Vol. 24, n.°1, pp. 45-64, 2025
Revista UIS Ingenierías
https://revistas.uis.edu.co/index.php/revistauisingenierias
Universidad Industrial de Santander

Evaluation of the Influence of Rapid Drawdown in Some Colombian Earth Dam Systems and Reservoir Zones Through Numerical Modeling

Evaluación de la influencia del vaciado rápido en algunos sistemas de presas de tierra y zonas de embalse colombianos mediante modelización numérica

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Received: 30 August 2024. Accepted: 31 December 2024. Final version: 3 February 2025.

Abstract

Rapid drawdown occurs when the reservoir level drops at such a rate that the material that makes up the slopes surrounding the reservoir or body of the dam is incapable of adequately dissipating the pore pressure. The numerical study of this phenomenon's influence becomes relevant to determine the effect of the variables and provide recommendations for a possible eventuality or the design of future projects. Using the GeoStudio 2012 software, this phenomenon was evaluated using numerical modeling by the simple and coupled analysis of two dams and three existing reservoir areas in Colombia. These structures were subjected to five emptying rates and four cases of drawdown levels. Parametric curves were obtained that represented the behavior of the safety factor in which a height of 2/3 of the normal level resulted in the most significant condition. Additionally, it was determined that the most critical situation corresponds to the day of or the one immediately following the end of the water drop. The simple analysis was greatly affected by the alteration of the conditions and characteristics of the dam soil. Conversely, the coupled analysis was greatly impacted by the drawdown level above the rate. These results made it possible to obtain the intervals of reduction percentages that the safety factor can suffer depending on the drawdown level.

Keywords: numerical modeling; rapid drawdown; earth dams; reservoirs; Colombia.

Resumen

El vaciado rápido se presenta cuando el nivel del embalse desciende a una velocidad tal que el material que constituye los taludes aledaños al vaso o al cuerpo de la presa no es capaz de disipar la presión de poros adecuadamente. Luego, el estudio numérico de la influencia de este fenómeno se hace relevante con el fin de parametrizar el efecto de variables, brindando así, recomendaciones para una posible eventualidad o para el diseño de futuros proyectos. Dado lo anterior, mediante el software GeoStudio 2012 se realizó la evaluación de este fenómeno con modelización numérica por

ISSN Online: 2145 - 8456

How to cite: V. Campos-Martínez, O. González-Plaza, L. G. Cruz-Velasco, "Evaluation of the Influence of Rapid Drawdown in Some Colombian Earth Dam Systems and Reservoir Zones Through Numerical Modeling," *Rev. UIS Ing.*, vol. 24, no. 1, pp. 45-64, 2025, doi: https://doi.org/10.18273/revuin.v24n1-2025005

análisis simples y acoplados de dos presas y tres zonas de embalse existentes en Colombia, donde fueron sometidos a cinco tasas de vaciado y cuatro casos de alturas de desembalse. Se obtuvieron curvas paramétricas que representan el comportamiento del factor de seguridad, donde se sustenta que a 2/3 de la altura del agua desde el nivel normal se presenta la condición más significativa, además de que la situación más crítica corresponde al día o al inmediatamente siguiente en que termina el descenso del agua. En cuanto al análisis simple se observó muy afectado bajo la alteración de las condiciones y características del suelo de la presa, mientras que en el análisis acoplado se evidenció la importancia de la altura de vaciado por encima de la velocidad de desembalse donde fue posible la obtención de intervalos de porcentajes de reducción que puede sufrir el factor de seguridad en función de la altura a desembalsar.

Palabras clave: modelización numérica; desembalse rápido; presas en tierra; embalses; Colombia.

1. Introduction

Colombia has an outstanding capacity to produce hydroelectric energy for the public interest. That is why the importance of studying the local behavior of reservoirs and dams arises to guarantee the safety and efficiency of projects located near populated areas [1]. Climate change is currently underway and the general precipitation cycles are not very different from the anomalies that occur every few years. Locally, the Niño phenomenon is a periodic climatic condition that causes a significant decrease in the amount of precipitation and humidity in the Caribbean and Andean regions. What's more, these districts involve the country's 10 hydroelectric plants which generate most of Colombia´s energy [2].

In times of decreased rainfall, the inputs of water to the reservoir are less than the outputs. This causes a phenomenon in which the water level in the reservoirs decreases in a relatively short time. These reductions could cause instability problems on the slopes of the dam upstream (in land dams) or on the slopes surrounding the reservoir in the event that the soil is not suitable to dissipate the pore pressure caused. As a result, these occurrences can produce a collapse in the structure that can go from a local problem that can be corrected to a total failure [3].

The failure of dams due to landslides is the most susceptible to analysis and quantification with existing methods for the study of slope stability [4]. What is more, the evaluation of the drawdown phenomenon is a coupled problem due to the fact that there are variations of both hydraulic and geotechnical conditions [5]. These factors cause a discrepancy to occur between the idealization of the characteristics that are adopted for the analysis and the observations of the real world, making the analysis of the phenomenon by conventional methods cumbersome.
In 2016, Alonso and Pinyol [6] presented a study to determine the causes of a large landslide on the slope of the Canelles reservoir in Spain. A morphological and geological study of the area revealed that it was the reactivation of an old landslide due to a decrease in the water level of the reservoir that reached rates between 0.5 m/day and 1.2 m/day after a long period with the level close to the maximum. A coupled analysis was carried out for a section of the reservoir under study using a finite element program analyzing data 4 years prior to the event. This allowed the hypothesis to be validated due to the presence of clay with high plasticity and low permeability which caused the slope's instability.

Two more cases related to the application of rapid outflow numerical analysis in real-world cases were presented. Their aim was to evaluate different approaches to calculate pore pressure distributions during and after the event. To do this, a study of a single slope was carried out under different conditions and analytical methods. They concluded that a simple analysis using a pure flow analysis without drainage led to significant errors in the distributions of the pore pressures when compared to a coupled hydraulic-mechanical analysis.

Besides, Alonso and Pinyol [6] also evaluated a slope upstream from the Glen Shira dam (United Kingdom) under similar conditions where the results of the numerical modeling were compared with field measurements. The results indicated that the classic methods of evaluation of pure flow without drainage were conservative and unrealistic.

Two years later, in 2018, Gao and his colleagues [7] performed a series of numerical simulations to study the influence of rapid drawdown on the stability of slopes. Using a sensitivity analysis, they developed an estimation model that relates the safety factor to the angle of inclination of the slope, the permeability of the soil, and the discharge rate.

In that same year, Burgos along with other researchers [8] performed a study where they analyzed the variation of the safety factor in the geometry of the La Herradura dam located in Cuba. Using the mechanics of partially saturated soils under different load states and the implementation of the GeoStudio 2012 software, the safety factor could be evaluated using the Bishop and Morgenstern-Price methods.

From the study, the importance of the implementation of the laws of mechanics on partially saturated soils was analyzed. This was primarily due to the existence of increases above 5% in the safety factor, where the more influential load states occur at the end of construction and during a rapid drawdown. On the other hand, the variation between the evaluated equilibrium limit methods found no significant variation.

Then, one year later, a group of researchers [9] analyzed the behavior of the Campolattaro dam in Italy under the assumption of a strong seismic event and a subsequent rapid drawdown. They used a coupled analysis in a two-dimensional model which was carried out after a series of near-realistic loading events. Variations in the drawdown rate from 0.5 m/day to 4 m/day and emptying ratios were implemented which resulted in a reduction rate of 1 m/day as the required rate necessary to safely discharge the reservoir after a strong earthquake. They also included other alternative ratio and drawdown rate combinations.

In 2019 with a local case, Tapia [10] studied the Mancilla dam, located in the municipality of Facatativá, Cundinamarca. He studied the behavior of the dam on the land during rapid drawdown conditions using numerical modeling in 2D and 3D. He analyzed discharge rates from 0.1 m/day to 1.0 m/day in one or several drawdowns and performed a sensitivity analysis of the deformational response in the upstream slope surface. The stability of the slope upstream due to the release event was found to remain stable with a continuous release of 0.64 m/day to 0.88 m/day without jeopardizing stability. However, uncertainty arises from the fact that the operator performs drawdowns during blocks that last 4 to 6 hours, but not continually for 24 hours.

In the same year, Kahot [11] conducted a study related to rapid unloading in which the most influential parameters were soil cohesion and coefficient of internal friction, his work resulted in a formula to determine the compaction necessary to achieve the required level of cohesion when the coefficient of internal friction of a soil is estimated.

The infiltration and stability of a slope of the Khassa Chai earth dam in Iraq were studied by Alfatlawi [12] using a finite element numerical method, GeoStudio 2012, his study determined that the slope stability depends on how fast the pore water pressure dissipates and that the minimum F.S was reached in 10 hours in the case of 1 day drawdown.

In 2020, Llanque [13] in his study of slope stability analysis in the situation of rapid drawdown considered the transient flow condition, including suction, thus demonstrating that it is possible to increase the safety factor in relation to the simplified analysis that is usually adopted. On the other hand, Siacara [14] in his study combines limit equilibrium analysis with seepage analysis to investigate the safety of an earth dam during casting and over time.

By 2021, Noori [15] conducted a study using GeoStudio 2012 software to determine the influence of shell permeability on the upstream slope stability of an earthfill dam and the change in pore water pressure at different embankment heights during rapid release. In the same year, Soralump [16] was able to demonstrate by numerical analysis that strain softening was the main cause of upstream slope movement in the Khlong Pa Bon dam in Thailand, this study was accompanied by piezometer results, a retrospective analysis, inclinometer data and an annular shear test.

In 2022, Utepov [17], using the finite element method in GeoStudio, was able to determine that a rate of descent of one meter per day is considered to be rapid draining. Flores [18] carried out an investigation in which he demonstrated that for rapid draining phenomena the safety factor of the upstream slope in earth dams depends on the transient flow velocity.

Finally, in the study of Li [19], a methodology is proposed for the analysis of the influence of spatial variations and degradation coefficients on the stability of the slopes of a reservoir, as results the research found that the critical degraded value varies with the rate of reduction, the higher the rate of reduction, the higher the critical degraded value.

The described background above demonstrates that by using numerical modeling and finite elements, the analysis and quantification of the variations suffered by the resistance of the materials and the safety factor of the stability of the slope during the phenomenon become more realistic. This method also allows the comparison of hypothetical cases with real-world events to determine the impact of the assumptions and characteristics when evaluating a rapid drawdown.

In the current study, numerical modeling was carried out using the GeoStudio 2012 software [20]. The modeling is based on the geometry and geotechnical characteristics of some Colombian reservoirs and flexible dams. This process allows us to highlight the most critical situations that may arise and provide possible solutions for the design and efficiency of energy storage and dam safety. What is more, With the analysis of the variables that influence the stability of the slopes, it will be possible to create parametric curves in order to understand the influence of each of the variables. This will help us to determine the behavior of the slopes according to the conditions of the region and the soils in the region. The behavior of the slopes upstream of the dam and those surrounding the reservoir before rapid drawdown can also be analyzed for possible effects if there was a change to any of these variables.

2. Metodology

The methodology developed in the study mainly utilized modeling within the GeoStudio 2012 [20] program. This was primarily done due to the ease of interaction and efficient application in the evaluation of the performance of dams and reservoir slopes with different levels of complexity. The application allowed for a detailed transitory analysis as well as long-term solutions which are time sensitive. The integration of the stages and problems that comprise the simulation of a rapid drawdown was possible using the SEEP/W, SLOPE/W, and SIGMA/W extensions. This allowed the analysis of the results to be easily performed from one starting point to another [21].

In fact, SEEP/W is a finite extension that allows the flow of groundwater in porous systems to be analyzed. Additionally, it can be integrated with SLOPE/W to calculate the safety factor of the slope in question using transitory changes in pore pressure using limit equilibrium methods. Similarly, SIGMA/W allows a stress-strain analysis on earthen structures involving soil-structure interactions, coupled stress, and pore pressure response. In addition, SIGMA/W takes into consideration strength reduction stability using finite elements [21].

There are two methodologies for analyzing the rapid drawdown of structures that hold back water: simple analysis and coupled analysis. The phenomenon is initially understood in a stationary state that assumes the initial conditions in which the water is at the normal level of the reservoir and a transient state in which the drawdown process is simulated. Models were subjected to four cases of drawdown height for each model and five drawdown rates corresponding to 0.3 m/d, 0.5 m/d, 1.2 m/d, 2 m/d, and 4 m/d as shown in Table 1.

The difference between the methodologies is present in the considerations of the parameters that influence the problem. On the one hand, simple analysis simulates a simple transient water filtration through which the water level inside the reservoir decreases. On the other hand, a coupled analysis takes into consideration the stresses and deformations produced by the change in conditions caused by the variation of the water level in the reservoir, which also takes into account the mechanics of partially saturated soils. This is evident in the problem-solving programming using the built-in products and analysis methods [22] in the software as shown in Figure 1.

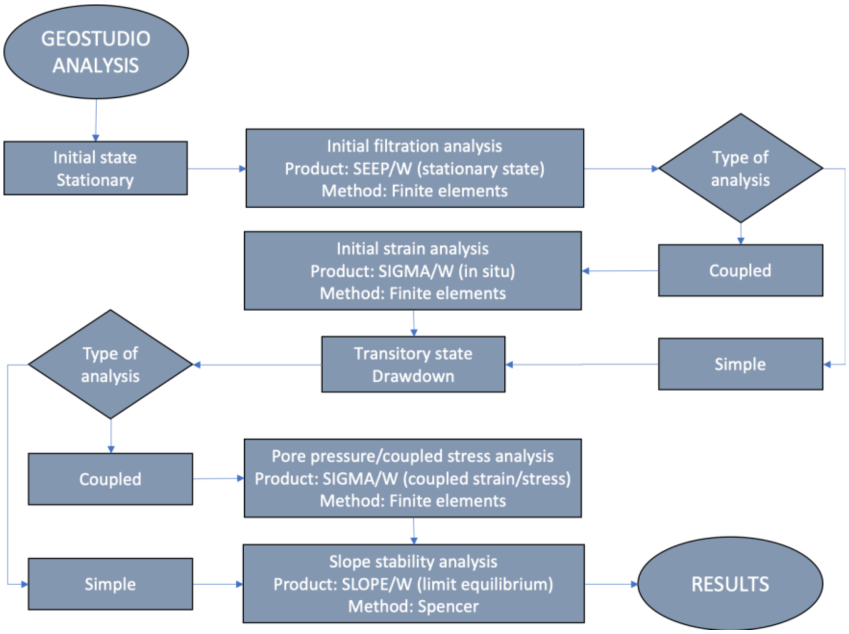

Figure 1. Simple and coupled analysis methodology. Author’s source.

Table 1. Cases of variation of the water level for discharge

Water level variation (Δh)	Case A	Case B	Case C	Case D
From	NWL.	NWL.	NWL.	NWL.
To	Bottom	NWLO.	2/3 $\mathbf{H_{NE}}$	1/3 $\mathbf{H_{NE}}$

Author's source.

Numerical modeling relies on three basic steps: pre-processing, processing, and post-processing. The former consists of obtaining all the information necessary to create the geometry and the characterization of the models. The Riogrande II and Mercaderes dams, as well as the reservoir areas of the latter along with those of Hidroituango and Salvajina, were considered to model. The study areas were proposed in different locations in Colombia (geographic coordinates are showed in Table 2) in order to cover varies layouts and site conditions.

Table 2. Geographic coordinates of the study areas

Dam	Coordinates	
	Longitude	Latitude
Mercaderes dam	76°59'5.64'' W	1°48'13.44'' N
Riogrande II dam	75°26'27.58'' W	6°30'28'' N
Hidroituango dam	75°39'46.02'' W	7°8'4.95'' N
Salvajina dam	76°42'24.13'' W	2°56'31.98'' N

Author's source.

The characterization of the models in the GeoStudio the characterization of the models in the GeoStudio software (20) was carried out using boundary conditions in the stages of each of the described analyzes and the parameters requested by each of the methods. These conditions were obtained from different sources, which included documentation, the use of data from the SGC (24) and IGAC (25), and correlations from Google Earth when data was scarce. Similarly, the estimation of the suction property was made according to the recommendations of the same software. The key geotechnical parameters are presented from Tables 3 , 4, 5, 6 and 7, and the geometric sections of each of the study areas are shown from Figures 2 , 3, 4, 5 and 6.

Table 3. Materials that make up the Mercaderes dam and its characteristics

Material	γ (kg/m^3)	E (kPa)	ν	k (m/día)	Mv (1/kPa)	C (kPa)	ϕ (°)
Core (SC – SM)	**1850**	$\mathbf{7x10^4}$	0.30	$\mathbf{8.6x10^{-4}}$	$\mathbf{1.1x10^{-5}}$	**12**	**20**
Rockfill (GP)	**2100**	$\mathbf{4x10^5}$	**0.20**	**0.0864**	$\mathbf{2.3x10^{-6}}$	-	38
Transition and crest (GW)	**1950**	$\mathbf{2.5x10^5}$	0.30	$\mathbf{8.6x10^{-3}}$	$\mathbf{3x10^{-6}}$	-	30
Foundation (Soft rock claystone)	**2300**	$\mathbf{4x10^5}$	0.17	$\mathbf{8.6x10^{-4}}$	$\mathbf{2.3x10^{-6}}$	-	40

Author's source.

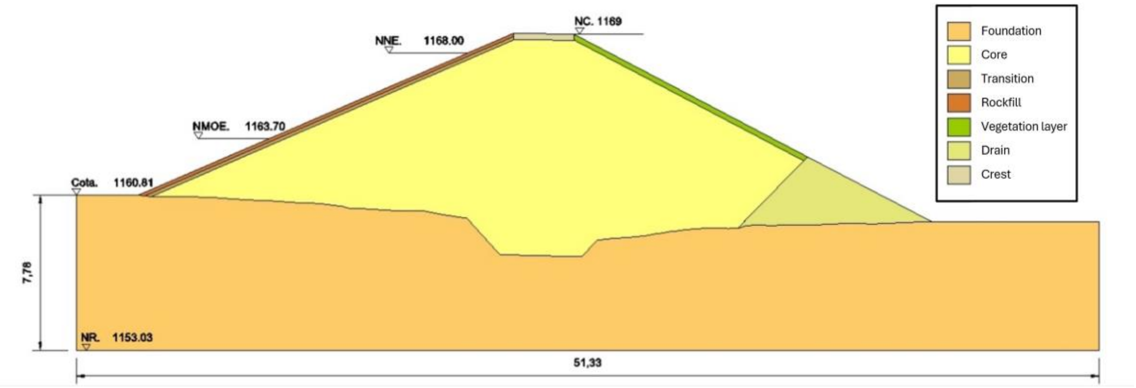

Figure 2. Mercaderes Dam Section. Author's source.

Table 4. Materials that make up the Riogrande II dam and its characteristics

Material	**γ (kg/m^3)**	**E (kPa)**	**ν**	**k (m/día)**	***Mv* (1/kPa)**	***C* (kPa)**	**Φ (°)**
Embankment (Fractured rock)	2000	$5x10^{5}$	0.20	0.0864	$1.8x10^{-6}$	5	38
Core (SM)	1540	$7.5x10^{4}$	0.30	$8.6x10^{-4}$	$9.9x10^{-6}$	15.7	35
Stabilizing embankment (SW)	1900	$1.5x10^{5}$	0.30	$8.6x10^{-3}$	$5x10^{-6}$	8	34
Counterweight (SW)	2200	$9.5x10^{4}$	0.30	$8.6x10^{-3}$	$7.8x10^{-6}$	*8*	30
Cofferdam and pre-cofferdam (GP)	1900	$1x10^{5}$	0.30	$8.6x10^{-2}$	$7.4x10^{-6}$	-	36
Foundation (Sound rock)	2750	$4.2x10^{6}$	0.15	$8.6x10^{-3}$	$2.3x10^{-7}$	-	40

Author's source.

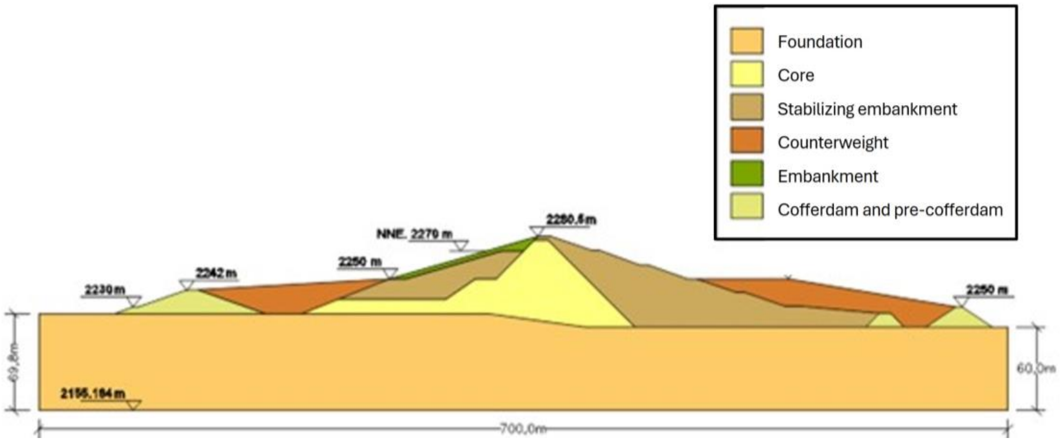

Figure 3. Riogrande II Dam Section. Author's source.

Table 5. Materials comprising the study section of the Mercaderes reservoir area and their characteristics

Material	**γ (kg/m^3)**	**E (kPa)**	**ν**	**k (m/día)**	***Mv* (1/kPa)**	***C* (kPa)**	**ϕ (°)**
Reservoir soil (SC – SM)	1850	$7x10^{4}$	0.30	$8.6x10^{-4}$	$1.1x10^{-5}$	12	20

Author's source.

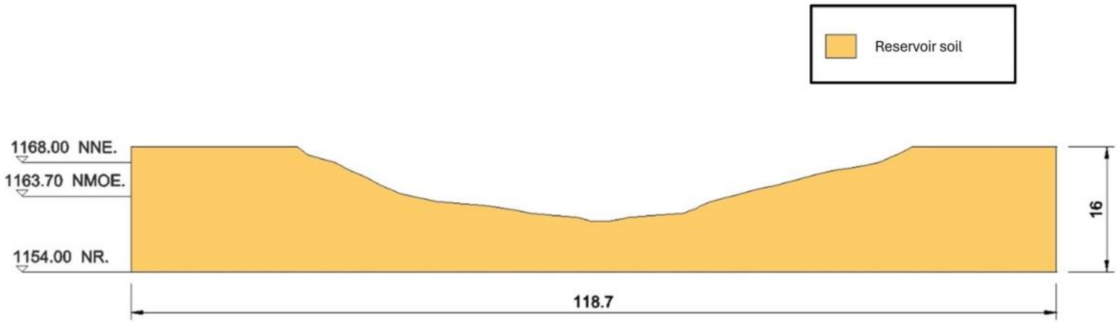

Figure 4. Mercaderes reservoir slope section. Author's source.

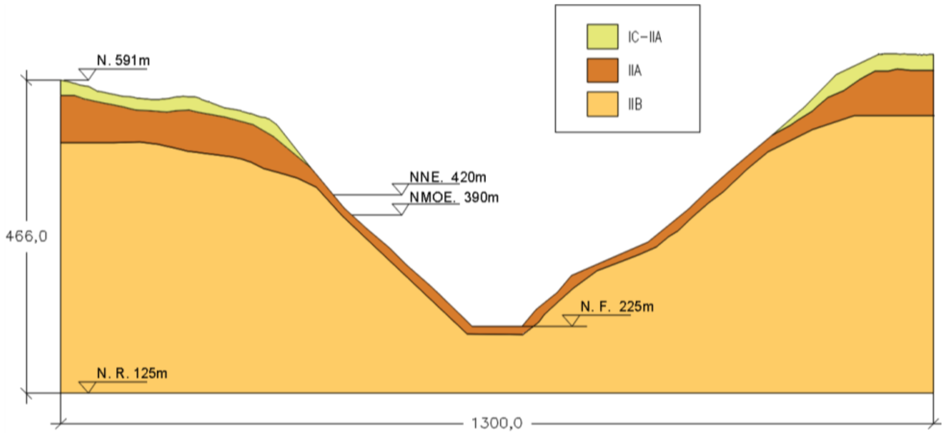

Figure 5. Hidroituango reservoir embankment section. Author’s source.

Table 6. Materials that make up the study section of the Hidroituango reservoir area and its characteristics

Material	**γ (kg/m^3)**	**E (kPa)**	**ν**	**k (m/día)**	***Mv* (1/kPa)**	***C* (kPa)**	**ϕ (°)**
IC-IIA (Soil and rock blocks)	**1700**	$4x10^4$	**0.25**	$8.6x10^{-4}$	$2.1x10^{-5}$	**35**	**40**
IIA (Highly fractured and weathered rock)	**2100**	$5x10^4$	**0.20**	$8.6x10^{-4}$	$1.8x10^{-5}$	**35**	**48**
IIB (Slightly weathered rock)	**2300**	$9x10^4$	**0.15**	$8.6x10^{-4}$	$1.1x10^{-5}$	**40**	**48**

Author’s source.

Table 7. Materials composing the study section of the Salvajina reservoir area and their characteristics

Material	**γ (kg $/m^3$)**	**E (kPa)**	**ν**	**k (m/día)**	***Mv* (1/kPa)**	***C* (kPa)**	**ϕ (°)**
Ksac (Aguaclara Formation: sandstone)	**2100**	$4x10^5$	0.23	$8.6x10^{-3}$	$2.2x10^{-6}$	**23**	**40**
ksbt (Timba Basalts)	**2750**	$6x10^5$	0.20	$8.6x10^{-3}$	$1.5x10^{-6}$	23	**42**
pgech (Chimborazo Formation: siltstone)	**2300**	$7x10^5$	0.30	$8.6x10^{-4}$	$1.1x10^{-6}$	**28**	**40**
Qc (Fluvioglacial deposits)	**1850**	$7x10^4$	0.20	$8.6x10^{-3}$	$1.3x10^{-5}$	**28**	**40**

Author’s source.

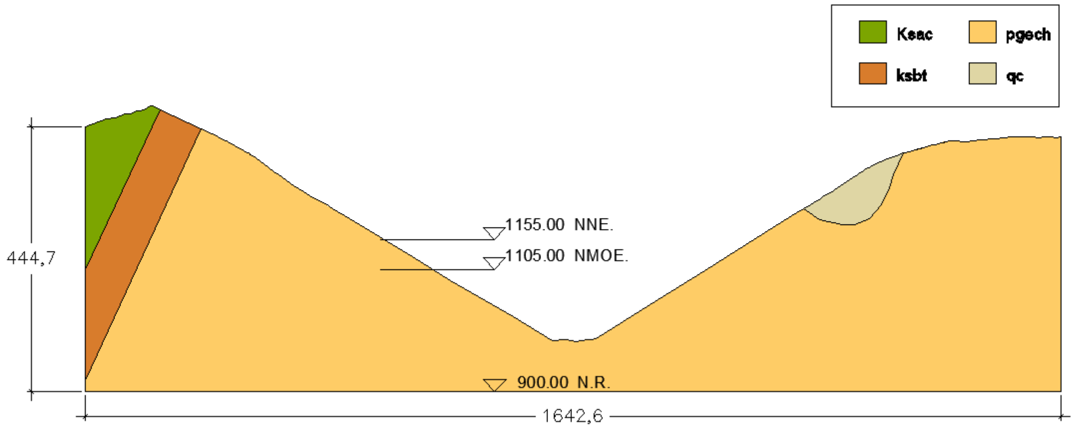

Figure 6. Salvajina reservoir slope section. Author’s source.

Then, the processing was performed using the GeoStudio 2012 software (20) and the simulation of the discharge was carried out taking into consideration height and speed. Finally, the results obtained were processed, organized, and analyzed in the post-processing step.

3. Results

3.1. Analysis by model

3.1.1 Mercaderes dam

The main difference observed between the behavior of simple and coupled analysis is how quickly the factor of safety is recovered during the former. This value stabilizes once a few days have passed after the most recent critical FS value which is produced by the drawdown, whereas the coupled analysis to a time of 1000 days has not yet managed to stabilize the safety factor. This effect is explained by the behavior of the water table over time. As a matter of fact, since the coupled analysis takes into account matric suction, which is directly related to the pore pressure describing a tensional behavior, this makes the pore pressure dissipation more difficult due to the permeability variation as shown in Figure 7.

According to the variation of SF during the different drawdown cases, in the coupled analysis, the reduction of the SF value ranges from 30% to 49%, depending on the water level to be discharged.

As expected, the lowest Δh results in the lowest reduction and vice versa. Likewise, there is a maximum variation of 2% of the values obtained by the different drawdown rates with respect to the initial SF value. By contrast, the difference among the results of cases subject to the same drawdown rate was up to 19 % in relation to the initial value. Then, the best case concerning the lowest drawdown level resulted in a recovery of up to 75% of the initial FS value while the worst resulted in a recovery of 60%.

In terms of the simple analysis, the variation in the reduction percentage becomes more evident. First, the change in the safety factor obtained from the same case under different rates is up to 17% concerning the initial one and, second, the same rate under different Δh is up to 18%.

On the other hand, the curves that represent the behavior of the safety factor as a function of the level of drawdown, regardless of the rate and the analysis, tend to be a straight line with a strong negative slope until an Δh close to 4.5m. Then, there is a point of inflection passing to a much smaller negative slope. Therefore, from the above, it can be concluded that the most incident level of drawdown is close to 2/3 of the height of the water level in the reservoir, as shown in Figure 8. Moreover, the poor sensitivity of the change in the drawdown speed on the value of the critical factor in the coupled analysis is also observed in the Figure 8, where the curves are very close to each other. In contrast, the simple analysis curves show a considerable variation depending on the drawdown rate.

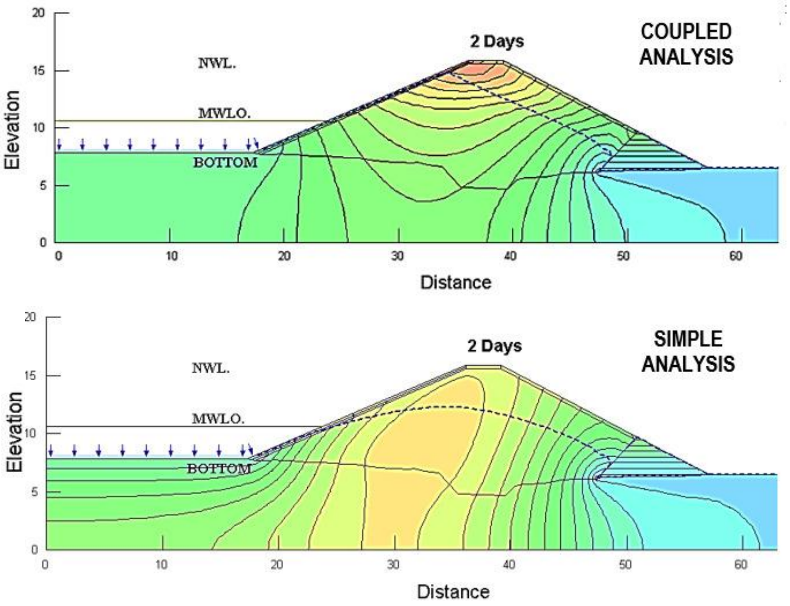

Figure 7. Diagram of total pressure heads: Mercaderes dam. Author's source.

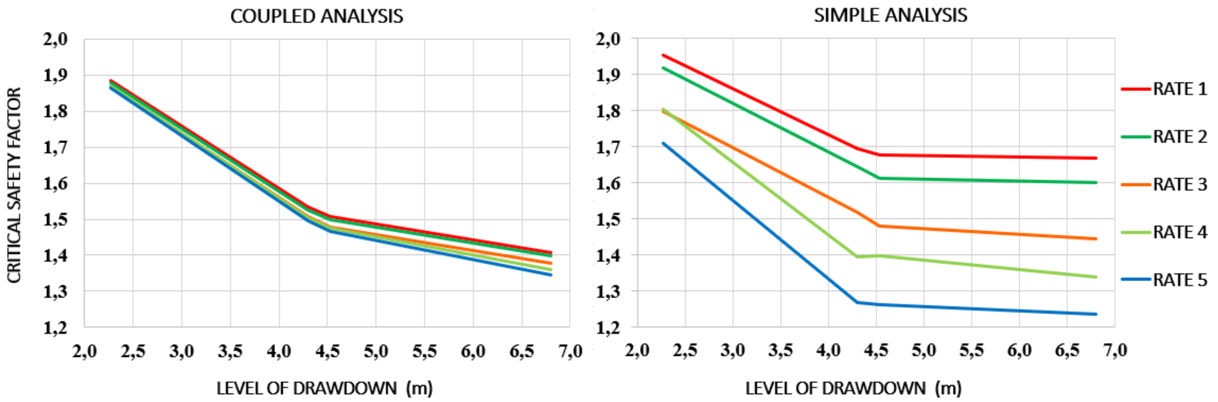

Figure 8. Variation of the SF values depending on the discharge height: Mercaderes dam. Author’s source.

To conclude, it is evident that neither of the two methods in terms of the SF value will be more conservative than the other. This is due to the fact that the functions that describe its behavior through the change in the discharge rate intersect at a certain speed. Additionally, it is noted by both analyzes that in most models the most critical SF value occurs on the day or the day immediately following the day when the discharge occurs.

3.1.2 Riogrande II dam

Firstly, as in the case of Mercaderes dam, the behavior of the simple analysis is characterized by the "fast" recovery of stability which occurs between 100 and 200 days, while the analysis coupled to 1000 days shows that it has not stabilized yet. As shown in Figure 9, the simple model has greater facility to dissipate pressures than the coupled model.

Secondly, it is noteworthy the coincidence or proximity between the safety factor values per case for each of the rates, both in the simple and coupled analysis. This similarity is attributed to the short height of the most significant slope exposed to the water from the reservoir. At 20 m (NWL. – NWLO.) the water level has been completely released and any further discharge will not generate instability.

However, the recovery of the SF values is affected by Δh due to the influence of the location of the water table after the discharge event. What is more, this affectation is more noticeable in the simple analysis due to its rapid recovery. The fact that case A always coincides with case C is because the water table is located outside the critical failure surface, while in cases B and D the critical area is affected by the water level inside the ground as shown in Figure 10.

In this way, the simple analysis resulted in a recovery rate of up to 98% and a minimum of 88%. Since this represents the final condition in the long term, the change in the instability of the water level is quite insignificant. Concerning the reduction produced by a discharge event, all the cases behave similarly and even identically. As a result, the discharge height becomes irrelevant in terms of the SF value at the most unstable moment of the occurrence. The variation of the rate may see a change of up to 23% between values.

As regards the coupled analysis, a variation in the critical SF value of up to 5% per case is observed between drawdown rates. In addition, little differentiation of values of SF between cases is also obtained due to the geometry of the dam, as previously mentioned. On the other hand, regarding the recovery of the safety factor at 1000 days, it varies in a range of 75% to 82%.

Therefore, it can be suggested that the drawdown speed is more influential than the drawdown height due to Riogrande II dam’s geometry. Besides, although this geometry offers great stability, a reduction of up to 38% and 36% of the initial safety factor value is achieved in the simple and coupled analysis, respectively. Additionally, there is still a greater influence of the drawdown rate in the simple analysis than in the coupled one, as it is illustrated in Figure 11.

Finally, no method in terms of the value of the FS is more conservative than another in all models. However, the simple analysis for rates between 0 and 3 m/day obtains highly variable SF values but higher than the coupled analysis. In contrast, the latter remains more stable throughout the increase in drawdown speed which tends to create a constant SF. It is shown in Figure 12.

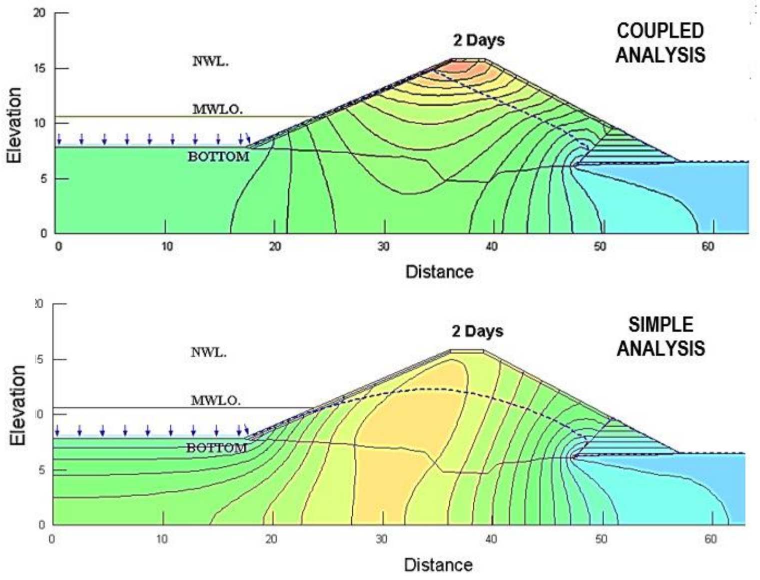

Figure 9. Total pressure head diagram: Riogrande II dam. Author's source.

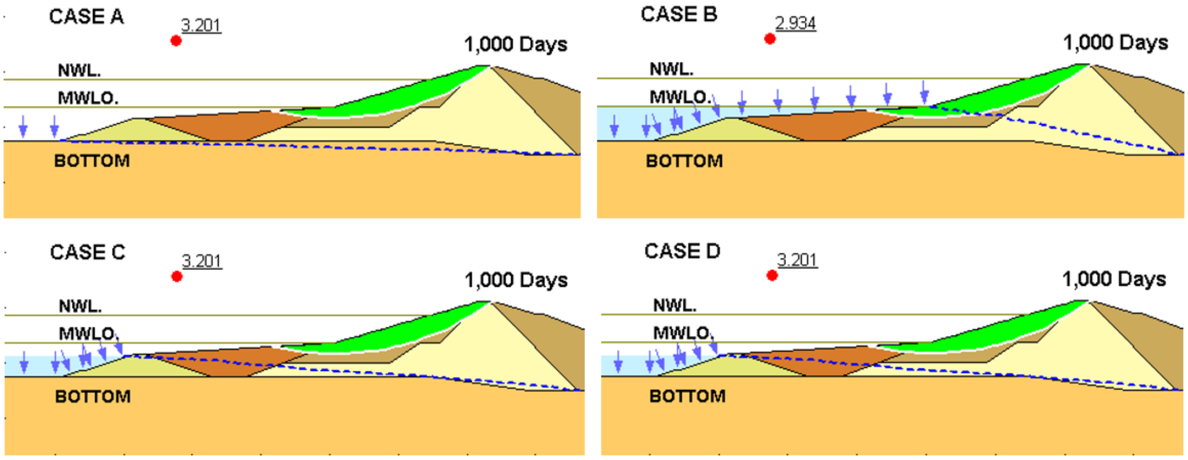

Figure 10. Slope stability analysis, rate 1: Riogrande II dam. Author's source.

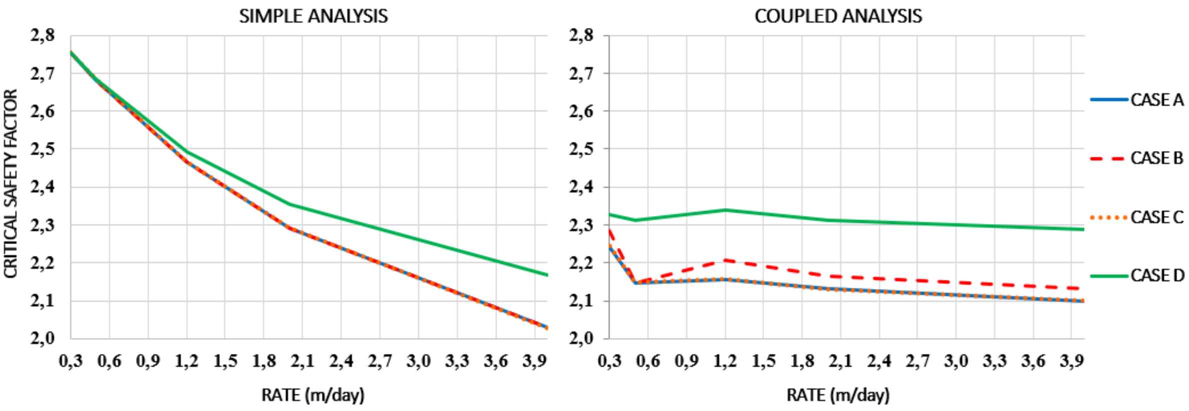

Figure 11. Variation of the SF as a function of the rate: Riogrande II dam. Author's source.

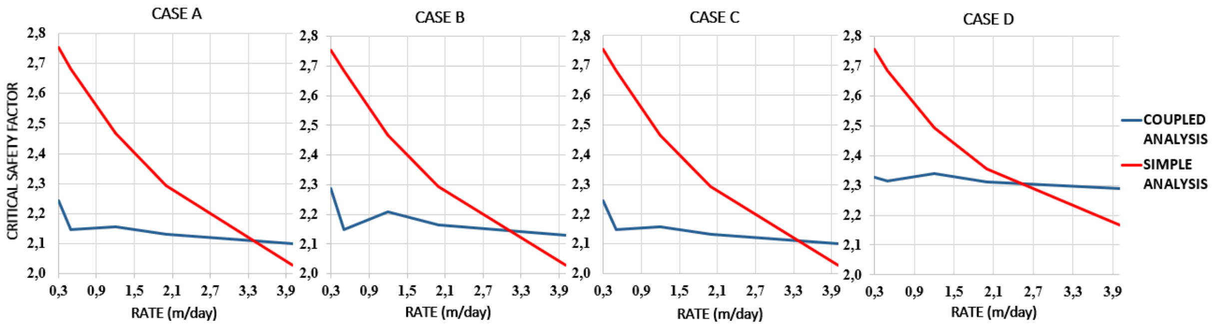

Figure 12. Variation of the SF by type of analysis: Riogrande II dam. Author's source.

3.1.3 Mercaderes reservoir zone

In general, the simple analysis presents an ease of pressure dissipation compared to the simple analysis, as shown in Figure 13. However, although a slow recovery of the safety factor is observed in the coupled analysis, without being able to stabilize after of 2000 days, the most critical SF value is higher than the one presented in the simple analysis.

In addition, both analyzes gave as a result that the most critical moment occurred on the day of drawdown or the day immediately after, coinciding with what was observed in the previous analyses.

According to the behavior of the safety factor as a function of the drawdown level (Figure 14), the coupled analysis demonstrates the low disturbance that the drawdown rates have under the same Δh. This tends to move towards the same critical value of SF for all rates over time. On the contrary, in the simple analysis, the curves are more pronounced and the speed with which the download is carried out becomes a little more relevant.

On the other hand, a trend is observed in the behaviors of both analyzes in all the rates of a line with a strong negative slope that at 2/3 of the height of the normal water level in the reservoir presents an inflection point passing to a much smaller negative slope.

Finally, the variation of the critical safety factor concerning the discharge rate of both models typically results in a more stable SF value when using the coupled analysis. This remains stable and in all cases above the values obtained from the simple analysis, which also includes a more marked variation with respect to the change in the drawdown rate. It is shown in Figure 15.

3.1.4 Hidroituango Reservoir Zone

The both slopes exposed to the discharge showed very similar behaviors. Similar trends of better pore dissipation were observed by the simple analysis as is illustrated in Figure 16. However, the most critical SF values on both slopes, in all cases, and drawdown rates were lower than those obtained in the coupled analysis.

Initially, the attention was focused on the irregularities that observed in the behavior of the critical SF over time (Graph 6) in the simple analysis; however, this event occurs due to the change of stratum that occurs in the size of the slices. The mechanical characteristics and the amount of soil per stratum within the voussoir directly influence its stability. Therefore, it is impossible to estimate a pattern on the day of the occurrence of the most critical stability. In contrast, the coupled analysis is not susceptible to this variation and coincides with the fact that the most critical state occurs on the day the drawdown ends or the day immediately following as has been seen in the previous analyses as shown in Figure 17.

On the other side, it is necessary to clarify that neither of the two analyzes in a period of 2000 days reaches the final stabilized conditions. An evaluation to such an extent becomes unhelpful and time-consuming, since a more critical condition and a more unlikely event will probably never occur because the water level in the reservoir would have to be permanent over time.

The simple analysis for both the variation of the rate and the drawdown level is very irregular and uncertainty lies in characterizing the behavior of the embankment after emptying. On the other hand, the coupled analysis presents more reasonable results which demonstrate that Δh is more relevant when compared to the drawdown speed. It is important to note that this is particularly true when the reservoir is at 2/3 of the height of the normal water level in the reservoir as shown in Figure 18.

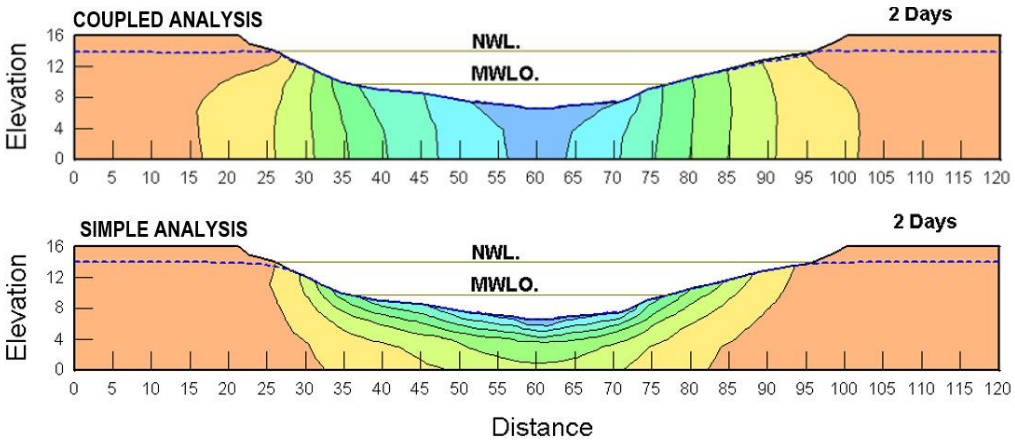

Figure 13. Total pressure head diagram: Mercaderes reservoir. Author’s source.

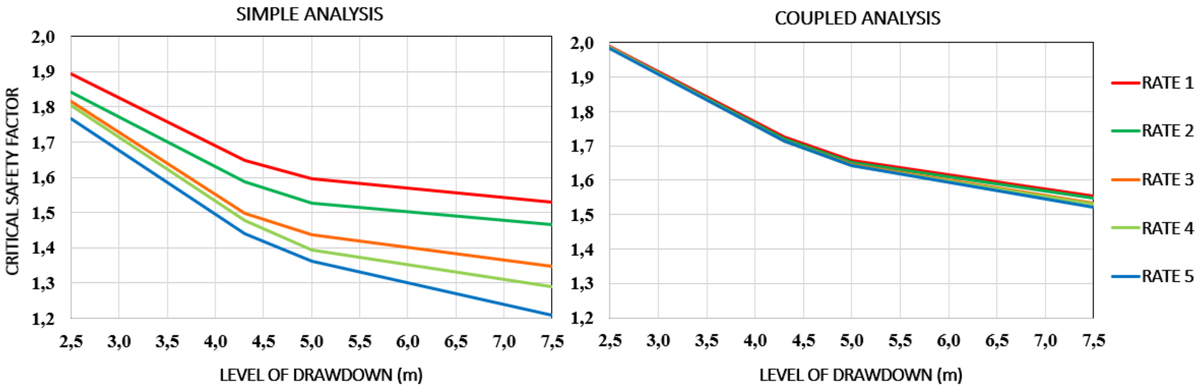

Figure 14. Variation of the SF depending on the discharge level: Mercaderes reservoir. Author’s source.

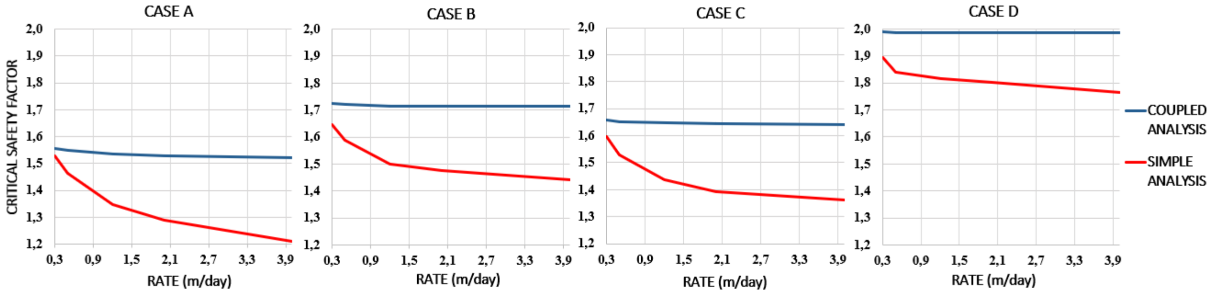

Figure 15. Variation of the SF by type of analysis: Mercaderes reservoir. Author’s source.

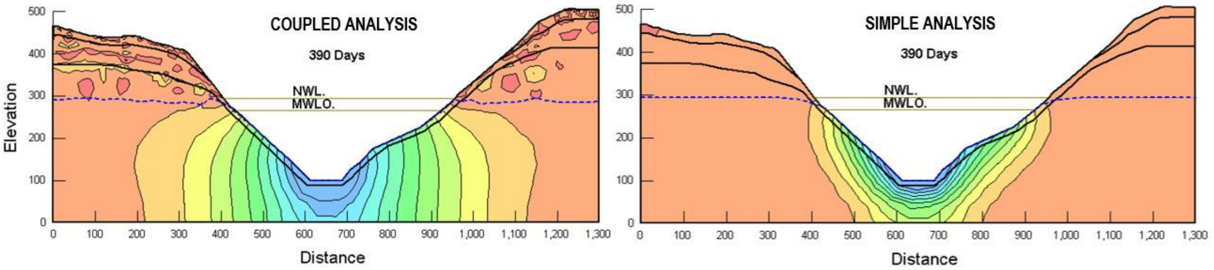

Figure 16. Diagram of total pressure heads: Hidroituango reservoir. Author’s source.

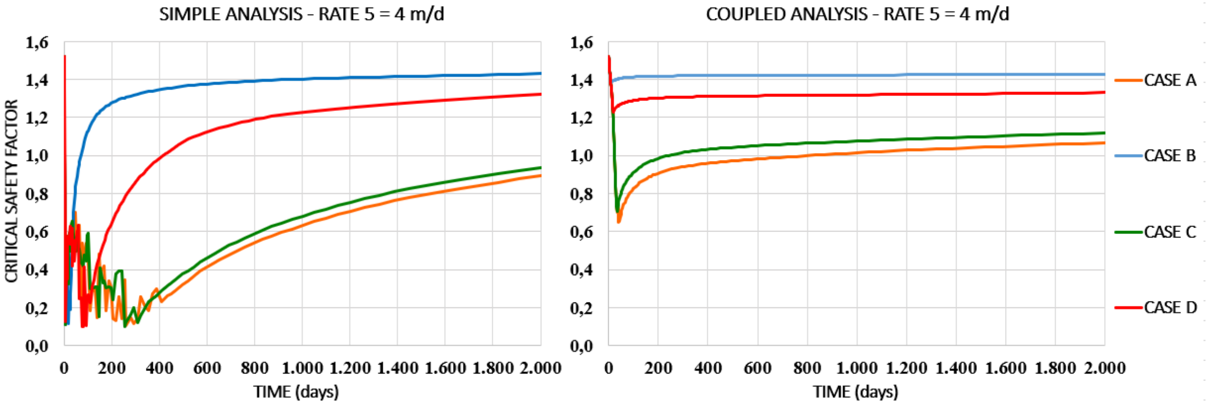

Figure 17. The behavior of the SF over time: Mercaderes reservoir. Author's source.

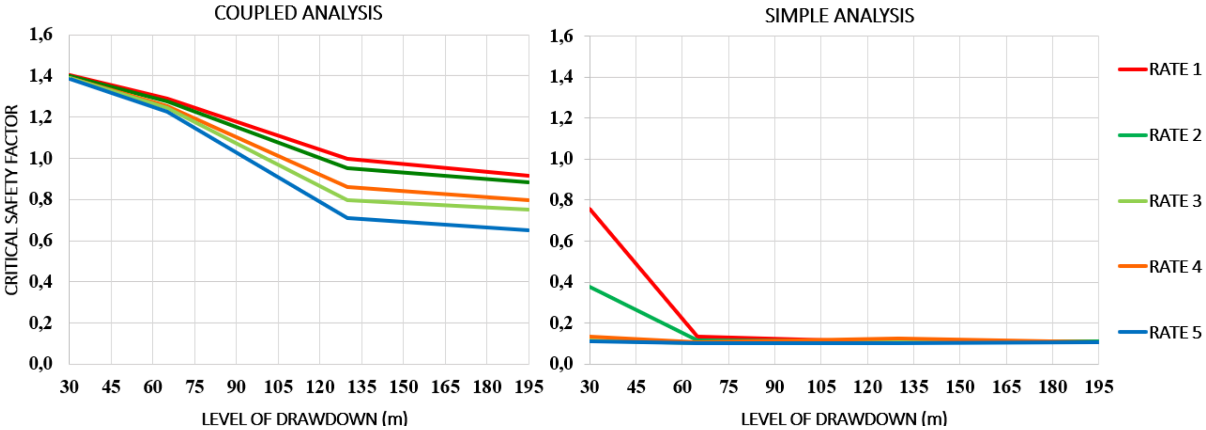

Figure 18. Variation of the SF depending on the discharge level: Hidroituango reservoir. Author's source.

3.1.5 Salvajina reservoir zone

In general, the behavior of this model is very similar to that of the Mercaderes reservoir zone with the equivalence of the magnitude much greater than this one. This is primarily reflected in the amount of time required (>2000 days) for the stabilization of the land due to the new conditions, after a drawdown. It is shown in Figure 19.

The behavior of the safety factor as a function of time maintains the same characteristics as seen in the previous models. The comparisons between the simple and coupled analyses were also similar in that there is a greater influence on the drawdown rate in the simple analysis.

The safety factor values also represented a smaller reduction in the coupled analysis than the simple one. This behavior is similar to the characteristics in the reservoir zone models and not in the dams as shown in Figure 20. Additionally, the value of the critical safety factor is more sensitive to the variation of the drawdown height at levels higher than 2/3 of the normal water level height than at heights greater than this.

3.2. Analysis by method

3.2.1 Simple analysis

The analyzes referring to the slopes of the Hidroituango reservoir zone remain in all cases at a very high percentage and resistant to any change in the discharge rate. This is followed by the curves of the slopes of the Salvajina reservoir, which maintain a characteristic behavior of a pronounced variation in low discharge rates and at higher speeds a smaller reduction change. Similarly, the Riogrande dam also has similar behavior, but with less considerable variation. Finally, the models of the Mercaderes dam and the slopes belonging to the same reservoir show a very flat variation as shown in Figure 21.

In the graph above, no trend or pattern is observed that relates to the behavior of all the evaluated models. This is primarily due to the great influence that geometry and soil types have on the models with a simple analysis. Typically, there is greater variability in the percentage of reduction concerning a change in the discharge rate as the slope of the land increases. The slopes of the Hidroituango reservoir present an anomaly in the typical behavior that would be expected. This could be attributed to the critical conditions to which it is subjected due to the steep slope of the embankments.

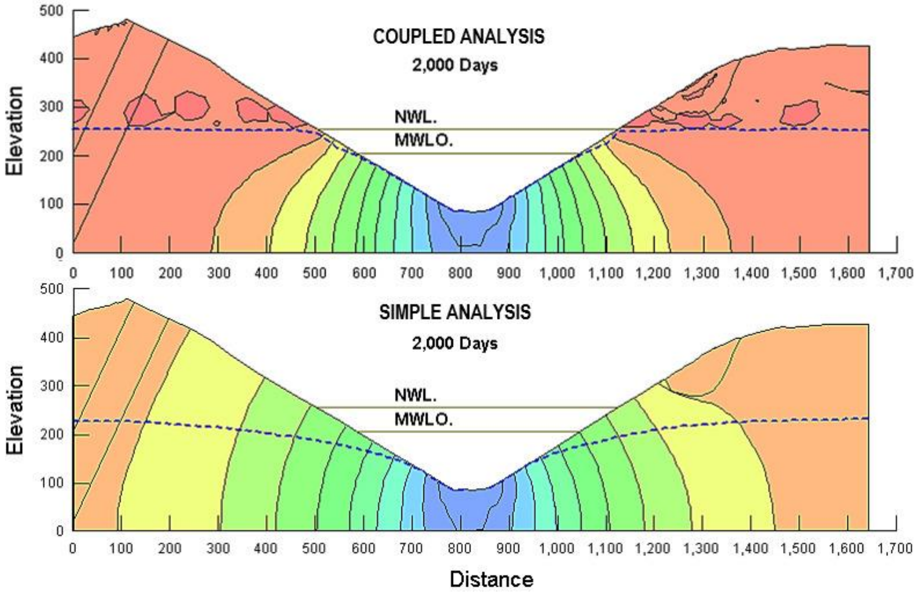

Figure 19. Diagram of total pressure heads: Salvajina reservoir. Author's source.

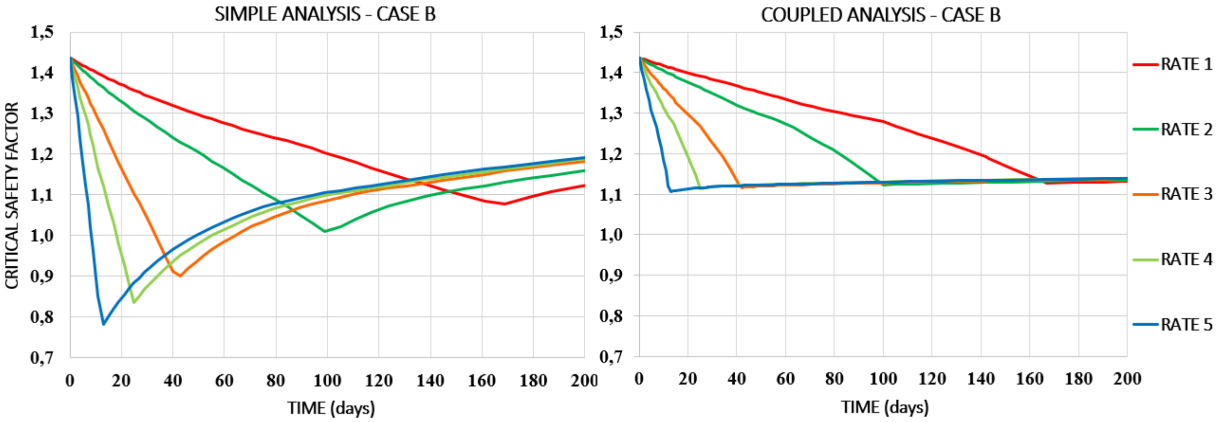

Figure 20. The behavior of the SF over time: Salvajina reservoir. Author's source.

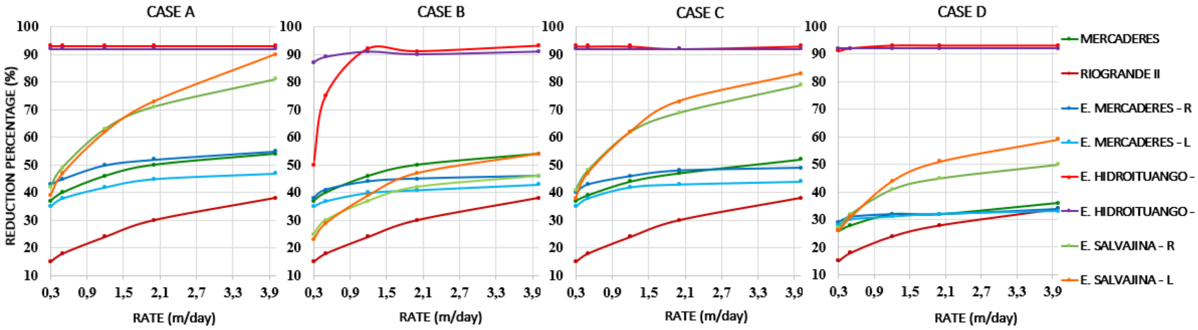

Figure 21. Reduction percentage vs release rate: simple analysis. Author's source.

Additionally, a trend was observed where a more pronounced variation in reduction percentage for discharge heights is less than 2/3 of NNE. For larger discharge heights, a change in slope that produces a smaller variation as height increases was also noted. As expected, the highest reduction percentages are obtained as the degree of inclination of the slope is greater. This was different in the models of the Hidroituango reservoir and the Riogrande II dam which maintained a different behavior concerning the variation in the percentage of reduction due to the discharge height which was a fixed rate as shown in Figure 22.

The curves belonging to Hidroituango are demonstrated that due to the high slopes of the surrounding landscape, extremely critical conditions are produced when they are subjected to a discharge. As a result, it becomes understandable how a variation is present at first in lower heights, then it becomes more stable for higher rates and heights with a decrease in the safety factor almost in its entirety

On the other hand, Riogrande II presents a variable reduction in the safety factor of its behavior as a consequence of the unusual geometry that this model has at the NMOE level. This dam presents a sudden change, going from a considerable slope of the embankment to an almost horizontal one, for which the most critical moment of the dam occurs, resulting in higher discharge heights being unable to influence its stability.

3.2.2 Coupled analysis

Demonstrates that the discharge rate is not relevant in terms of the percentage of reduction obtained from the models. Additionally, similar values among the models, despite the diversity of characteristic geometric and mechanical features that each one of them, were found. The exception was with the slopes of the Hidroituango reservoir, which do not necessarily follow this trend, especially that of the left slope. This is justified because it represents the model whose results are very sensitive due to the irregularity of the topography and stratigraphy as shown in Figure 23.

As expected, higher safety factor reduction percentages are obtained as the discharge height and embankment slope of the model increase. Additionally, the models in all discharge rates behave under the same curve style, where a pronounced percentage of variation is observed in discharge heights less than 2/3 of the height of the initial water level (NNE). As the water level decreases, the safety factor is maintained with a very low variation as shown in Figure 24.

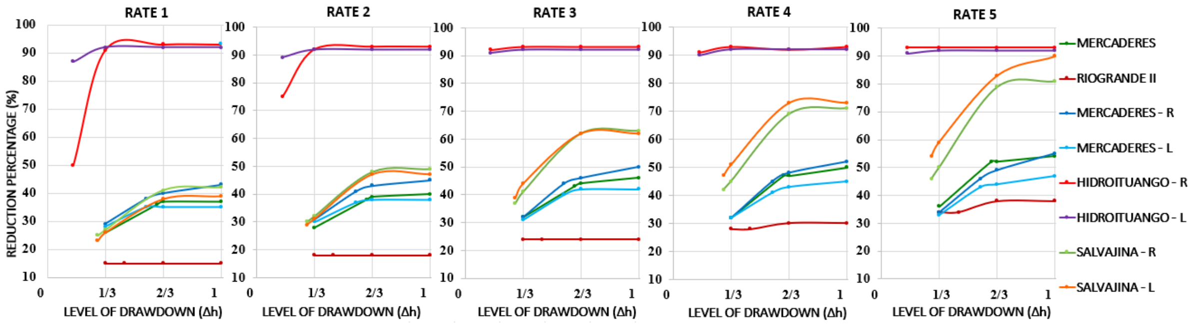

Figure 22. Reduction percentage vs level of drawdown: simple analysis. Author’s source.

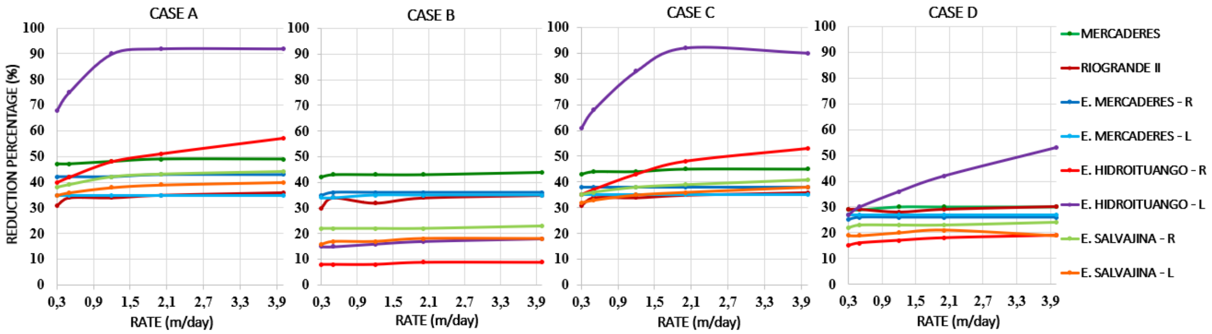

Figure 23. Reduction percentage vs release rate: coupled analysis. Author’s source.

The model of the Riogrande II dam does not closely follow the aforementioned characteristics since it has an unusual geometry concerning the other models. After it reaches a discharge height at the NMOE level, a change is found where the slope of the embankment is almost zero which creates a critical condition to which this dam can be subjected under the occurrence of an outflow.

Given that it was observed and supported by the results that there is not a considerable incidence of the variation of the unloading rate, but there is in the emptying height. Statistical analysis intervals were obtained with a level of confidence of 97% in which a proximity of the percentage of reduction to the safety factor that can be obtained from a slope subjected to any discharge provided as shown in Table 8.

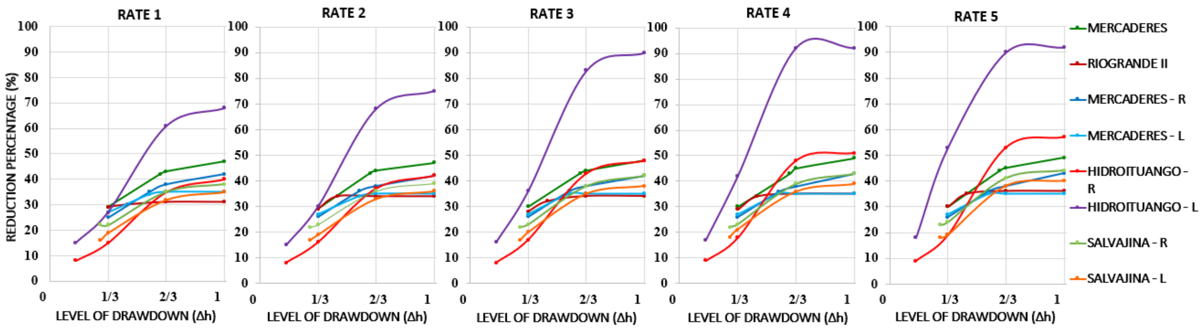

Figure 24. Reduction percentage vs level of drawdown: coupled analysis. Author's source.

Table 8. Statistical study of the reduction percentage

Rate m/d	Mercaderes	Riogrande II	Mercaderes zone - right	Mercaderes zone - left	Hidroituango zone – right	Salvajina zone - right	Salvajina zone – left	Nz	97%
	Reduction percentage (%)								
Case A									
0.3	47	31	42	35	40	38	35	Confidence interval	
0.5	47	34	42	35	42	39	36		
1.2	48	34	42	35	48	42	38	38.64 - 43.01%	
2.0	49	35	43	35	51	43	39		
4.0	49	36	43	35	57	44	40		
Case C									
0.3	43	31	38	35	35	35	32	Confidence interval	
0.5	44	34	38	35	37	36	33		
1.2	44	34	38	35	43	38	35	36.37 - 39.91%	
2.0	45	35	38	35	48	39	36		
4.0	45	36	38	35	53	41	38		
Case D									
0.3	29	29	25	27	15	22	19	Confidence interval	
0.5	29	29	26	27	16	23	19		
1.2	30	28	26	27	17	23	20	22.76 - 26.10%	
2.0	30	29	26	27	18	23	21		
4.0	30	30	26	27	19	24	19		

3.2.3 Typical curves

Due to the similarities between the models, despite their geometric and geotechnical differences, it was possible to identify typical characteristic curves that define the typical behavior of the safety factor as a function of time, level, and drawdown rate. These curves are presented in Figure 25.

4. Conclusions

Both analyzes are influenced by the geometry, topography, stratigraphy, and the mechanical, elastic, and hydraulic parameters of each particular model; however, it was possible to identify characteristic curves of the behavior of the safety factor in a discharge, where the following aspects stand out: a. The succession of the most critical unloading condition is present on the day or the day immediately following the end of a decrease in the water level; b. The discharge at a height of 2/3 from the normal water level presents a point of the greatest incidence of instability since emptying at a lower height presents less critical conditions and greater heights do not achieve a considerably greater critical condition; c. The coupled analysis does not present a considerable variation of the SF as a function of the discharge rate, while the opposite is true in the simple analysis.

The most critical situation corresponds to the day or immediately following the end of the drawdown, this result agrees with the research of Alatlawi (12), where it is shown that the minimum safety factor is reached 10 hours after the water level reduction.

The confirmation that one type of analysis is more conservative or critical than another is not strictly correct; however, the variability of these conditions by altering the emptying conditions, such as the rate and height of the discharge, is questionable.

The stability analysis using a simple analysis is very susceptible to the variation in the speed and height of the discharge. This occurs because a simple analysis does not take into consideration matric suction, and deformations, and assumes a soil with an invariant permeability capable of dissipating pore pressure sometimes as fast as the water level decreases. Additionally, its sensitivity to stratigraphic changes and topographic irregularities generates numerical alterations and discontinuities in the behavior of stability over time. In contrast, the coupled analysis understands and is capable of simultaneously resolving the saturated flow and the mechanics of partially saturated soils within the discharge event. This results in no sudden variations depending on the discharge height, speed, or discharge rate adopted in the model.

In relation to the type of analysis, simplified or coupled, what was found in this study agrees with the research of Llanque (13), where it was shown that, for slope stability in rapid pouring when considering the transient flow analysis, including suction, the S.F. increases in relation to the simplified analysis

The coupled analysis model also provides values that are usually higher, but realistic due to the contemplation of a coupled problem that makes it possible to get more real-world answers. Based on the results obtained from this same analysis, a suggestion of intervals was obtained in which the possible reduction percentage of the critical safety factor is understood concerning the reservoir-filled condition of an embankment as a function of the discharge height are presented below: I. for 1/3 NNE.: (23% - 26%); II. for 2/3 NNE.: (37% - 40%); III. for NNE.: (39% - 43%).

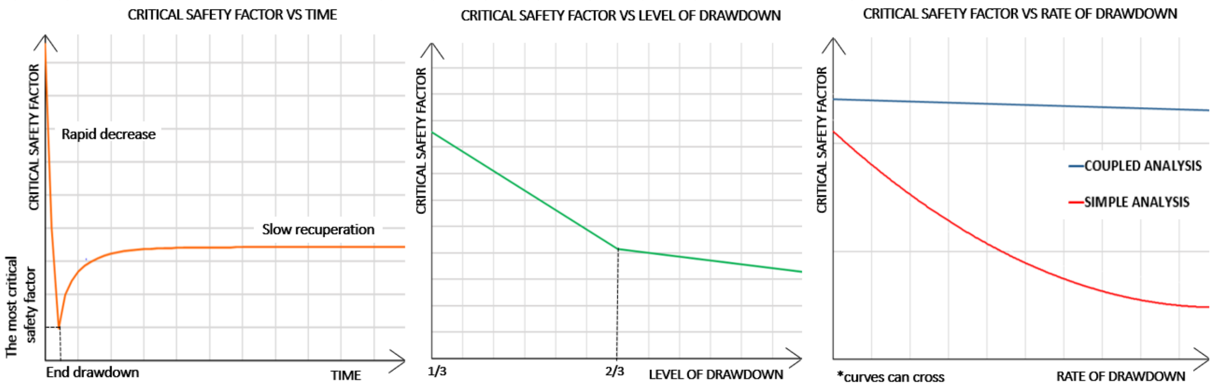

Figure 25. Characteristic curves. Author’s source.

Although the understanding of the problem through the software and coupled analysis takes into account the stress-strain behavior during the unloading process for the stability analysis, the importance of displacements and settlements was not evaluated. Future studies should take into consideration safety and functionality.

Funding and acknowledgments

Universidad del Cauca.

Autor Contributions

V. Campos Martínez: Investigation, Formal analysis, Writing – original draft. O. González-Plaza: Investigation, Formal analysis, Writing – original draft. L. Cruz-Velasco: Conceptualization, Project administration, Writing – review & editing.

Conflicts of Interest

The authors declare that there is no conflict of interests of any kind regarding the publication of the results of our research work.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

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