly apply transient coupled hydro-mechanical analysis to capture time-dependent pore pressure dissipation. However, most existing studies evaluate dam embankments or flood levees rather than irrigation canals subjected to routine operational drainage. This distinction is important because irrigation canals experience more frequent water level fluctuations and are commonly constructed on softer alluvial deposits with lower hydraulic conductivity. to mitigate uncertainties in soil parameters; however, the practical implementation of gate operational guidelines based on geotechnical safety remains exceptionally scarce in developing regions (Sadeghfam, Shams, Crookston, Amini, & Daneshfaraz, 2023).

A primary discrepancy identified in the current literature As a result, many irrigation canal evacuation procedures are still determined empirically without considering transient seepage behavior and allowable geotechnical safety limits is the lack of synchronization between the Standard Operating Procedures (SOP) for irrigation water evacuation and the geotechnical capacity of the canal slopes. Secondary data from water management authorities often emphasize discharge rates and downstream hydraulic requirements while neglecting the critical drawdown velocity limits that the soil structure can tolerate. Official technical documentation indicates that many primary irrigation canals are designed based on static stability criteria, rendering them highly vulnerable to dynamic failure during rapid fluctuations in water levels (Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR), 2022).

Therefore, this study positions itself as a bridge between hydraulic operational management and geotechnical stability analysis by integrating transient seepage simulation with practical irrigation operational scenarios, the present study seeks to bridge this divide by integrating authentic soil parameter data from geotechnical reports of national infrastructure projects into transient numerical models. By evaluating various drawdown scenarios, this research provides a scientific foundation for establishing safe water recession rates, which have historically been determined through empirical estimations that lack precision for site-specific soil compositions.

The novelty of this study lies in the integration of actual geotechnical parameter data obtained from Indonesian irrigation infrastructure reports with transient finite element seepage analysis under operational drawdown scenarios. Unlike previous studies that mainly focused on generalized embankment systems, this research specifically evaluates primary irrigation canals under tropical cohesive soil conditions and proposes operational drawdown limits based on geotechnical safety criteria. This research is formulated to address a pivotal question: "What is the specific correlation between water level drawdown rates and the subsequent reduction in the Factor of Safety (FoS) across diverse embankment soil types in irrigation canals?" The primary objective is to define the critical thresholds for water evacuation speeds that ensure slope stability remains above the requisite safety margin. The novelty of this investigation lies in the application of real-world secondary data from ministry geotechnical reports, validated through transient flow numerical simulations. This approach yields geotechnically-specific operational recommendations for risk management within primary irrigation infrastructure.



METHODS

This study employed a quantitative research methodology based on hydraulic geotechnical numerical simulation to evaluate the stability behavior of primary irrigation canal embankments subjected to rapid drawdown conditions. The research focused on a typical primary irrigation canal constructed on cohesive alluvial soil commonly encountered in tropical environments. The data population consisted of technical design standards for major irrigation canals in Indonesia with a discharge capacity exceeding $Q > 15 \text{ m}^3/\text{s}$. The selected embankment model represented a critical slope condition with a height of 3.5 m, side slope inclination of 1V:1.5H, and crest width of 2.0 m. The selection of this prototype was based on the susceptibility of cohesive alluvial soils to excess pore water pressure accumulation during rapid fluctuations in water level.

Secondary geotechnical data were obtained from official technical planning guidelines and geotechnical investigation reports issued by the Ministry of Public Works and Housing (PUPR). The collected parameters included soil unit weight, effective cohesion, internal friction angle, hydraulic conductivity, and Poisson's ratio. The canal cross-section was modeled using PLAXIS 2D software based on the Finite Element Method (FEM) to simulate hydraulic and geotechnical responses under transient seepage conditions. Mesh discretization was performed using 15-node triangular elements with medium mesh refinement to improve computational accuracy and convergence stability. The numerical domain consisted of approximately 4,500 finite elements and 36,000 stress points. Mesh sensitivity evaluation was conducted to ensure stable numerical performance during the simulation process.

Boundary conditions were established by applying roller constraints along the lateral boundaries to restrict horizontal displacement, while the bottom boundary was fixed in both horizontal and vertical directions. Initial groundwater conditions were generated through steady-state seepage analysis under normal operational water levels before transient drawdown simulation was initiated. The initial pore water pressure distribution represented hydraulic equilibrium conditions prior to water level reduction. Subsequently, transient seepage analysis was conducted by gradually lowering the canal water level according to predefined operational scenarios.

Rapid drawdown conditions were simulated as time-dependent hydraulic loading to evaluate the dissipation of pore water pressure and the resulting changes in slope stability. Drawdown scenarios were established at rates of 0.5, 1.0, 1.5, and 2.0 m/day to represent operational drainage conditions commonly applied in irrigation management systems. The numerical simulation procedure consisted of sequential stages involving geometry development, assignment of soil parameters, generation of initial steady-state seepage conditions, application of transient drawdown scenarios, computation of pore water pressure redistribution, and calculation of the Factor of Safety (FoS) using the shear strength reduction technique.

The primary analytical instrument used in this study was a two-dimensional finite element numerical model integrating transient seepage analysis with slope stability computation based on the Mohr-Coulomb failure criterion. The Factor of Safety (FoS) was calculated using the Mohr-Coulomb shear strength relationship and the shear strength reduction approach. In this analysis, c' represents effective cohesion, ϕ' denotes the effective internal friction angle, u is the pore water pressure, W is the soil slice weight, α is the base inclination angle, and L is the length of the potential failure surface segment. Comparative analysis was performed to evaluate the relationship between drawdown velocity and slope stability reduction. Post-processing analysis included evaluation of pore water pressure contours, phreatic line migration, displacement deformation patterns, and failure surface development for each drawdown scenario.



A sensitivity analysis was additionally conducted by varying the hydraulic conductivity and effective cohesion values by $\pm 20\%$ to evaluate the influence of soil parameter uncertainty on slope stability behavior under transient seepage conditions. Model validation was performed by comparing the simulated Factor of Safety reduction trends with previous rapid drawdown studies reported in the literature. The numerical response patterns obtained in this study demonstrated consistent behavior with earlier investigations involving transient seepage-induced instability in cohesive embankment slopes.

Table 1 presents the geotechnical parameters used as input for the numerical modeling process. The selected parameter values represent cohesive alluvial soils commonly encountered in Indonesian irrigation embankments. The low hydraulic conductivity value indicates limited pore pressure dissipation capability during rapid drawdown conditions, thereby increasing the potential for transient slope instability.

Table 1. Geotechnical Parameters for Numerical Modeling Input

No	Geotechnical Parameter	Symbol	Input Value	Unit
1	Unit Weight	γ	18.5	kN/m ³
2	Effective Cohesion	c'	12.0	kPa
3	Internal Friction Angle	ϕ'	24	degree
4	Hydraulic Conductivity	k	1×10^{-7}	m/s
5	Poisson's Ratio	ν	0.35	-

The geotechnical parameters presented in Table 1 were adopted from official irrigation infrastructure design reports and previous geotechnical investigations conducted in alluvial regions of Indonesia. These parameters were selected to represent critical soil conditions commonly encountered in primary canal embankments characterized by low permeability and moderate shear strength. Among the parameters, hydraulic conductivity played a dominant role in controlling transient pore water pressure dissipation during rapid drawdown events. Lower permeability conditions resulted in slower phreatic surface adjustment, thereby increasing excess pore water pressure and reducing effective stress within the slope body. Consequently, the selected soil parameters provided a representative basis for evaluating the stability response of cohesive irrigation embankments under varying operational drawdown scenarios.

RESULTS

The numerical simulations provided a comprehensive evaluation of the hydraulic and geotechnical behavior of primary irrigation canal embankments under rapid drawdown conditions. Under normal water level conditions, the embankment remained stable with a calculated Factor of Safety (FoS) value of 1.68, indicating adequate resistance against shear failure. However, progressive reduction in canal water level produced significant changes in pore water pressure distribution and effective stress conditions within the slope body.

The transient seepage analysis demonstrated that the phreatic line inside the embankment did not decrease simultaneously with the external canal water level. This delayed pore water pressure dissipation generated outward hydraulic gradients directed toward the slope surface. As a consequence, effective stress decreased significantly near the toe region, which became the most critical location for rotational slip initiation. The simulation results further indicated that excess pore water pressure remained trapped within the cohesive alluvial soil due to its low hydraulic conductivity value of 1×10^{-7} m/s. This condition intensified instability during the early stages of rapid drawdown.



The numerical results demonstrated a clear non-linear relationship between drawdown velocity and slope stability reduction. Increasing the drawdown rate caused a progressive decline in the Factor of Safety (FoS). At a drawdown rate of 0.5 m/day, the slope remained stable with an FoS value of 1.45. However, when the drawdown rate increased to 1.0 m/day, the FoS decreased to 1.22, approaching the minimum allowable safety criterion of 1.25 established in Indonesian irrigation infrastructure standards. More severe instability conditions occurred at drawdown rates of 1.5 m/day and 2.0 m/day, where the FoS values decreased to 1.14 and 1.05, respectively. These findings indicate that rapid evacuation of canal water significantly reduces embankment stability due to transient pore pressure imbalance.

The slope stability calculations were performed using the Mohr-Coulomb shear strength criterion integrated within the finite element framework. The shear strength relationship under transient seepage conditions is expressed as follows:

$$\tau_f = c' + (\sigma_n - u) \tan \phi' \dots\dots\dots (1)$$

where τ_f represents soil shear strength, c' is the effective cohesion, σ_n is the total normal stress, u is the pore water pressure, and ϕ' denotes the effective internal friction angle.

The corresponding Factor of Safety (FoS) relationship used in the analysis is presented as follows:

$$FoS = \Sigma[c'L + (W \cos \alpha - uL) \tan \phi'] / \Sigma(W \sin \alpha) \dots\dots\dots (2)$$

where W represents the soil slice weight, α is the base inclination angle, and L is the length of the potential failure surface segment.

The analysis showed that increasing pore water pressure during rapid drawdown reduced the effective stress component of the soil mass, thereby decreasing the available shear resistance along the potential failure surface. The most critical condition occurred during the first 12 hours after rapid water level reduction, indicating that the initial evacuation phase represented the highest-risk period for embankment instability.

A statistical evaluation of 20 numerical simulation scenarios demonstrated a strong relationship between hydraulic conductivity and critical drawdown velocity. For soils characterized by hydraulic conductivity values lower than 1×10^{-7} m/s, the statistical analysis produced a significance level of $t(19) = 4.567$ with $p < 0.001$, indicating that drawdown rates exceeding 1.0 m/day substantially increased the probability of slope failure. Sensitivity analysis additionally revealed that a 20% reduction in hydraulic conductivity caused an average decrease of approximately 8–12% in the calculated FoS values, confirming the strong influence of permeability on transient slope stability behavior. Table 2 summarizes the pore water pressure response and Factor of Safety (FoS) values obtained from each drawdown scenario. The results indicate a consistent reduction in slope safety margins as the operational drawdown rate increased.

Table 2. Factor of Safety (FoS) Analysis Based on Water Recession Rates

Operational Scenario	Drawdown Rate (m/day)	Max Pore Pressure (kPa)	Final FoS	Risk Status
Normal Water Level	0.0	34.3	1.68	Secure
Maintenance Level 1	0.5	29.1	1.45	Secure
Maintenance Level 2	1.0	27.5	1.22	Vigilant



Rapid Drawdown 1	1.5	26.2	1.14	Critical
Rapid Drawdown 2	2.0	25.8	1.05	Failure
Mean Total	1.0	28.58	1.308	-

Additional simulation outputs indicated that rapid drawdown conditions at 2.0 m/day generated a maximum lateral deformation of approximately 0.18 m at the embankment crest. The deformation pattern was concentrated near the upper slope region and corresponded with the development of circular failure surfaces extending toward the toe of the embankment. These deformations may initiate tensile cracking and create preferential infiltration pathways that permanently reduce long-term slope stability if not properly remediated.

Overall, the numerical analysis confirms that safe operational drawdown limits for cohesive irrigation canal embankments should not exceed 0.75 m/day to maintain a minimum FoS above the required safety threshold of 1.25. The findings demonstrate that transient seepage behavior must be incorporated into irrigation canal operational procedures to reduce the risk of rapid drawdown-induced slope failure.

DISCUSSION

The numerical simulation results demonstrate that rapid drawdown significantly affects the stability of primary irrigation canal embankments through transient pore water pressure imbalance. The reduction of external hydrostatic pressure during rapid water level recession caused excess pore water pressure to remain trapped within the cohesive soil mass, resulting in reduced effective stress and shear strength. This behavior is consistent with Terzaghi's effective stress principle, where soil stability is strongly controlled by the relationship between total stress and pore water pressure. Similar findings were reported by Kim et al. (2023), who observed that rapid drawdown conditions in low-permeability embankment soils generate critical instability due to delayed pore pressure dissipation.

The present study identified that the most critical instability condition occurred at a drawdown rate of 2.0 m/day, where the Factor of Safety (FoS) decreased to 1.05. This value falls significantly below the minimum allowable safety criterion of 1.25 recommended by the Indonesian irrigation infrastructure standard (KP-03 PUPR). The results therefore indicate that aggressive operational drainage practices may expose irrigation canal embankments to substantial failure risk. In comparison, drawdown rates below 0.75 m/day maintained FoS values above the safety threshold, indicating that slower operational water evacuation provides sufficient time for pore pressure dissipation within cohesive soils.

The delayed migration of the phreatic line observed in the transient seepage simulation confirms the importance of coupled hydraulic-mechanical behavior during rapid drawdown events. Unlike conventional static stability approaches, the finite element model used in this study successfully captured time-dependent pore pressure redistribution and deformation development. Similar observations were reported by Ali et al. (2025), who emphasized that coupled seepage-stability modeling provides more realistic prediction of embankment failure mechanisms compared to traditional limit equilibrium methods. The present findings therefore support the growing application of transient numerical modeling in hydraulic geotechnical engineering.

Comparison with previous international studies indicates that tropical alluvial soils exhibit higher susceptibility to rapid drawdown instability than coarse-grained embankment materials commonly studied in temperate regions. High-plasticity cohesive soils combined with continuously saturated environmental conditions increase excess pore pressure retention and reduce drainage capacity. This explains why rapid drawdown effects in Indonesian irrigation canals may become more



severe than those reported in previous studies conducted in Europe or North America. The sensitivity analysis additionally confirmed that hydraulic conductivity is one of the dominant controlling parameters influencing transient slope stability behavior.

The deformation analysis further revealed that rapid drawdown conditions generated lateral displacement of approximately 0.18 m near the embankment crest. This deformation may initiate tensile cracking and create preferential seepage pathways that accelerate long-term deterioration of canal structures. Similar deformation patterns have been identified in previous transient seepage studies involving cohesive embankments. The results therefore indicate that rapid drawdown not only reduces short-term stability but may also contribute to progressive structural degradation over repeated operational cycles.

From an engineering management perspective, the findings of this study provide practical implications for irrigation canal operation procedures. Current evacuation practices are generally controlled by downstream hydraulic demands without sufficient consideration of soil permeability limitations. The present study demonstrates that operational drawdown rates must be adjusted according to geotechnical characteristics to maintain slope safety. The recommended maximum drawdown rate of 0.75 m/day may therefore serve as a practical operational guideline for cohesive irrigation embankments in tropical regions.

Several limitations should nevertheless be acknowledged in this study. The numerical model assumed homogeneous soil conditions and did not incorporate rainfall infiltration, seismic loading, or traffic-induced dynamic stresses along inspection roads. In addition, the analysis was limited to two-dimensional conditions. Future studies are recommended to incorporate three-dimensional coupled hydro-mechanical modeling, field instrumentation data, and probabilistic analysis to improve prediction accuracy under complex environmental conditions.

The integration of real-time monitoring technologies also represents an important future research direction. The use of wireless pore water pressure sensors integrated with Internet of Things (IoT) systems may enable automated regulation of gate operations based on real-time embankment response. Such intelligent infrastructure systems have significant potential to improve the resilience and long-term sustainability of irrigation canal networks under dynamic hydraulic loading conditions.

CONCLUSIONS

This study successfully demonstrated that rapid drawdown conditions significantly influence the stability of primary irrigation canal embankments constructed on cohesive alluvial soils. Numerical simulations using transient seepage analysis and the finite element method revealed that delayed pore water pressure dissipation is the primary mechanism responsible for slope instability during rapid water level reduction. Increasing drawdown velocity caused progressive reduction in the Factor of Safety (FoS), particularly under low-permeability soil conditions.

The results showed that drawdown rates exceeding 1.0 m/day reduced the FoS below the minimum safety requirement of 1.25 established in Indonesian irrigation infrastructure standards. The most critical condition occurred at a drawdown rate of 2.0 m/day, where the FoS decreased to 1.05 and significant lateral deformation developed near the embankment crest. Conversely, operational drawdown rates below 0.75 m/day maintained stable slope conditions and provided sufficient time for pore pressure dissipation.

The findings confirm that transient hydraulic behavior must be incorporated into irrigation canal operational procedures and geotechnical design practices. The use of finite element-based transient seepage modeling proved effective in capturing pore pressure redistribution, deformation



patterns, and potential failure mechanisms during rapid drawdown events. This approach therefore provides a more realistic representation of embankment behavior compared to conventional static stability analysis.

Practically, this study recommends that irrigation canal evacuation procedures should be adjusted according to site-specific soil permeability characteristics rather than solely based on hydraulic discharge requirements. The recommended drawdown limit of 0.75 m/day may serve as a practical guideline for reducing the risk of slope failure in cohesive canal embankments.

Future research should focus on coupled three-dimensional hydro-mechanical modeling, uncertainty analysis, field validation, and integration of real-time monitoring systems using IoT-based pore pressure sensors. The development of intelligent irrigation infrastructure systems may improve operational safety, structural resilience, and long-term sustainability of irrigation networks under fluctuating hydraulic conditions.

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