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Stability and Deformation Behavior of Earth Dams under Variable Reservoir Drawdown Rates and Material Properties

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Abstract: Reservoir drawdown is a critical loading condition that alters seepage and stress distributions in earth dams, potentially inducing instability and excessive deformation. Understanding the coupled hydraulic-mechanical response during drawdown is therefore essential for ensuring long-term dam safety and performance. The stability and deformation response of earth dams during reservoir drawdown were systematically investigated, with particular emphasis placed on the coupled effects of drawdown rate, core geometry, core permeability, core strength, and shell strength. Two-dimensional finite element analyses were performed using PLAXIS 2D to evaluate the factor of safety against instability and the associated crest settlement under a range of representative conditions. The numerical results indicate that an increase in the reservoir drawdown rate leads to a noticeable increase in the factor of safety against horizontal instability, whereas the corresponding influence on crest settlement is negligible. Variations in core geometry were found to exert a pronounced effect on dam performance: an increase in undrained core width results in larger crest settlement while simultaneously reducing the factor of safety. In contrast, higher core permeability slightly improves the factor of safety, although its influence on crest settlement remains marginal. The mechanical properties of dam materials were shown to play a dominant role in both stability and deformation behavior. In particular, increases in core and shell strength parameters significantly enhance the factor of safety while substantially reducing crest settlement. These results provide valuable insight for the design, assessment, and risk-informed management of earth dams subjected to rapid or controlled reservoir drawdown conditions.

Keywords: Drawdown rate; Core geometry; Core permeability; Core strength; Shell strength; Factor of safety

1 Introduction

Since dams are essential for agriculture, power generation, flood control, and water storage [1], their stability is essential to their safe operation. Drawdown, or the dropping of the reservoir water level, is a crucial element influencing dam stability. Reservoir drawdown is commonly implemented for flood management and maintenance purposes; however, excessively rapid drawdown may induce adverse hydraulic and mechanical responses that compromise dam stability. Slope instability, seepage issues, or even structural failure could result from an abrupt or severe drawdown. In order to detect possible risks and create safe operating procedures, it is crucial to analyze dam stability at different drawdown rates. Changes in pore water pressure within the dam body and its foundation constitute a primary concern during reservoir drawdown. The hydrostatic pressure on the dam reduces as the reservoir water level falls, which redistributes stress throughout the foundation and structure. Particularly in saturated soils, this may result in less effective stress, which reduces shear strength and raises the possibility of settling or sliding. Low permeability decreases pore pressure dissipation in clay-rich soils, making weak zones vulnerable to internal erosion or shear failure. This makes the issue more serious. Because rapid drawdown significantly increases the risk of instability, the pace of drawdown is consequently a crucial aspect.

During drawdown, increased seepage through the dam or its foundation creates another type of risk. Water may still pass through or beneath the dam even when the external pressure on it reduces as the water level decreases. Significant or quick drawdown may increase seepage and create internal erosion (piping) of the dam's materials, which may threaten stability and, if neglected, may lead to failure. Additionally, seepage can weaken the soil and perhaps cause liquefaction or foundation instability by generating significant hydraulic gradients, particularly in permeable embankment dams. Therefore, the drawdown rate is crucial since faster drawdowns increase the possibility of negative seepage effects. Figure 1 presents an example of seepage occurrence in an experimental earth dam.

Figure 1. Seepage in an experimental earth dam, modified from study [2]

A rapid drop in reservoir water level also reduces the supporting water pressure on embankment slopes, altering stress distribution and increasing the risk of sliding or slope failure, especially in loose or poorly compacted soils. The faster the drawdown, the higher the instability risk. Hence, the drawdown rate, soil properties, and slope geometry must be carefully evaluated. An illustration of a slope failure is shown in Figure 2.

Figure 2. Failure of a slope in Taiwan [3]

The downstream side of a dam may likewise be in danger due to rapid or extensive drawdown. The downstream base or dam foundation may be eroded, scoured, or undermined as a result of changed flow conditions brought on by decreasing reservoir levels, which raises the danger of failure. In severe situations, erosion may cause loose rock or soil to develop sinkholes. Furthermore, the downstream foundation may become weakened by weathering and temperature fluctuations in formerly submerged areas, which could result in settlement or structural instability.

In recent decades, several researchers have conducted numerical and experimental studies to assess the stability of dams and embankments under various drawdown rates. Analytical methods and recommended effective strategies have been proposed to prevent dam failure during drawdown events. Khatun et al. [4] experimentally studied the stability of a model riverbank made of uniform, cohesionless soil under rapid drawdown. Through laboratory tests, the effect of drawdown rate and ratio on pore pressure, deformation, and shear strength was analyzed. The results showed that stress changes from drawdown mainly influence pore pressure variations near the slope toe and that drawdown rate has a greater impact on bank deformation than drawdown ratio. Xu et al. [5] analyzed dam slope stability during rapid reservoir drawdown using the finite element method and unsaturated soil shear strength theory. By simulating pore-water pressure dissipation and considering matrix suction effects, it was found that rapid drawdown poses the highest risk of slope failure. As excess pore pressure dissipates and the unsaturated zone expands, slope stability improves due to increased shear strength from matrix suction. Intensified dam monitoring during drawdown was recommended to prevent failures. Azadi et al. [6] investigated earth-shell dam stability under rapid drawdown and transient flow using coupled finite-element and limit equilibrium methods. The results showed that lower core permeability and restricted seepage increase upstream slope instability. Stability decreases with deeper slip surfaces and lower hydraulic hydration, and faster drawdown rates (0.2–0.6) further reduce the factor of safety. Siacara et al. [7] integrated seepage analysis with limit equilibrium methods to evaluate the time-dependent safety of an earth dam, including conditions during drawdown.

Cheng et al. [8] examined the effects of rapid reservoir drawdown on bank slope stability using a coupled hydro-mechanical analysis in ABAQUS, applied to the Dahua landslide at the Dahuaqiao Hydropower Station. Their results highlighted the critical role of drawdown-induced hydrodynamic pressure in landslide behavior. Wu et al. [9] proposed a novel framework that integrates Bayesian inference with transient unsaturated seepage simulations to assess the probability of core seepage failure during rapid drawdown conditions. Their study emphasized that controlling the drawdown rate and closely monitoring seepage pressure are essential to ensure the overall safety of the project.

Souliyavong et al. [10] analyzed how drawdown rate, hydraulic conductivity, and shear strength affect the upstream slope stability of earth dams using the general limit equilibrium method. It was found that stability decreases as water levels drop, but dams with more permeable materials are more stable. Slower drawdown rates and higher shear strength (saturated or unsaturated) increase the factor of safety, with the lowest stability occurring when the reservoir level is reduced by approximately two-thirds. Kim et al. [11] examined the effect of tensile cracks on shallow slope failures during drawdown, especially under extreme rainfall. Numerical simulations showed that the upstream slope is most vulnerable right after drawdown, while the downstream slope faces the highest risk at the beginning of overflow. Berilgen [12] analyzed submerged slope stability during drawdown using coupled seepage and finite element methods. Results showed that pore-water drainage rate, soil permeability, and drawdown rate critically affect stability, while common fully drained or undrained design assumptions may not reflect real behavior.

Hou et al. [13] proposed a criterion for rapid drawdown assessment based on the percentage reduction in the factor of safety compared to steady-state seepage. The results showed that acceptable reductions depend on the slope's importance, engineering objectives, and initial factor of safety, with slopes having higher values of initial factor of safety tolerating greater reductions without compromising stability. Gao et al. [14] used a 3D rotational failure mechanism via limit analysis to study slope stability under water drawdown. It was found that during slow or steady drawdown, the factor of safety initially decreases to a minimum before slightly increasing, due to the balance between internal pore-water pressure work and external water pressure on the submerged boundary. Fattah et al. [15] used finite element analysis to study seepage in an earth-shell dam, considering water levels, material properties, and boundary conditions. It was found that during rapid reservoir drawdown, pore-water pressures decrease both gradually through drainage and instantaneously due to elastic response. The pressures drop linearly, indicating steady-state flow, while negative pore pressures were observed downstream where water levels fell below the ground surface.

Sica et al. [16] studied rapid drawdown in earth dams, considering scenarios where reservoir lowering follows a major earthquake. The results showed that prior seismic events reduce dam stability, especially in the early stages of drawdown. Faster drawdown further lowers the factor of safety, with initial soil conditions having the greatest influence on instability. Sun et al. [17] analyzed a landslide slope under varying reservoir drawdown conditions. Expressions for normal stress on the sliding surface were developed considering hydrodynamic pressures and groundwater effects. The results showed that when the reservoir level drops by 0.6 m/day, the slope's factor of safety decreases by about 14%, and for a 30 m drop at 1.2 m/day, it decreases by about 16%. It was concluded that increasing the drawdown rate negatively affects slope stability, but the additional reduction in the factor of safety is relatively small. Utepov et al. [18] analyzed the Chardara embankment dam, finding that drawdown and reservoir levels strongly affect slope stability. Minimum factor of safety ranged from 2.5 to 0.56, with a strong negative correlation (–0.997) between pore-water pressure and stability. Variations in the factor of safety due to drawdown were statistically significant ($p < 0.05$).

Drawdown is essential for dam operations but can impact stability by causing pore pressure fluctuations, seepage, slope instability, and downstream erosion. Rapid lowering of water levels may increase foundation stress and weaken the structure. While most existing studies focus mainly on drawdown rate and often overlook permeability and other structural factors, the novelty of this study lies in evaluating a broad set of parameters-drawdown rate, core geometry, permeability, and mechanical properties-and their combined effects on dam stability and deformation. This comprehensive approach provides a more complete understanding of dam behavior during drawdown than has been reported in the existing literature. This study uses PLAXIS 2D to analyze dams with different core geometries and materials under varying drawdown rates, evaluating soil and hydraulic behavior and calculating the factor of safety. The study provides insights for safe and effective drawdown management and improved dam engineering practices.

2 Numerical Modeling

The numerical models presented in this study assume a homogeneous, elastic-perfectly plastic dam and foundation with linear stress-strain behavior. Steady-state, plane strain conditions were adopted, ignoring dynamic loads, seismic events, and three-dimensional effects. Drawdown was applied uniformly and symmetrically across the reservoir, without sudden fluctuations.

2.1 Dam Geometry

The dam under consideration is 30 m high, with base and top widths of 172 m and 5 m, respectively. The dam is made out of a well-graded shell on both sides and a clay core. The water level behind the dam is typically 25 m high. Figure 3 illustrates a schematic view and geometrical details of the numerical model in PLAXIS 2D. The location of the measuring point indicates where the outputs (horizontal displacement and crest settlement) were calculated in this study.

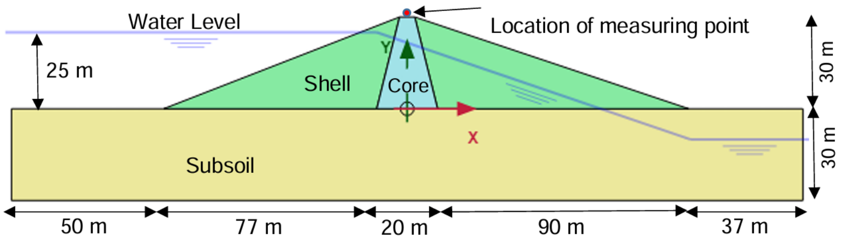

Figure 3. Geometrical details of the numerical model in PLAXIS 2D

2.2 Soil Model

Stability analyses of dams under different drawdown rates were conducted using PLAXIS 2D, a finite element program capable of simulating geotechnical problems under various loading conditions. A linear elastic-perfectly plastic Mohr-Coulomb constitutive model [19] was used to characterize the mechanical behavior of the subsoil in order to precisely simulate the behavior of the dam construction, which is made up of core, shell, and subsoil layers. Since all the analyses were performed entirely under static conditions and no dynamic analysis was conducted, this model can be sufficient for this purpose. This approach reduces computational time while reasonably capturing soil shear strength. However, it does not account for nonlinear stress-strain behavior, strain-hardening/softening, or time-dependent effects, which may slightly affect predicted deformations and the factor of safety. Future studies could adopt more advanced constitutive models and dynamic or coupled analyses to improve accuracy.

2.2.1 Core layer (undrained material)

The dam's core, composed of low-permeability clay [20], is assumed to behave under undrained conditions, remaining nearly saturated during rapid drawdown. This captures the limited dissipation of excess pore pressures, which can temporarily increase stability risks, and was modeled in PLAXIS 2D by preventing volume changes due to water movement.

2.2.2 Shell layer (drained material)

The shell layer, typically made of granular materials like sand or gravel, was modeled as drained due to its high permeability. During drawdown, pore pressures dissipate quickly, reflecting the natural behavior of coarse-grained soils, which are usually unsaturated and allow rapid drainage under changing water levels.

2.2.3 Subsoil layer (drained material)

The subsoil layer beneath the dam was also modeled as drained, reflecting its natural earth composition with sufficient permeability and thickness to allow gradual pore pressure dissipation. This assumption captures the typical behavior of the subsoil under steady-state or slow pore pressure changes and ensures it can act in a drained manner even when the core or shell layers remain undrained during rapid drawdowns. Table 1 presents the engineering properties used for different layers in the numerical model in Figure 3.

Table 1. Engineering properties used for different layers in the numerical model

Layer	γ (kN/m^3)	E (MPa)	c' (kPa)	ν	S_u (kPa)	φ' (°)	k (m/day)
Core	18	15	-	0.35	5	-	0.0001
Shell	20	20	5	0.33	-	31	1
Subsoil	21	50	1	0.3	-	35	0.01

Note: γ, E, c', φ', ν, S_u, and k denote unit weight, Young's modulus, cohesion, friction angle, Poisson's ratio, undrained shear strength of clay and permeability, respectively.

It should be noted that the drawdown rate critically affects dam stability by influencing effective stresses within soil layers. Under undrained conditions, the core experiences slow-dissipating pore pressures, temporarily increasing stress and failure risk. In contrast, drained shell and subsoil layers can quickly dissipate excess pressures, providing more stable conditions. By modeling the core as undrained and the shell and subsoil as drained, the study realistically captures the differing responses of soil layers to varying drawdown rates, ensuring an accurate assessment of the dam's internal stability, particularly under rapid drawdown scenarios.

Groundwater flow modeling in PLAXIS 2D is essential for examining the behavior and stability of geotechnical constructions like dams. The groundwater flow subtree, which lets the user define how water interacts with the soil at various limits, controls the groundwater flow. The boundary conditions for groundwater flow were established as open boundaries on the model's surface and lateral sides, and a closed boundary at the model's base.

2.3 Drawdown of Upstream Level

In this study, it is assumed that the upstream reservoir water level decreases from 25 m to 5 m during drawdown. It means that the variation in the head (ΔH) is 20 m, as shown in Figure 4.

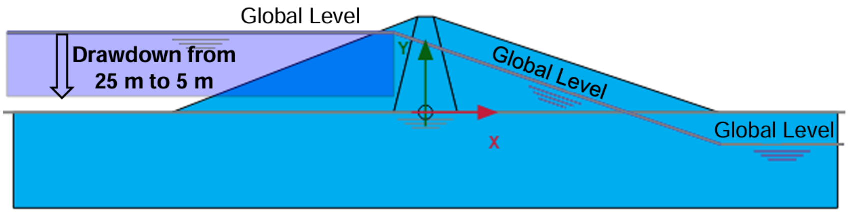

Figure 4. Illustration of upstream drawdown

3 Results and Discussion

This section presents and discusses the results of the two-dimensional numerical analyses regarding the influence of drawdown rate, core geometry, core permeability, and core/shell layer strengths on the dam's stability and deformation. Three core geometries were modeled, and for each, the effects of hydraulic and loading conditions were systematically investigated. Drawdown rates of 5, 25, and 50 days were considered to represent rapid, intermediate, and gradual scenarios, while core permeability was set at 10^{-5} m/s, 10^{-4} m/s, and 10^{-3} m/s. The core layer strength (S_u) was assigned values of 5, 20, and 40 kPa, and the shell layer strength (c') was set to 5, 10, and 40 kPa.

3.1 Factor of Safety Analysis

In the calculation of the factor of safety, PLAXIS 2D progressively reduced the soil's shear strength parameters, $\tan\varphi'$ and c', as well as its tensile strength, until failure occurred. A multiplier, denoted by $\sum \mathrm{Msf}$, was used in PLAXIS 2D to define the values of the soil strength parameters at each stage of the analysis. This multiplier was calculated as:

$$\sum \mathrm{Msf} = \frac{\tan\varphi_{\text{input}}}{\tan\varphi_{\text{reduced}}} = \frac{c_{\text{input}}}{c_{\text{reduced}}} = \frac{\mathrm{S}_{\text{u, input}}}{\mathrm{S}_{\text{u, reduced}}} = \frac{\text{Tensile strength}_{\text{ input}}}{\text{Tensile strength}_{\text{ reduced}}} \tag{1}$$

where, the strength parameters with the subscript "input" represent the properties defined in the material dataset, while those with the subscript "reduced" denote the values after reduction during the analysis. The factor Msf was initially set to 1 at the beginning of the calculation to assign all material strengths their input values. PLAXIS 2D was employed to calculate the factor of safety using the load advancement (number-of-steps) procedure. The incremental multiplier Msf was used to define the initial increment of strength reduction during the initial calculation step. The strength parameters were then automatically and successively reduced until all calculation steps were completed. Finally, the factor of safety was calculated as:

$$\text{Factor of Safety} = \frac{\text{Available strength}}{\text{Strength of failure}} = \text{Value of} \sum \text{Msf at failure} \tag{2}$$

3.1.1 Effect of drawdown rate on dam stability

Figure 5 compares the factor of safety versus displacement for dam models subjected to drawdown periods of 5, 25, and 50 days, during which the water level drops from 25 m to 5 m, as shown in Figure 4. The figure shows that the factor of safety increases significantly as the drawdown period extends. During rapid drawdown (5 days), the reservoir level drops faster than pore pressures can dissipate in the low-permeability core, resulting in high excess pore pressures, reduced effective stress, and lower soil shear strength. This makes the dam more susceptible to instability. In contrast, longer drawdown durations (25–50 days) allow pore pressures to dissipate gradually, increasing effective stress and shear strength, while slower hydraulic changes reduce the risk of slope failure. The calculated factors of safety are 1.12, 1.36, and 1.48 for 5, 25, and 50 days, respectively, showing a 32% improvement from the shortest to the longest drawdown. These results emphasize the importance of controlled, gradual drawdown for enhancing dam stability, particularly in structures with low-permeability materials, and highlight the critical role of reservoir operation strategies in ensuring long-term safety.

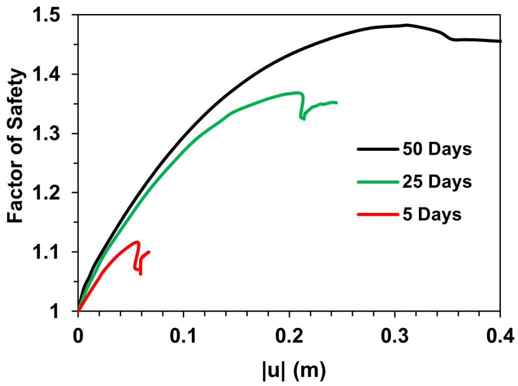

Figure 5. Effect of drawdown rate on dam stability

3.1.2 Effect of core geometry on dam stability

Figure 6 compares the factor of safety versus the horizontal displacement of the crest for dam models with three core widths: 10 m, 15 m, and 20 m. The figure shows that increasing the core width reduces the factor of safety against the horizontal displacement of the crest. A wider undrained core retains excess pore water pressure for a longer period during drawdown because of its low permeability. When pore pressures dissipate slowly, the effective stresses within the core remain low, which in turn reduces its shear strength. This weaker internal resistance allows larger horizontal deformations to develop in the upper part of the dam. As a result, increasing the width of the undrained core leads to reduced overall stability and a lower factor of safety against horizontal displacement of the crest.

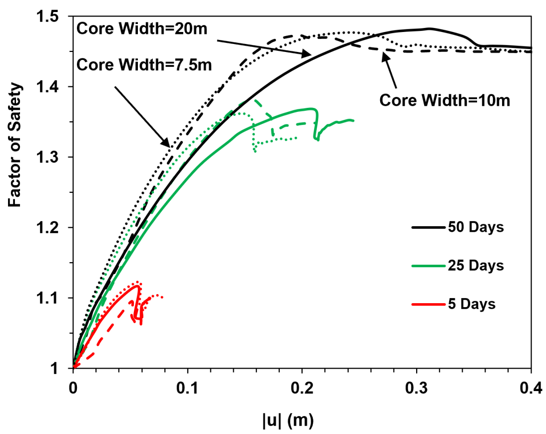

Figure 6. Effect of core geometry on dam stability

3.1.3 Effect of core permeability on dam stability

Figure 7 compares the factor of safety versus the horizontal displacement of the crest for dam models with core permeability of 10^{-3} m/s, 10^{-4} m/s, and 10^{-5} m/s. When the core permeability increases, pore water pressures dissipate more quickly during reservoir drawdown. Faster dissipation leads to a more rapid increase in effective stress within the core, which improves the shear strength of the material. This strengthened core provides greater resistance against horizontal deformation of the crest. The effect becomes more pronounced at higher drawdown rates, because rapid water-level reduction generates larger excess pore pressures. In a low-permeability core, these pressures remain trapped and significantly reduce stability. In contrast, a more permeable core can relieve excess pore pressures even during fast drawdown, resulting in a noticeably higher factor of safety.

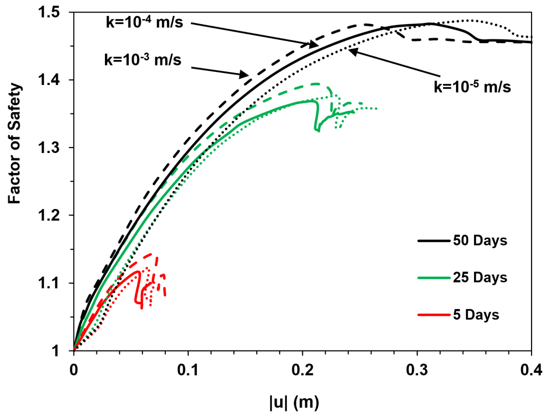

Figure 7. Effect of core permeability on dam stability

3.1.4 Effect of core strength on dam stability

Figure 8 compares the factor of safety versus the horizontal displacement of the crest for dam models with core strength (S_u) values of 5 kPa, 20 kPa, and 40 kPa. According to the figure, increasing the strength of the undrained core directly enhances its shear resistance. A stronger core can better withstand the shear stresses and deformations that develop during reservoir drawdown. Because the core plays a central role in supporting the upstream-downstream load transfer, higher undrained shear strength improves the internal stability of the dam, reduces horizontal deformation, and prevents the development of potential failure surfaces. As a result, increasing the core strength leads to a significant increase in the factor of safety, since the dam can resist larger stresses before reaching failure conditions.

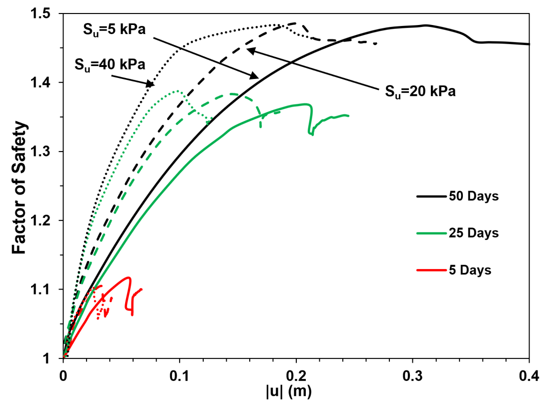

Figure 8. Effect of core strength on dam stability

3.1.5 Effect of shell strength on dam stability

Figure 9 compares the factor of safety versus the horizontal displacement of the crest for dam models with three different shell strength (c') values of 5 kPa, 10 kPa and 40 kPa. According to the figure, increasing the strength of the shell material from 5 kPa to 40 kPa results in a considerable increase in the factor of safety. This can be explained by the fact that the shell zones constitute the outer portions of the dam body, which are critical in resisting sliding along potential slip surfaces. During drawdown or other loading conditions, these outer zones are subjected to shear stresses that must be mobilized to maintain overall stability. The shell material's cohesion directly contributes to resisting these shear forces. Therefore, higher shell strength enhances the dam's ability to withstand driving forces and increases the overall factor of safety.

Unlike the core, which primarily controls seepage and pore pressure distribution, the shell zones play a more significant role in the structural stability of the dam by forming the majority of the material along potential failure surfaces. When the cohesion of the shell is increased, the shear strength of the soil along these critical surfaces rises, which improves the dam's resistance against sliding and reduces the likelihood of slope failure. Consequently, the calculated factor of safety reflects this improvement, demonstrating that the dam is considerably more stable with stronger shell material. From an engineering perspective, this finding highlights the importance of shell material properties in dam design. By selecting materials with higher cohesion or by improving the shell through compaction and quality control during construction, engineers can significantly enhance dam stability. This approach not only increases the global factor of safety but also contributes to reducing deformation and potential serviceability issues, thereby improving the long-term performance and reliability of the structure.

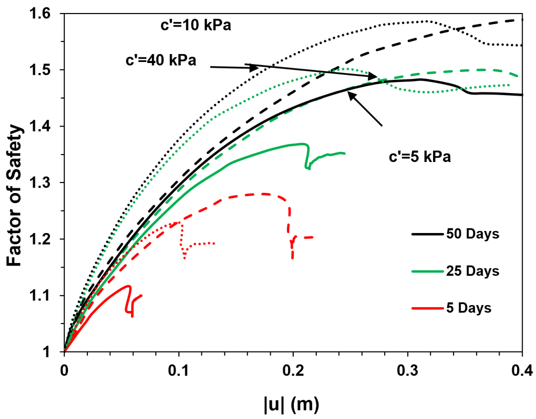

Figure 9. Effect of shell strength on dam stability

3.2 Crest Settlement Analysis

3.2.1 Effect of drawdown rate on crest settlement

Figure 10 compares the settlement of the crest for dam models subjected to drawdown periods of 5, 25, and 50 days, during which the water level drops from 25 m to 5 m. Drawdown rate has little effect on crest settlement because the settlement is mainly governed by the effective stress changes within the dam body rather than the drawdown rate. Since the total reduction in water level (from 25 m to 5 m) is the same in all cases, the final stress state and deformation are nearly identical, resulting in similar crest settlements of about 9 cm.

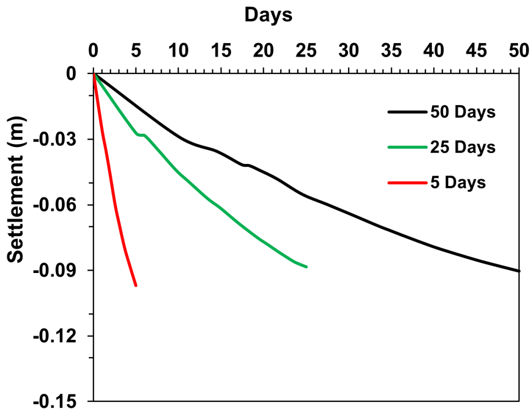

Figure 10. Effect of drawdown rate on crest settlement

3.2.2 Effect of core geometry on crest settlement

Figure 11 presents the crest settlement for dam models with core widths of 10 m, 15 m, and 20 m. As shown in the figure, increasing the core width (i.e., the extent of the undrained zone) leads to greater crest settlement, particularly when the drawdown period increases from 5 to 50 days. The increase in crest settlement with a wider core is mainly caused by the higher proportion of low-permeability (undrained) material in the dam body. A wider core restricts pore water dissipation during drawdown, leading to excess pore pressure buildup and a greater reduction in effective stress. This results in larger deformation and settlement, especially when the drawdown rate is faster, as there is insufficient time for pore pressure equalization within the core.

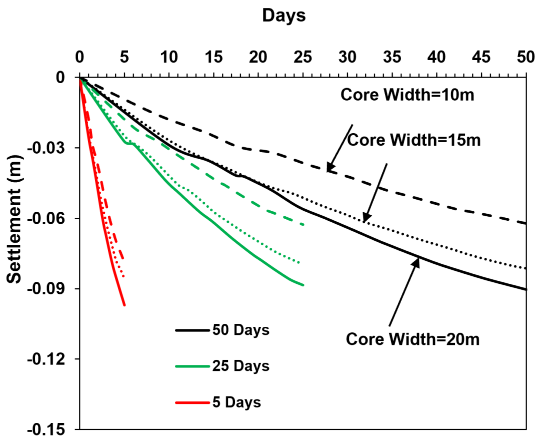

Figure 11. Effect of core geometry on crest settlement

3.2.3 Effect of core permeability on crest settlement

Figure 12 compares the crest settlement of dam models with core permeability of 10^{-3}, 10^{-4}, and 10^{-5} m/s. According to the figure, increasing the core permeability from 10^{-5} m/s to 10^{-3} m/s slightly decreases the crest settlement of the dam. The slight decrease in crest settlement with increasing core permeability is caused by the faster dissipation of pore water pressures during the drawdown. When the core is more permeable, excess pore pressures generated by the reduction in water level can dissipate more quickly, leading to a more uniform and stable effective stress distribution within the dam body. As a result, the deformation and settlement of the crest are slightly reduced.

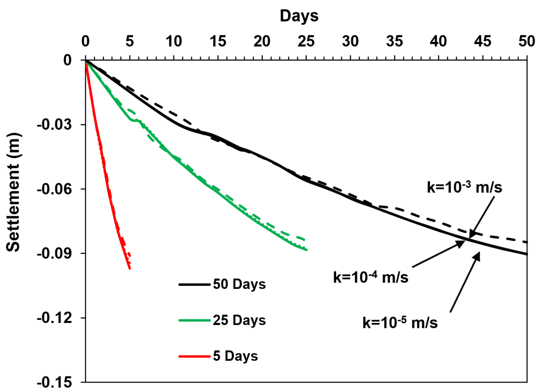

Figure 12. Effect of core permeability on crest settlement

3.2.4 Effect of core strength on crest settlement

Figure 13 compares the crest settlement of dam models with core strength (S_u) values of 5 kPa, 20 kPa, and 40 kPa. According to the results, increasing the core strength decreases the crest settlement, especially when the rate of drawdown decreases. The decrease in crest settlement with increasing core strength during slower drawdown is attributed to the improved stability and reduced deformation of the stronger core material. When the drawdown rate is low, pore water pressures have sufficient time to dissipate, allowing the effective stress to increase gradually. In this condition, a stronger core (with higher S_u) undergoes less compression and shear deformation, resulting in smaller crest settlement.

3.2.5 Effect of shell strength on crest settlement

Figure 14 compares the crest settlement for the dam models with three different shell strength (c') values: 5 kPa, 10 kPa, and 40 kPa. According to the results, increasing the shell strength decreases the crest settlement. This is because a higher shell strength improves the shear resistance and overall stiffness of the dam body, allowing it to better resist deformation under loading and reducing the magnitude of vertical displacement at the crest.

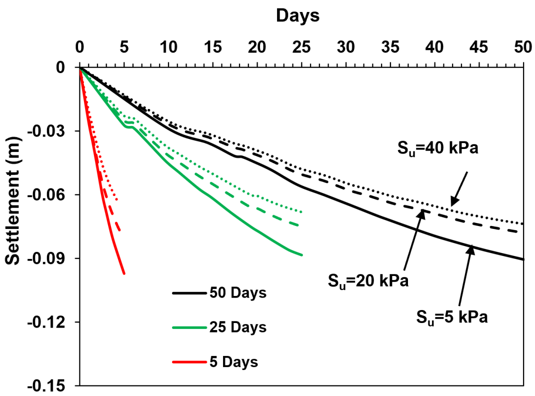

Figure 13. Effect of core strength on crest settlement

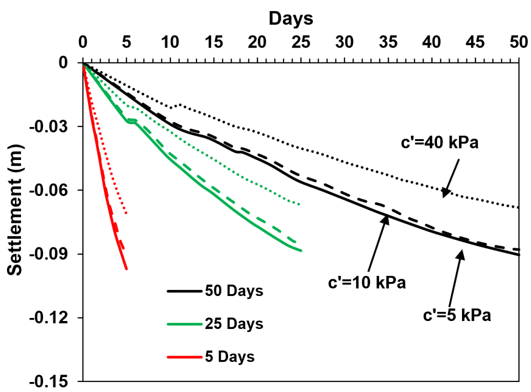

Figure 14. Effect of shell strength on crest settlement

4 Conclusion

This study demonstrates that the stability and deformation behavior of earth dams during reservoir drawdown are governed by a complex interaction of hydraulic and geotechnical parameters. By examining not only drawdown rate but also core geometry, permeability, and the mechanical properties of core and shell materials, the research expands beyond the narrowly focused approaches commonly found in the literature. It should be noted that since the outcomes and conclusions of the present study are consistent with previous findings reported in the literature, the use of the Mohr-Coulomb model is considered reasonable and justified for the current analysis.

This integrated perspective provides a more realistic and comprehensive understanding of dam performance under fluctuating reservoir conditions. The numerical analyses conducted using PLAXIS 2D highlight how variations in undrained zones, permeability contrasts, and strength parameters shape both the factor of safety and the crest deformation patterns during drawdown. These findings underscore that dam stability cannot be reliably assessed by drawdown rate alone; instead, it depends on the combined hydraulic response and mechanical resistance of the dam's internal structure. Overall, the study contributes to improved dam safety assessment by identifying the key controlling mechanisms and by demonstrating how different design and material configurations influence performance under operational drawdown. The insights gained can assist engineers in optimizing core and shell design, selecting appropriate material properties, and establishing safer drawdown procedures to minimize instability risks. This work therefore supports more informed decision-making for dam operation, maintenance planning, and future design improvements. Key findings are listed as follows:

- Slower drawdown rates increase safety by allowing pore pressure dissipation, while rapid drawdown reduces stability. Crest settlement remains nearly unchanged, as it depends on total stress change. This indicates that controlling the drawdown rate can enhance stability without significantly affecting settlement for the studied dam configurations.
- Slower drawdown rates (25–50 days) improve dam stability by allowing excess pore pressures in the low-permeability core to dissipate, increasing effective stress and shear strength. Rapid drawdown (5 days) temporarily reduces stability, highlighting the importance of controlled drawdown procedures for maintaining safety.
- The results suggest that dams with wider, low-permeability cores require careful drawdown management to

maintain stability. Operators should consider slower, controlled water-level reductions to allow pore pressures to dissipate, reducing horizontal displacement and crest settlement. In design, the findings highlight the importance of optimizing core width and permeability to balance structural stability and operational requirements, providing guidance for safer dam operation and maintenance procedures.

- Lower core permeability leads to higher excess pore pressures during drawdown, temporarily reducing stability under rapid water-level reductions, while higher permeability allows faster dissipation, limiting deformation. In the field, this emphasizes the need to balance seepage control and transient stability when selecting core materials and planning drawdown procedures to ensure dam safety.
- Increasing core permeability slightly reduces crest settlement by allowing faster pore pressure dissipation and more uniform stress distribution. In practice, selecting cores with appropriate permeability can help minimize deformation during drawdown while maintaining overall dam stability.
- Increasing the undrained core strength significantly enhances dam stability by improving shear resistance, reducing horizontal deformation, and limiting crest settlement—especially under slower drawdown. In practice, selecting stronger core materials can increase the factor of safety and reduce deformation, guiding safer dam design and controlled drawdown procedures.
- Increasing shell strength significantly improves dam stability by enhancing shear resistance and stiffness, reducing deformation and crest settlement. In practice, using stronger shell materials can help prevent sliding along potential slip surfaces and increase safety, informing design and material selection for more resilient dams.

Overall, this research provides practical guidance for optimizing drawdown procedures, contributing to safer and more reliable dam operation.

Author Contributions

Software, A.A.R.A.; validation, A.A.R.A.; formal analysis, A.A.R.A.; writing—original draft preparation, A.A.R.A.; conceptualization, M.S.; methodology, M.S.; supervision, M.S.; writing—review and editing, M.S. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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