2-Dimensional and 3-Dimensional Drawdown Analysis of Sediment Dam

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ABSTRACT: This study analyzes the stability of four sediment dams (A, B, C, and D) at PT XYZ, using two-dimensional and three-dimensional limit equilibrium methods. The scenarios considered are existing condition, rapid drawdown, one empty pond, and pond at full capacity containing water/slurry from mining activities. The results indicate that the factor of safety is lowest in the rapid drawdown scenario, followed by one empty pond, existing condition, and full capacity ponds. The average difference in factor of safety between the existing condition and rapid drawdown is 0.31. The presence of water/slurry increases the normal stress on the dam, resulting in a higher factor of safety for the full ponds scenario. Surface-altering optimization is also used to enhance the accuracy of analyses. The study emphasizes the importance of considering multiple scenarios when conducting geotechnical analysis for sediment dams, especially changes in water level.

Keywords: dam stability, sediment dam, limit equilibrium method, rapid drawdown analysis.

1 INTRODUCTION

Water management facilities, such as settling ponds, are an integral part of the hydrotechnical structures used in the mining industry. Sediment dams, constructed using available overburden materials, are a common design feature of settling ponds. The design of sediment dams is heavily influenced by the capacity of the settling pond to accommodate the inflow and outflow of water/slurry from mining activities.

Water movement in soil media is a critical issue with significant negative consequences. Seepage forces resulting from water flow can significantly impact the stability of soil particles, with the critical hydraulic gradient being the main parameter that describes their influence. Exceeding this gradient can alter the mechanical and physical properties of the soil, potentially leading to quicksand, hydraulic uplift, piping, suffusion, or clogging, depending on the groundwater conditions.

Rapid drawdown poses a significant threat to the stability of hydrotechnical structures. This threat is mainly associated with cohesive soils that have low permeability, where pore pressure does not disperse at the same rate as the external water level changes. This can lead to an increase in shear stress and a decrease in the dam's factor of safety (FS), potentially causing slope failures.

Changes in external water level, especially rapid drawdown, significantly impact the stability of hydrotechnical structures. Water is present on both sides of these structures, making both slopes susceptible to loss of stability. The sediment dam of PT XYZ settling pond is particularly vulnerable to rapid changes in external water level, as evidenced by significant damages observed during a site inspection on Dam A, B, C, and D (Figure 1).

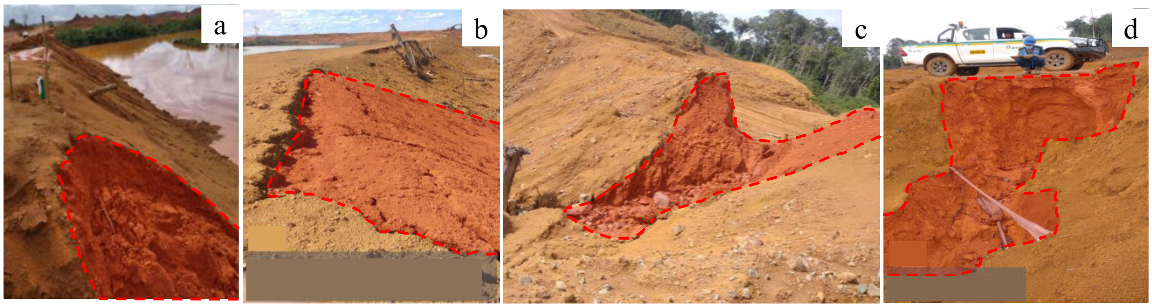

Figure 1. Cracks and failures on (a) Dam A, (b) B, (c) C, and (d) D with a displacement range of 10 – 50 cm.

This paper aims to analyze the phenomena that affect the stability of the sediment dam of a settling pond under conditions of rapid changes in external water level. This purpose of the study is to explain the reasons behind the observed damage to the structures.

2 DATA

This study analyzes the stability of four dams - Dam A, B, C, and D - that serve as boundaries to settling ponds. These dams are adjacent to water bodies, including settling ponds and swamps with varying water levels.

The dams are composed of overburden materials which are the side rocks from bauxite mining, such as clayey rocks, and do not involve any reinforcements. The dams are also used as roads for heavy equipment units, resulting in a distributed load of 90 kN/m2 in the stability analysis of the dams.

Laboratory tests were conducted according to the ISRM Suggested Method to determine the strength parameters of the materials, such as unit weight, cohesion, and friction angle. The hydraulic conductivity value (K) was determined using a commonly accepted general value in the field. Table 1 summarizes the material properties used in the analysis, which served as the basis for the stability analysis of the sediment dams.

Table 1. Physical and mechanical parameters of dam materials.

Parameters		Overburden	Peaty clay	Silty clay 1	Silty clay 2	Sand
Material color						
Cohesion	[kPa]	33.15	24.27	17.39	16.77	16.77
Friction angle	[°]	34.43	16.75	35.07	26.63	31.04
Unit weight	[kN/m^3]	13.18	10.96	12.37	10.29	11.70
Hydraulic Conductivity	[m/s]	10^{-6}	10^{-7}	10^{-7}	10^{-7}	10^{-5}

Figure 2 illustrates the location of the dam cross-section to be analyzed, as well as the locations for documentation of cracks and landslides on the dam. The 3D analysis extends the 2D section to a length of 200 meters to meet the requirement of B/H (width/height) $\geq$ 10. Table 2 shows the dimensions of each dam, including its base, height, and slope angle.

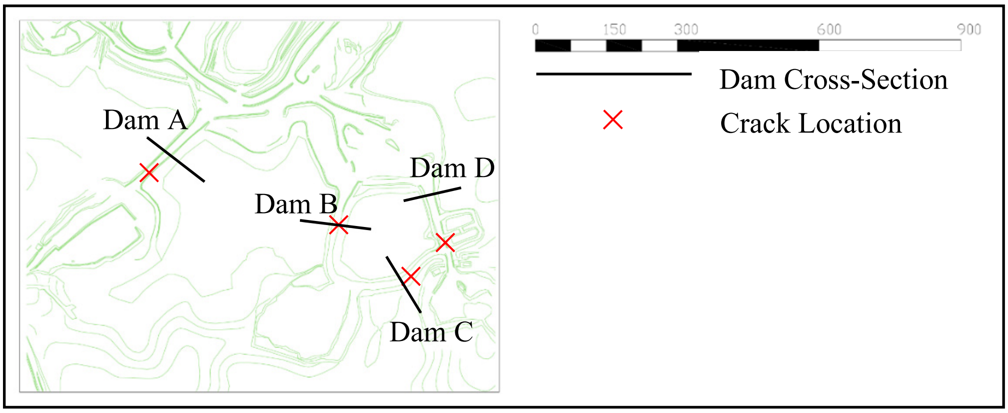

Figure 2. Location of the dam cross-section and documentation of cracks.

Table 2. Dam dimensions.

Dam Dimensions		Dam A	Dam B	Dam C	Dam D
Height	[m]	10.70	10.70	5.80	7.34
Upper Base	[m]	20.00	24.75	8.07	25.15
Lower Base	[m]	37.50	34.73	27.80	40.46
Slope Angle	[°]	51.00	65.00	30.50	42.00
B/H		18.69	18.69	34.48	27.25

3 METHODS

Slope stability analysis was conducted using Bishop's 2-dimensional and 3-dimensional limit equilibrium method (LEM) which represents an uncoupled analysis approach. Calculations were performed using Rocscience Slide2 and Slide3 software, which can test the stability of the slopes not only at constant water level but also after a rapid drawdown. The computations were conducted for four scenarios based on the water level: existing conditions, rapid drawdown conditions, pond at full capacity conditions, and one empty pond while the other is in full pond condition.

The water level in existing conditions varies from 0.3 to 4.6 meters below the upper base of the dam based on direct on-site measurement. For the rapid drawdown condition, the existing water level is used and the reservoir is assumed to be drained without any specified drawdown rate. In the pond at full capacity condition, the water level is maintained at 0.3 meters below the upper base of the dam, indicating that the pond is full but not flooded. For the empty pond condition, the water level is assumed to be 1 meter below the upper base of the dam, to represent a condition where the pond is empty but not dry and still contains some water.

The groundwater seepage in the dam body is calculated through steady-state finite element analysis (FEA). Steady-state conditions arise when the flow on a surface under consideration has a constant magnitude and direction. As groundwater seepage FEA cannot be used on rapid drawdown conditions in the Slide software, the water surface results obtained from the steady-state FEA are imported for further analysis.

The dam stability analysis is calculated using the circular slip surface method for 2-dimensional and the sphere method for 3-dimensional as recommended by Bishop's method, which is suitable for slip surfaces with such shapes. Surface-altering optimization (SAO) is also used to determine the factor of safety value if the slip surface conditions are not perfectly circular/sphere. Surface-altering optimization is a tool that modifies the geometry of a given slip surface based on a derivative-free constrained linear optimization.

The rapid drawdown condition analysis is conducted using the B-bar method, which considers the changes in pore water pressure and the shear strength of the dam material during rapid drawdown to calculate the factor of safety against failure. The pore pressure coefficient $\overline{B}$ used is 1, assuming the most pessimistic condition.

4 RESULTS AND DISCUSSION

Figure 3a shows the results of the steady-state finite element analysis used to obtain the groundwater seepage for slope stability analysis. Figures 3b and 4 depict the stability analysis results of the dam under rapid drawdown conditions in 2D and 3D. The results of the stability analysis of slopes are presented in Table 3.

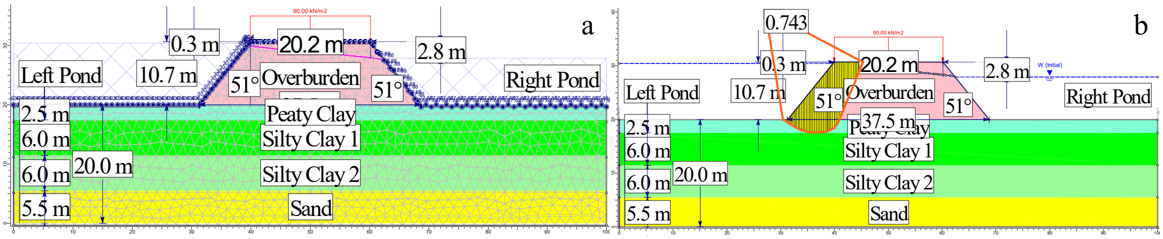

Figure 3. Dam A 2-dimensional analysis under rapid drawdown conditions using surface-altering optimization a. steady-state finite element analysis b. slope stability analysis.

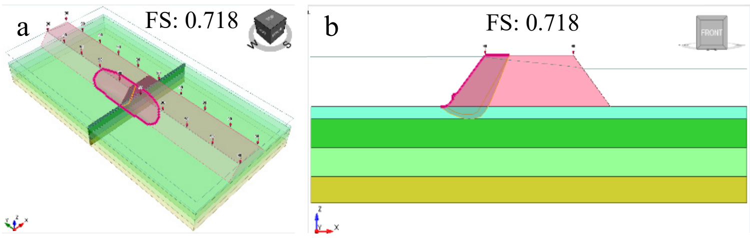

Figure 4. Dam A 3-dimensional analysis under rapid drawdown conditions using surface-altering optimization a. side view b. front view.

Table 3. Dam stability analysis results.

Sediment Dam	Scenarios	2D FS	3D FS	2D FS SAO	3D FS SAO
Dam A	Rapid Drawdown	0.94	1.11	0.74	0.75
	One Empty Pond	1.19	1.42	0.98	0.99
	Existing	1.57	1.85	1.21	1.23
	Full Pond	1.84	2.15	1.41	1.51
Dam B	Rapid Drawdown	0.91	1.18	0.72	0.79
	One Empty Pond	1.18	1.41	0.93	0.96
	Existing	1.25	1.44	0.97	1.02
	Full Pond	1.66	2.11	1.55	1.44
Dam C	Rapid Drawdown	1.50	1.79	1.32	1.36
	One Empty Pond	1.49	1.81	1.27	1.32
	Existing	1.68	2.06	1.41	1.51
	Full Pond	1.97	2.44	1.61	1.69
Dam D	Rapid Drawdown	1.38	1.65	1.18	1.21
	One Empty Pond	1.42	1.70	1.18	1.22
	Existing	1.62	1.98	1.30	1.34
	Full Pond	1.90	2.35	1.49	1.54

Based on the calculation results, the factor of safety values from the lowest to the highest are the rapid drawdown condition, one empty pond condition, existing condition, and full ponds condition (Figure 5).

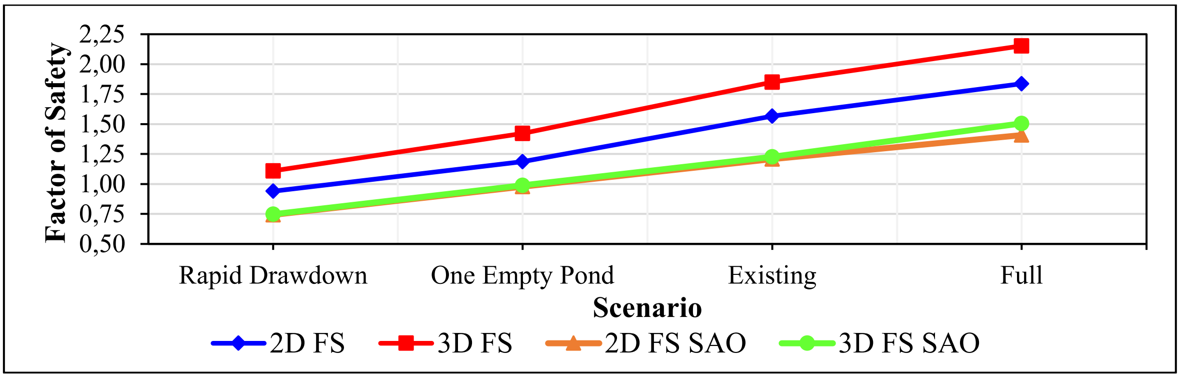

Figure 5. Stability charts of Dam A.

The results of the analysis provide evidence for the significance of considering the actual operational conditions of a structure in calculations. Traditionally, slope stability analyses are performed assuming constant water levels. In this particular case, the dam exhibited stability during both existing and full pond conditions. However, the results for the factor of safety indicated a loss of stability during the rapid drawdown and one empty pond conditions, which corresponds to the technical condition of the dam. The average difference in FS between the existing condition and the rapid drawdown condition is 0.31, with a maximum difference of 0.74 and a minimum difference of 0.09. The observed damage is attributed to the issue of pore pressure dissipation.

In all the conducted simulations, the lowest FS value was obtained from the 2-dimensional surface-altering optimization method. This result is similar to the findings in previous studies that the 3-dimensional factor of safety is larger than 2-dimensional factor of safety.

Furthermore, the 3-dimensional slip-surfaces were imported by selecting a middle cross-section and compared with the 2-dimensional slip surfaces (Figure 6). Without surface-altering optimization, the results showed differences in the slip-surface geometries between 2-dimensional and 3-dimensional analyses. However, with surface-altering optimization, the slip-surface geometries and factor of safety results were almost identical in both 2-dimensional and 3-dimensional analyses. This suggests that surface-altering optimization can be a valuable tool for modifying slip-surface geometries closer to the actual condition and improving the accuracy of the stability analysis.

Since the rapid drawdown condition simulates a pessimistic scenario, this method can be used as an initial guide in determining the dam dimensions. Once the dam is constructed and there is water in the pond, the water level can be monitored and further analyzed using time-dependent transient methods to obtain the latest slope stability.

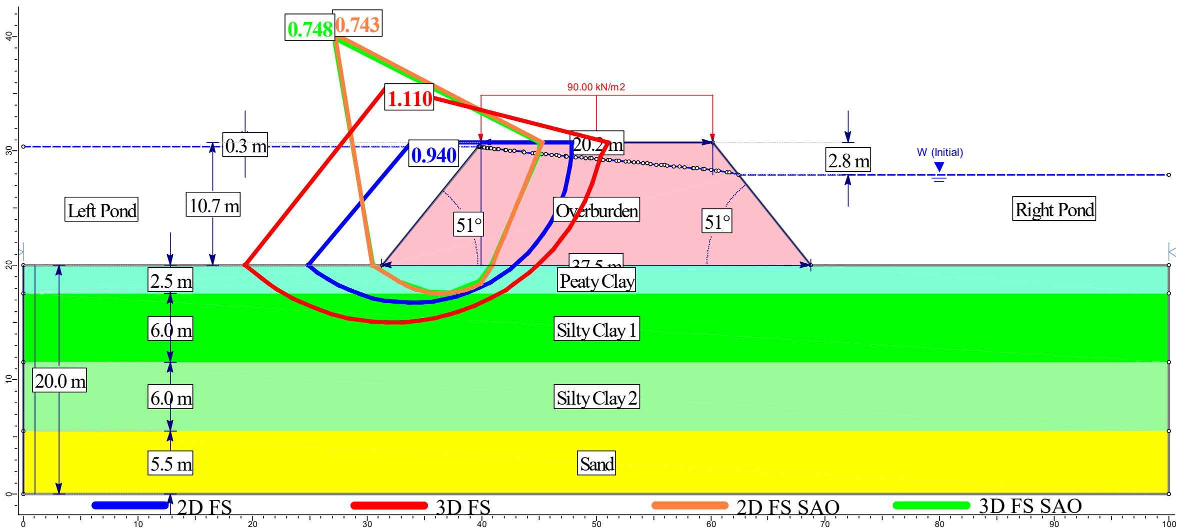

Figure 6. Dam stability results for slip-surfaces in 2-dimensional and 3-dimensional analyses, with and without surface-altering optimization.

5 CONCLUSION

The stability calculations conducted at constant water levels (existing and full ponds) demonstrate the dam's stability but fail to reflect its actual state. Additional analyses, including rapid drawdown and empty pond conditions, are crucial for considering all factors influencing hydrotechnical structure stability and highlighting the issue of pore-pressure dissipation resulting in stability loss.

The average difference in factor of safety between the rapid drawdown scenario and the existing condition is 0.31, where the 2-dimensional surface-altering optimization rapid-drawdown method yields the lowest factor of safety. Surface-altering optimization proves valuable in enhancing the accuracy of 2-dimensional and 3-dimensional stability analyses, aligning them closer to actual conditions. The analyses confirm the importance of considering multiple scenarios, particularly variations in water level, when conducting stability analysis of a sediment dam.

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