


Dynamic Analysis of Pore Water Pressure Variation and Stability in Earth Dams During Rapid and Slow Drawdown: Khassa Chai Earth Dam as a Case Study

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Abstract: This study uses static and temporal models to investigate the variation of pore water pressure (PWP) along the base of an earthen dam over 30 days. The analysis was performed at four elevations ($Y = 10, 20, 30,$ and 40 m) to capture the pressure distribution throughout the dam body. A detailed finite element mesh was used to ensure high-resolution results, with the pore water pressure variation recorded over ten time intervals, focusing on both fast and slow drawdown conditions. The fast drawdown analysis indicated that pore water pressure dissipated rapidly near the top face, resulting in steep hydraulic gradients, large pressure drops near the dam core, and the formation of negative pressures downstream. In compare, slow drawdown showed a more gradual dissipation of pore water pressure, especially at greater depths, driven by soil permeability. Statistical analysis revealed that the PWP's coefficient of variation (CoV) during slow drawdown increased significantly over time, reaching values of 21.3450 at 5 days, indicating increased variability and potential instability. In rapid drawdown, CoV values peaked at 1.0257 at 2.35 days and then declined steadily, indicating a more transient pressure fluctuation that stabilized over time. Shear strength values increased as pore water pressure dissipated, peaking at 110 m from the top surface, where hydraulic gradients were most pronounced. The factor of safety, which was initially 1.4 under steady-state conditions, decreased to 0.9 during rapid drawdown, but increased to 1.5 after 20–30 days as PWP levels stabilized, indicating a restoration of stability. These results underscore the urgent need for controlled drawdown rates to manage PWP dissipation and ensure dam stability, especially in areas with low-permeability soils.

Keywords: Dam Stability; Earth Dam; Finite Element Analysis; Hydraulic Gradient; Pore Water Pressure (PWP); Rapid Drawdown; Safety Factor; Shear Resistance; Slow Drawdown; Soil Permeability.

1. Introduction

The stability of earth dams is vital to the safety and functionality of water storage structures that support agriculture, water supply, and flood control. These structures face significant challenges during rapid changes in water level in the reservoir, such as depressions, which can cause large shifts in internal pressures. Understanding the behavior of pore water pressure (PWP) under such conditions is essential, as it directly affects the effective stress, shear strength, and stability of dam materials. A comprehensive understanding of pore water pressure dynamics enables engineers to assess the risks associated with slope failure, seepage, and structural deformation, ensuring long-term safety.

Several studies have explored these critical aspects because of their profound implications for dam safety. Venkatesh (2016) [13], analyzed the distribution of pore water pressure in earth dams using saturated and unsaturated seepage analysis. He revealed that negative pore pressures develop in downstream areas, increasing stresses in low-permeability soils during rapid depressions. The study

highlighted that horizontal displacement increases with depth and that horizontal drains and blankets effectively mitigate such displacement. Zidane (2017) [14], evaluated the seepage in Khassa Chai Dam using SEEP/W, demonstrating the pivotal role of the core in reducing seepage, while filters had little effect on seepage amounts but significantly reduced the exit slope. Similarly, Khasaf and Mazloun (2019) [7], applied the limit equilibrium method (LEM) to analyze the slope stability of Khassa Chai Dam under rapid drawdown and seismic conditions and found that the upper slope was unstable with a safety factor of 0.857 during rapid drawdown and combined seismic effects. The behavior of dams during water level fluctuations was also analyzed in different contexts. Pinyol et al. (2008) [1], emphasized the importance of coupled flow and deformation models to accurately predict PWP responses during rapid drawdown. Their analysis of the Shira earthen dam showed that coupled elastic flow models captured these dynamics effectively. Fateh et al. (2017) [3], examined the Khassa Chai and Alvand earthen dams under earthquake excitation and rapid drawdown, respectively, and found that horizontal drainage mitigated displacement and that slow PWP dissipation resulted in complex stability responses. Liu et al. (2022) [8] and (2024) [9], highlighted the influence of the soil-water characteristic curve (SWCC) on dam safety, noting that SWCC absorption increases free surface levels and affects stability factors during drawdown. Seepage and stability analysis further shed light on the effects of drawdown. Sari et al. (2017) [11], identified a direct relationship between water levels, PWP, and seepage discharge at the Sermo Dam, emphasizing the need for continuous monitoring. Zidan et al. (2022) [15], showed that core layers in the Shirin Earth Dam significantly reduced seepage and maintained safety factors during rapid reservoir emptying. Zhang et al. (2020) [16], added to this understanding by showing how soil composition and upper slope geometry affect seepage behavior during water level fluctuations.

Khassaf et al. (2013) [6], showed that rapid drawdown combined with seismic forces destabilized the upper slope of the Mandali Dam despite overall stability. Gholamzadeh and Khalkali (2024) [5], linked the High Dam project to a decrease in soil resistance, which directly affects stability factors during drawdown events. Studies on seepage control mechanisms, such as Nouri and Salim's (2021) [10], study on casing permeability, have shown that slower dissipation of the High Dam project compromises slope stability. Sudardja (2012) [12], emphasized monitoring seepage during rapid fluctuations to prevent failures, in line with the findings of Zidan et al. (2017) [14], on the effectiveness of the base layer.

The present research aims to study the changes in pore water pressure (PWP) and their effects on the stability of the upper and lower slopes of Khassa-Chai earthen dam under fast and slow drawdown scenarios using numerical modeling with GeoStudio.

2. Methodology

In this study, GeoStudio 2018 software was used to simulate the Khassa Earth Dam and evaluate the effect of subsidence on pore water pressure and slope stability. The software relies on basic seepage and slope stability equations to analyze the behavior of the dam under different scenarios: steady-state seepage, 30-day transient subsidence, and 5-day slow transient subsidence. For each case, slope stability was evaluated, and the corresponding factor of safety was calculated. The basic equations used by GeoStudio for this analysis include the Richards equation for unsaturated and saturated flow, which estimates the pore water pressure under transient conditions, [2] and [13]:

$$(1) \quad \frac{\partial \theta}{\partial t} = \nabla \cdot (K_s(\theta) \nabla h)$$

where:

θ : is the volumetric water content (m^3/m^3),

t: is time (seconds),

$K(\theta)$: is the hydraulic conductivity as a function of water content (m/s),

h: is the hydraulic head (meters), which consists of both the elevation head and the pressure head, with the latter being equivalent to the pore water pressure.

This equation governs the flow of water in both saturated and unsaturated zones, where h includes the PWP, allowing the program to model how the PWP changes over time, especially during drawdown events. Darcy's Law is used to analyze steady-state and transient seepage:

$$(2) \quad q = -K \nabla h$$

where:

q: is the flow rate per unit area (m/s),

K: is the hydraulic conductivity (m/s), which defines how easily water flows through the soil,

∇h : is the hydraulic gradient, representing the change in hydraulic head per unit distance (dimensionless).

Under steady conditions, Darcy's law helps determine the distribution of PWP through a dam, while the temporary form is applied to model how the flowing pore water evolves during drawdown, reflecting changes in water flow and pressure.:

$$(3) \quad \frac{\partial \theta}{\partial t} = \nabla \cdot (K \nabla h)$$

The temporary seepage flow equation is used to simulate the dissipation of the flowing pore water during the drawdown process:

$$(4) \quad S \frac{\partial h}{\partial t} = \nabla \cdot (K \nabla h)$$

where:

S: is the storage coefficient (dimensionless), representing the amount of water released or absorbed by the soil per unit change in the hydraulic head,

$\frac{\partial h}{\partial t}$ is the change in hydraulic head over time (m/s).

This equation captures the time-dependent changes in PWP, which is essential for understanding the effect of fast and slow drawdown on dam stability.

For each scenario, slope stability was evaluated using numerical methods, such as the Morgenstern-Price or Bishop methods, which are based on the calculated PWP. These methods evaluate the balance of forces acting on the dam and provide a factor of safety F_s based on the ratio of resisting forces to driving forces:

$$(5) \quad F_s = \frac{\text{Resisting forces}}{\text{Driving forces}}$$

Material properties were assigned based on data from the Khassa Dam Administration, and boundary conditions were determined according to the specific case being analyzed. Figure (1), illustrates the solution for the sample cases, illustrating the effects of rapid and gradual drawdown on pore water pressure (PWP) and slope stability. The results are presented and discussed in detail to highlight the impact of rapid and gradual subsidence on the public works project and the overall stability of the Khassa Earth Dam.

3. Results and Discussion

The variation of pore water pressure (PWP) over a 30-day instantaneous transition period along the base of the Khassa Earth Dam was analyzed at four different elevations ($Y = 10, 20, 30,$ and 40 m). This approach allows for a comprehensive assessment of the PWP distribution throughout the dam body and the monitoring of pressure changes at different depths. The finite element mesh used in the model is adequately optimized, ensuring a high level of detail and reliability in the results, which are consistent with the expected behaviors. Figures 5, 6, 7, and 8 show the PWP variation at these depths, based on the static and transient models, with the results recorded at ten-minute intervals during the simulation period.

3.1 Rapid Drawdown

Figures 2, 3, 4, and 5 show the changes in PWP at a depth of 10 m from the dam's base during the drawdown event, which was measured at different time intervals. Initially, at 0 s, the pore water pressure is at its peak, reflecting complete saturation within the dam. This high pressure results from the equilibrium between reservoir water and pore water within the dam body, with the maximum hydraulic pressure exerted by the reservoir. As drawdown begins, the pore water pressure decreases, especially during early periods such as 6 and 15 h. This initial decrease in pore water pressure is primarily caused by water dissipation from the pores near the upper surface, where the water level drop first affects the hydraulic pressure. The rapid decrease in pore water pressure in this region demonstrates the immediate response of the dam material to the loss of external pressure, with water being pushed out of the soil matrix by the newly created hydraulic gradient. Over longer periods, such as 1.21 days and beyond, the pore water pressure continues to decrease but at a slower rate, influenced by the permeability of the dam material. Low permeability soils resist rapid water flow, resulting in a gradual dissipation of PWP as water moves deeper into the dam. The observed peak in PWP at about 100 m along the base of the dam indicates the area of maximum inflow concentration of water, which arises from the highest hydraulic gradient in this area, which directs water flow towards areas of low pressure due to drawdown. After this peak, the PWP experiences a sharp decline as water continues to exit the dam. On the downstream side, the PWP eventually drops below zero, indicating negative pore pressures (suction). This phenomenon arises when the soil in this area begins to lose saturation, leading to tensile forces within the soil matrix. The appearance of negative pore pressures is a typical response during rapid drawdown; as the subsurface unsaturation increases, unsaturated pockets form, posing the risk of desiccation or cracking if not carefully managed. PWP profiles exhibit distinct behaviors over time. For shorter periods (e.g., 6 and 15 h), the curves are steeper, indicating a rapid redistribution of pore pressures in response to sudden changes in water levels. This rapid decline reflects the rapid adjustment of the dam materials near the surface to the decreasing hydraulic head. As time progresses (e.g., after 30 days), the curves flatten, indicating a more stable dissipation of pore pressures as the dam gradually equilibrates to the new hydraulic conditions. This flattening results from the slow movement of water through less permeable zones, where PWP changes gradually propagate. In general, the variation in PWP is influenced by a combination of the permeability of the dam material, the rate of water level decline, and the internal flow of water. The pronounced changes in the High Dam project near the upper surface during the early stages highlight the importance of managing drawdown rates to prevent excessive hydraulic gradients that could destabilize the slope or lead to internal erosion. As the High Dam project stabilizes, the dam approaches a new equilibrium state; however, this process requires careful management of drainage to avoid the development of critical pressures that could jeopardize the stability of the dam project stabilizes, the dam approaches a new equilibrium state; however, this process requires careful management of drainage to avoid the development of critical pressures that could jeopardize the stability of the dam.

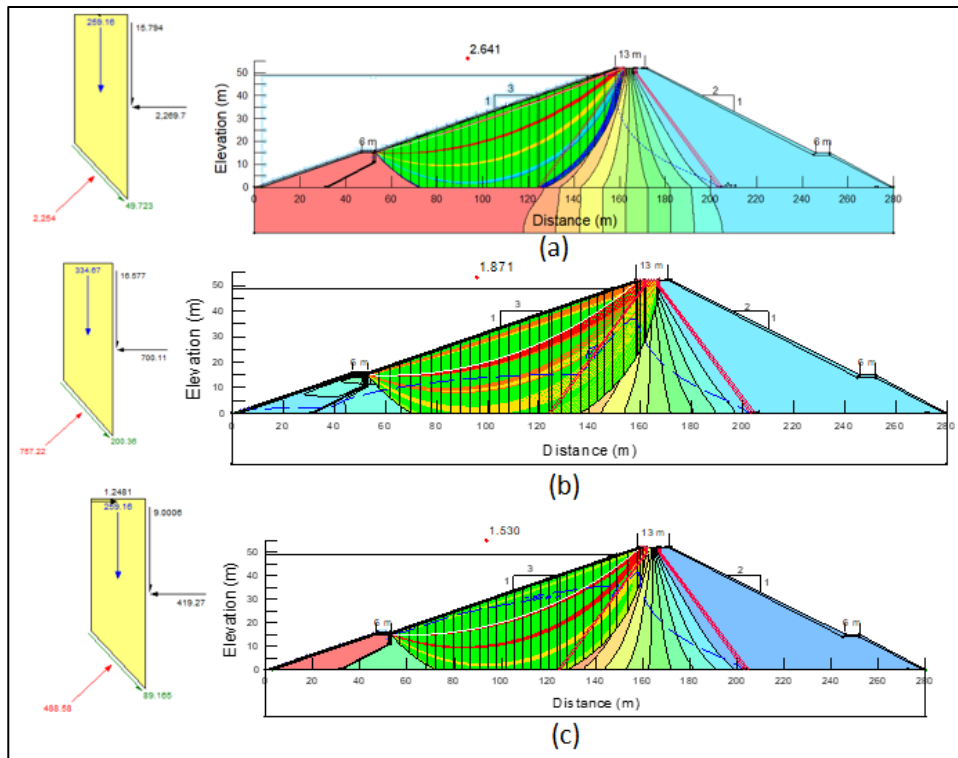


Figure 1: Solved Cases: Steady (a), Rapid Drawdown (b), and Slow Drawdown (c).

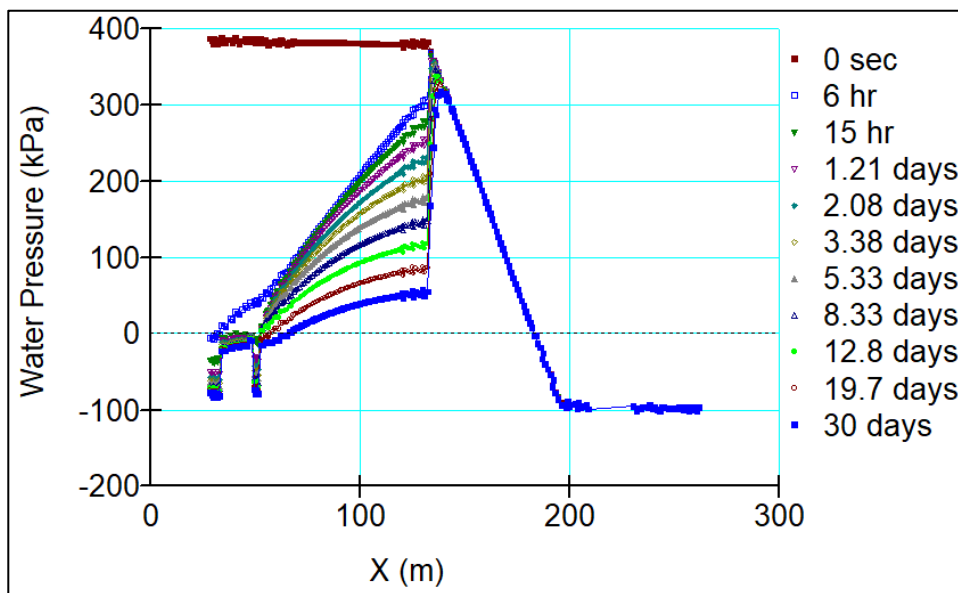


Figure 2: PWP Transient Drawdown Variation at $y=10$ m.

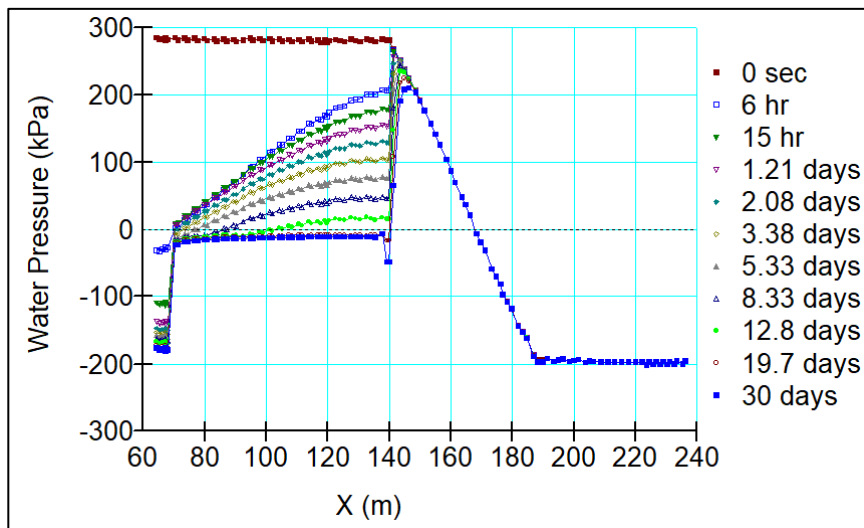


Figure 3: PWP Transient Drawdown Variation at y= 20 m.

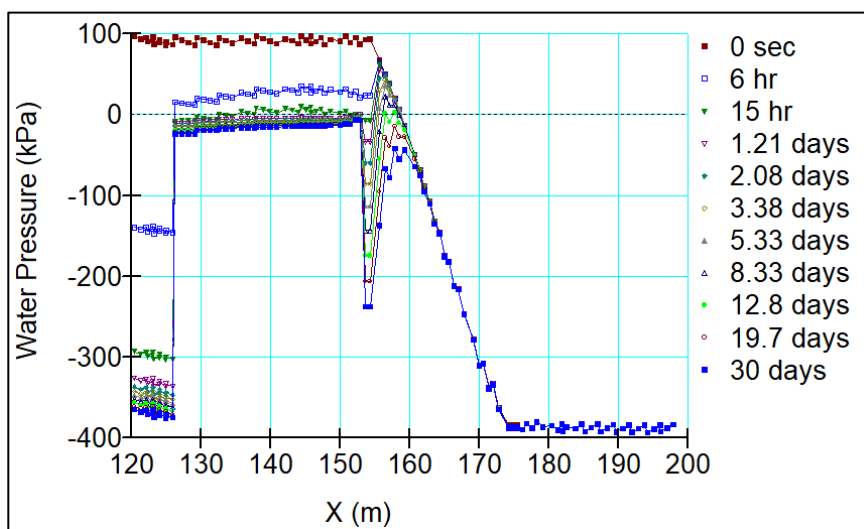


Figure 4: PWP Transient Drawdown Variation at y= 30 m.

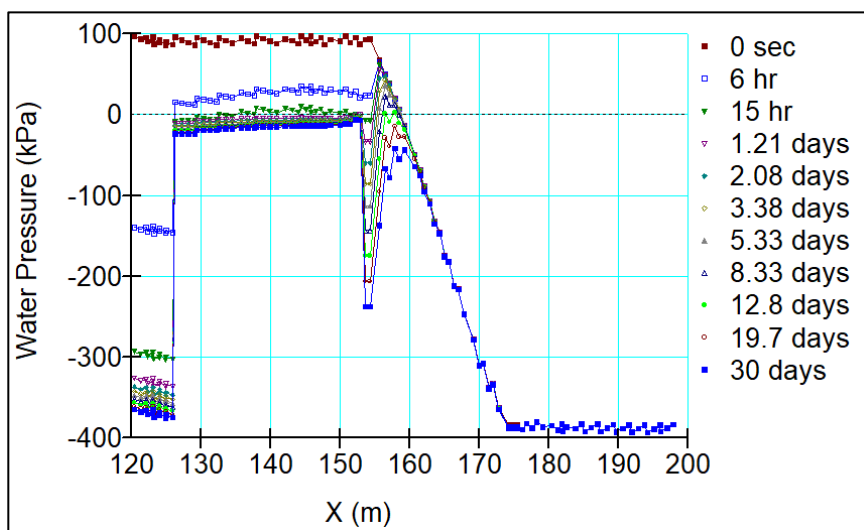


Figure 5: PWP Transient Drawdown Variation at y= 40 m

3.2 Slow Drawdown

Figures 6, 7, 8, and 9 show the variation of the pore water pressure (PWP) distribution at depths of 10 m, 20 m, 30 m, and 40 m from the base of Khassa Earth Dam, which were measured during different stages of the drawdown process. Initially, at time zero (steady state), the PWP shows constant values at each depth, reflecting the hydrostatic pressure from the water column. Under steady-state conditions, the PWP values are 400 kPa at $Y = 10$ m, 300 kPa at $Y = 20$ m, 200 kPa at $Y = 30$ m, and 100 kPa at $Y = 40$ m. These pressures remain stable up to about $X = 150$ m, after which rapid decreases in the PWP begin.

As the slow drawdown progresses over 5 days, large changes in PWP become apparent, particularly near the top surface, highlighting the complex response of the dam material to changing hydraulic conditions. At $Y = 10$ m, the PWP initially remains constant at 380 kPa until $X = 60$ m, consistent with a steady-state condition. After this point, the PWP drops sharply to 70 kPa, then gradually increases to 180 kPa at $X = 130$ m, before rising to 350 kPa. Thereafter, it rapidly decreases to -100 kPa at around $X = 200$ m. This variation illustrates the dynamic behavior of the dam material, with pronounced dips and rises associated with the falling water table and the emergence of suction pressures.

At $Y = 20$ m, the PWP starts at 300 kPa under steady-state conditions but shifts to -50 kPa during drawdown, reflecting the onset of the suction zone. As the distance increases, the pore water pressure gradually increases to 100 kPa at $X = 140$ m, reaches 250 kPa at $X = 145$ m, and then decreases to -200 kPa at $X = 190$ m. This behavior confirms the development of negative pore pressures associated with the decrease in water levels, which contributes to the formation of an unsaturated zone within the dam material, especially near the upper surface.

At $Y = 30$ m, the pore water pressure starts at 200 kPa under static conditions, followed by a gradual decrease. During drawdown, it starts at -150 kPa near $X = 90$ m, indicating a deeper suction zone. The pore water pressure then increases to -5 kPa at $X = 100$ m, then to 10 kPa at $X = 148$ m, and finally to 150 kPa at $X = 155$ m. However, it quickly decreases thereafter to about -300 kPa at $X = 180$ m. This sharp drop reflects the greater influence of subsidence at greater depths, where the hydraulic gradient causes more pronounced pressure losses and leads to the development of high suction pressures in deeper soil layers.

At $Y = 40$ m, the pore water pressure under steady-state conditions starts at 100 kPa, following a similar pattern during subsidence but showing more extreme fluctuations. It starts at -180 kPa at $X = 90$ m, indicating a stronger suction effect in deeper layers. The pressure rises to -20 kPa at $X = 125$ m, continues to 10 kPa at $X = 158$ m, and then drops sharply to -400 kPa at $X = 174$ m. The large magnitude of the pressure changes at this depth highlights the pronounced influence of suction processes on the deeper layers of the dam, where the hydraulic gradient is more pronounced, and the dam material is subjected to greater pressure as the water surface recedes.

3.3 Shear Resistance

In the steady-state analysis, shear strength values gradually fluctuated but remained below 18 kPa along the base of the Khassa Earth Dam, indicating a uniform distribution of pore water pressure (PWP) under normal conditions and hydraulic equilibrium between the reservoir and the dam body (Figure 10). This stable pore water pressure is associated with low shear strength, indicating balanced internal forces within the dam with minimal influence from water flow or pressure changes. In contrast, during rapid transient drawdown, the shear strength increased with distance from the top surface, peaking at $X = 110$ m before decreasing toward the dam toe. This pattern is associated with the dissipation of pore water pressure during drawdown; as reservoir water levels rapidly decrease, the hydraulic

gradient intensifies, causing the pore water pressure to decrease near the top surface. This decrease increases the effective stress, which enhances the shear strength as the dam core bears more of the load. The peak shear strength at $X = 110$ m corresponds to the steepest hydraulic gradient, which facilitates water flow from the dam interior to the downstream face. Over time, the shear strength continues to increase as the PWP continues to dissipate. For example, after 6 hours of pulling, the maximum shear strength reaches 60 kPa, and peaks at about 110 kPa after 30 days. This trend results from the continuous decrease in PWP, especially in the deeper layers, which enhances the soil's ability to resist shear forces.

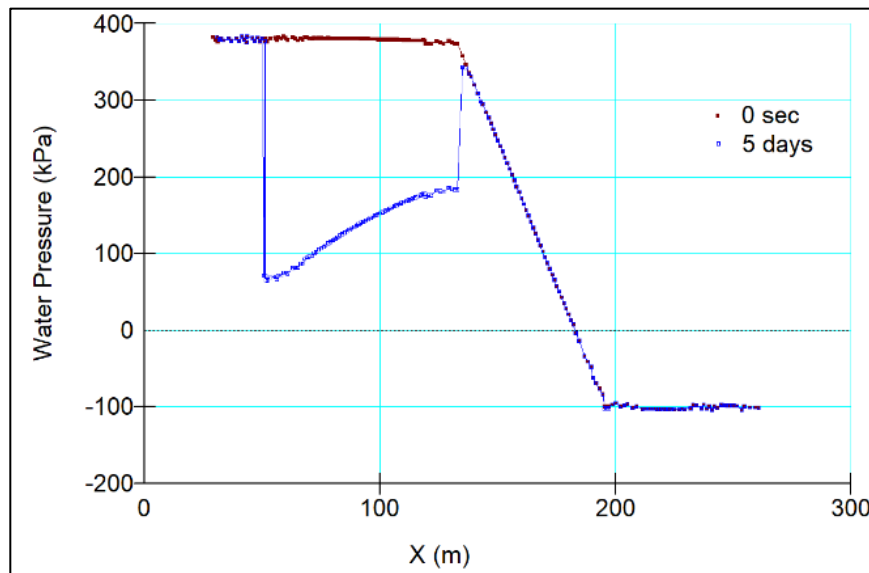


Figure 6: PWP Gradual Drawdown Variation at $y= 10$ m.

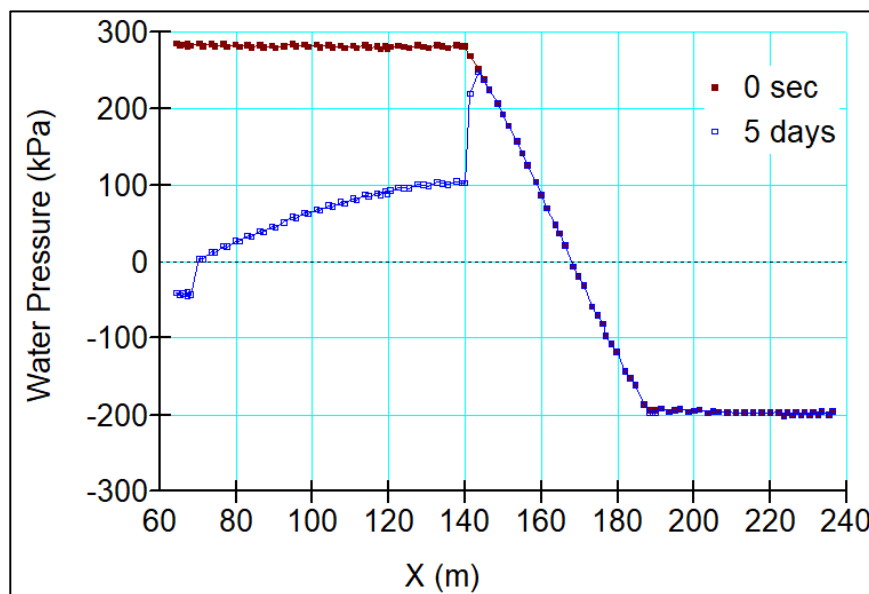
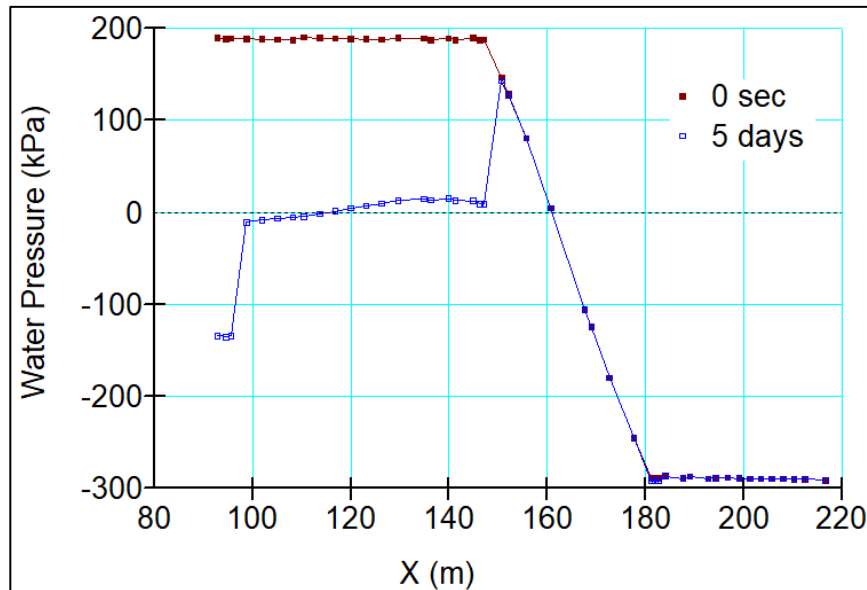
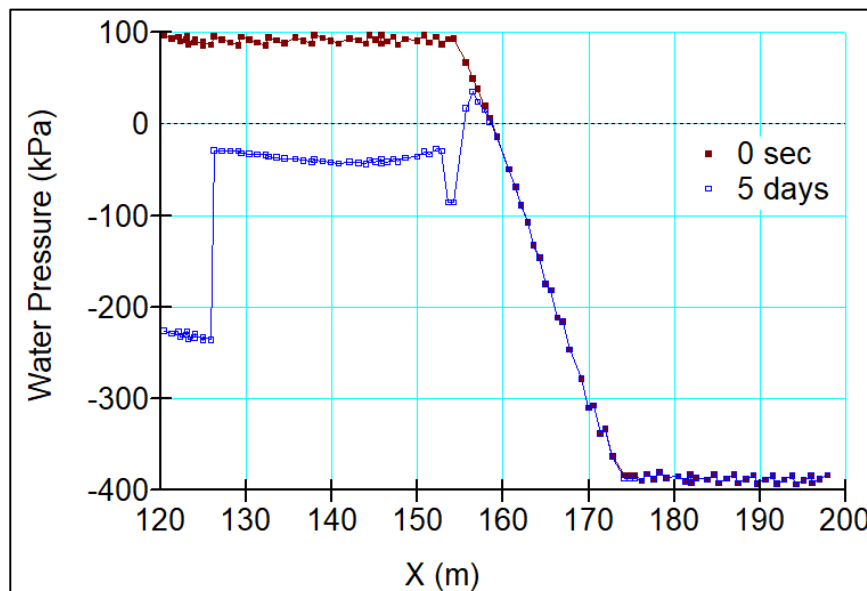


Figure 7: PWP Gradual Drawdown Variation at $y= 20$ m.

Figure 8: PWP Gradual Drawdown Variation at $y= 10$ m.Figure 9: PWP Gradual Drawdown Variation at $y= 20$ m

3.4 Safety Factor

In the steady-state analysis, the factor of safety begins at approximately 1.4, indicating that the dam can resist shear forces without significant internal stresses (Figure 11). This stability reflects a balanced pore water pressure (PWP) distribution within the dam, resulting in a high factor of safety. Conversely, during a rapid transient decline, the factor of safety drops sharply to around 0.9 at time $t = 0$ due to the sudden decrease in reservoir water level, which creates a large hydraulic gradient between the dam's upper and lower faces. This rapid decline in water level leads to a corresponding decrease in PWP near the upper side of the dam, increasing shear stresses while delaying PWP dissipation. As a result, the effective stress is lower, heightening the risk of instability. Over time, the factor of safety gradually increases, reaching about 1.5 after 20 to 30 days, due to the gradual dissipation of PWP throughout the dam. As PWP decreases, effective stress rises, allowing the dam to regain stability. By $t = 20$ to 30 days, the stresses induced by drawdown have largely dissipated, enabling the structure to approach a new equilibrium and surpass its initial safety factor. This fluctuation in the safety factor highlights the

dynamic interaction among PWP dissipation, effective stress, and shear strength. Initially, rapid drawdown results in high hydraulic gradients and low effective stress, leading to a lower safety factor. As PWP stabilizes and effective stress rises over time, the dam's strength is restored, enhancing the safety factor. This emphasizes the importance of managing drawdown rates to ensure a gradual process, thereby reducing instability risks and maintaining structural integrity.

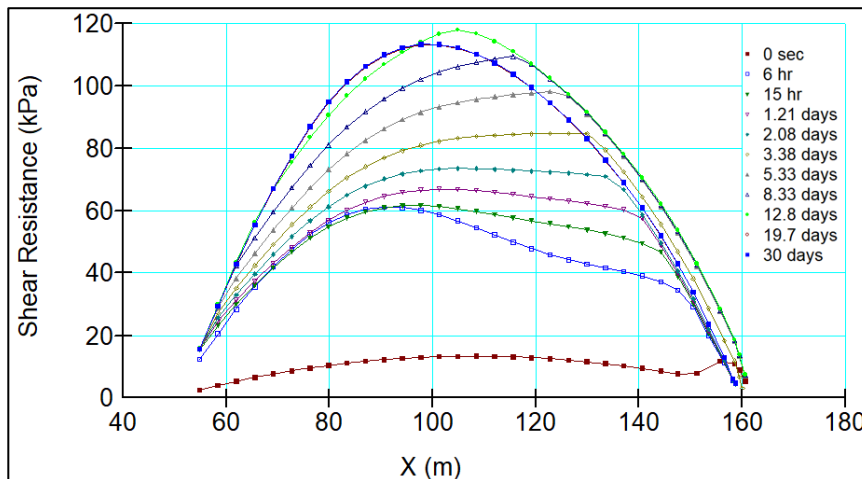


Figure 10: Transient Shear Resistance Variation.

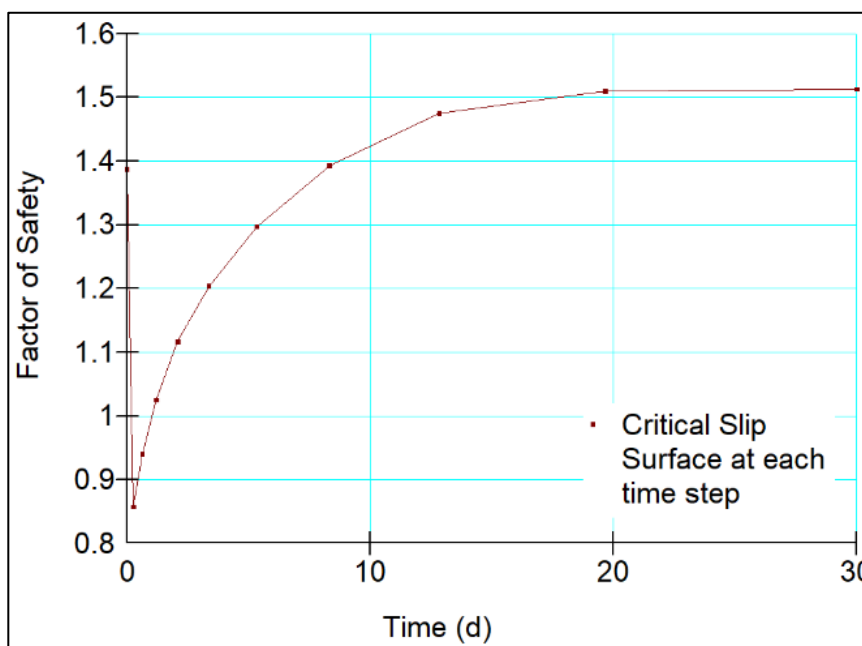


Figure 11: Safety Factor Variation.

4. Statistical Analysis and Comparison

In this section, the values of the coefficient of variation (CoV) of the pore water pressure (PWP) change under slow and fast drawdown conditions are summarized and compared to highlight the different behaviors observed in the dam pressure distribution. The values of the CoV at different time intervals are shown in Table 1.

Table 1: CoV for Slow and Rapid Drawdown PWP

Time (hrs/days)	Slow Drawdown CoV	Rapid Drawdown CoV	Discussion
t = 0 hr	0.7617	0.6294	Initial variation, with slow drawdown showing slightly higher CoV.
t = 6 hrs	0.8118	0.6640	There is a slight increase in CoV for both scenarios.
t = 15 hrs	0.6381	0.8384	CoV in rapid drawdown increases more than in slow drawdown.
t = 1.17 d	0.7306	0.9201	Both scenarios show rising CoV, but the rapid drawdown has a higher value.
t = 2d	1.7241	1.0257	Slow drawdown exhibits a much larger increase in CoV, signaling instability.
t = 3.21 d	5.4944	0.4907	Dramatic CoV increases in slow drawdown; rapid drawdown stabilizes.
t = 5 d	21.3450	0.5245	Very high CoV in slow drawdown, indicating significant instability.
t = 7.2 hr	-	0.6640	Early rapid drawdown fluctuations observed.
t = 17.8 hr	-	0.8384	Continued fluctuations in rapid drawdown, but less severe.
t = 8.93 d	-	0.5648	Stability starts to return in rapid drawdown.
t = 20.2 d	-	0.6829	Further stabilization in rapid drawdown.
t = 30 d	-	0.7571	Final stabilization in rapid drawdown.

Slow drawdown: The CoV values for slow drawdown show a steady increase, especially after $t = 2$ days, with a significant peak at $t = 5$ days (21.3450). This increase indicates an increasing variability in pore water pressure, indicating increased instability over time. The gradual dissipation of pore water pressure is likely to contribute to these fluctuations as the system slowly approaches equilibrium, making the dam behavior more unpredictable and potentially more dangerous to stability, especially in areas of low permeability soils. Rapid drawdown: In contrast, rapid drawdown shows a more transient behavior in pore water pressure fluctuations. Although the CoV initially increases, it quickly stabilizes after $t = 2.35$ days, reflecting the system's ability to adapt to rapid changes in water levels. Rapid pressure dissipation leads to faster stabilization, with the CoV showing a steady decline after the initial fluctuations. This behavior suggests that the rapid drawdown scenario induces less long-term instability than a slow drawdown, with the system stabilizing more quickly once the initial pressure fluctuations have subsided.

Slow versus rapid drawdown in earthen dams: Previous studies, such as Zhao et al. (2018), have observed that slow drawdown typically results in higher pore water pressure variation, especially in fine-grained soils, due to slow dissipation of pore pressure. This observation is consistent with the results of the slow drawdown scenario in our study, where increased CoV reflects greater instability over time. On the other hand, rapid drawdown is characterized by transient pressure fluctuations that

tend to stabilize more quickly, as observed in studies by Sharma and Saha (2017). These studies suggest that while rapid drawdowns may cause temporary disturbances in pore pressure, the system often returns to equilibrium quickly, which is consistent with the rapid drawdown behavior observed in our analysis. Effect of pore water pressure variation: Increased CoV in slow drawdown, especially after 2 days, indicates increased nonlinearity in soil mass and potential instability. The large CoV observed after 5 days suggests that seepage forces and capillary effects may play an important role in pressure fluctuations, as discussed by Vasconcelos et al. (2016). Such fluctuations can pose failure risks in dams with fine-grained materials if not carefully managed.

In contrast, rapid declines create more transient pressure increases, followed by stabilization, suggesting that the system is more resilient to rapid changes in water levels.

5. Conclusions

1. Pore water pressure behavior: The difference in pore water pressure during fast and slow drawdown significantly affects dam stability, with fast drawdown creating steep hydraulic gradients near the crest, increasing the risk of slope instability. The study highlights the importance of understanding how pore water pressure develops at different depths and how soil permeability affects stability.
2. Effect of drawdown rate: Rapid drawdown generates high-pressure gradients, posing risks to stability. Controlled gradual drawdown allows for pressure equalization and reduces the risk of internal erosion or slope failure.
3. Effect at 30 m depth: Pore water pressure peaks near the core at 30 m depth, emphasizing the need for gradual drawdown to avoid destabilizing pressure gradients. Long-term monitoring of deeper layers is essential to maintain dam stability.
4. Pore water pressure shifts and negative pressures: During drawdown, pore water pressure decreases, resulting in negative pressures at depths of 30 m and 40 m. These pressures pose risks such as cracking and increased seepage, which can compromise the integrity of the infrastructure.
5. Overall impact on stability: Deep layers experience delayed responses, and controlling drawdown rates is critical to avoid excessive pressure gradients that could lead to dam failure.
6. Increased shear strength: As pore water pressure dissipates, shear strength increases, highlighting the importance of managing drawdown rates to allow for uniform development of shear strength across the dam.
7. Trends in factor of safety: The factor of safety improves and stabilizes after 14 days of drawdown, indicating that controlled drawdown can enhance stability over time.
8. Comparison of slow and fast drawdown: Slow drawdown leads to persistent fluctuations, leading to long-term instability, especially after 2 days. In contrast, fast drawdown causes temporary fluctuations that stabilize more quickly, demonstrating the system's ability to adapt efficiently. These results are consistent with previous studies on the different effects of slow and fast drawdown on dam stability.

5. Conflict of Interest:

There is no conflict of interest for this paper.”

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