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Rapid Drawdown in Homogeneous Earth Dam Considering Transient Flow and Suction

Reducción rápida en presas de tierra homogéneas considerando flujo transitorio y succión

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ABSTRACT

The present work intends to demonstrate the advantages of considering transient flow regime in the stability analysis of the upstream slope for the rapid drawdown situation of a homogeneous earth dam. Upstream slope stability evaluations were carried out, considering pore pressure and suction from transient flow analysis while simulating rapid drawdown of the reservoir. The evaluations comprised different geometries of the upstream slope (from 1V:1.1H to 1V:2.5H) and heights varying from 10 m to 50 m, as well as several low permeability materials (SM, SM-SC, SC, ML, ML-CL, CL, MH and CH). In addition, equations relating the safety factor to such slopes or dam height were adjusted to the analysis data, in order to define the minimum slope for a certain dam height or the maximum height for a given upstream slope. The results have shown that, considering the transient flow condition, including suction, within the slope stability analysis of the rapid drawdown situation, increases the safety factor in relation to the simplified analysis that is usually adopted. This also results in much steeper slopes (for a safety factor of 1,1) than the ones recommended by the U.S. Bureau of Reclamation (USBR), suggesting the importance of performing transient flow analysis for rapid drawdown situations and considering its results instability analysis.

Keywords: rapid drawdown, unsaturated soils, suction, slope stability, homogenous earth dam

RESUMEN

El presente trabajo pretende demostrar las ventajas de considerar el régimen de flujo transitorio en el análisis de estabilidad de talud aguas arriba para la situación de reducción rápida de una presa de tierra homogénea. Se llevaron a cabo análisis de estabilidad de taludes aguas arriba, considerando la presión de poro / succión para análisis de flujo transitorio que simula la reducción rápida del embalse. Los análisis comprendieron diferentes geometrías del talud aguas arriba (de 1V: 1.1H a 1V: 2.5H), alturas que varían de 10 m a 50 m, así como varios materiales de baja permeabilidad (SM, SM-SC, SC, ML, ML-CL, CL, MH y CH). Además, las ecuaciones que relacionan el factor de seguridad con dichos taludes o la altura de la presa se ajustaron a los datos de análisis, para definir el talud mínimo para una determinada altura de la presa o la altura máxima para un determinado talud aguas arriba. Los resultados han demostrado que: teniendo en cuenta la condición de flujo transitorio, incluida la succión, en el análisis de estabilidad de taludes de la situación de reducción rápida, aumenta el factor de seguridad en relación con el análisis simplificado que generalmente se adopta. Esto también ha resultado en taludes mucho más pronunciados, para un factor de seguridad de 1,1, que los recomendados por la Oficina de Reclamación de los E.E.U.U. (USBR), sugiriendo la importancia de realizar análisis de flujo transitorio para las situaciones de reducción rápida y considerando sus resultados en el análisis de estabilidad.

Palabras clave: reducción rápida, suelos no saturados, succión, estabilidad de talud, presa de tierra homogénea

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Introduction

The stability of a slope depends on its geometry, soil properties and the forces to which it is subjected internally and externally (Berilgen, 2007). In the case where the slope is subject to partial or total submersion, the internal and external forces (pore water pressure and external water load) that affect the stability of the slope can change significantly.

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The rapid drawdown of the reservoir represents a critical situation for the upstream slope of an earth dam because lowering the water levels has in two negative effects: it reduces the stabilizing water pressure on the upstream slope while reversing the flow in the upstream slope material to dissipate the initial pore pressures, which takes significantly longer. Although this situation is mainly associated with massive dams, collapses due to this phenomenon are also common in natural slopes or embankments built along rivers and channels, due to the rising of water level caused by floods. When the flood water level is maintained long enough to saturate the material of the soil on the river margins, if the descent to the Normal water level (NW) is too quick, the delay in the dissipation of pore pressure on the slope generates an excess of pores pressures without their stabilizing counterpart, which may induce a failure in the slope, (Alonso and Pinyol, 2016).

The condition known as "instantaneous or rapid drawdown" is often a priority in the definition of the upstream slopes of an earth dam because it is the most unfavorable condition for slope stability (Cruz, 1996).

However, a more realistic or less conservative evaluation of the stability for the reservoir drawdown condition would take into account the aspects of unsaturated soil behavior, such as the influence of the variation of hydraulic conductivity on the dissipation of pore pressures and suction, which has direct influence on increasing resistance and, therefore, stability.

Dam stability in rapid drawdown conditions

Figure 1 below illustrates the typical section of a homogeneous dam on which the geometric analyses developed in this work were based.

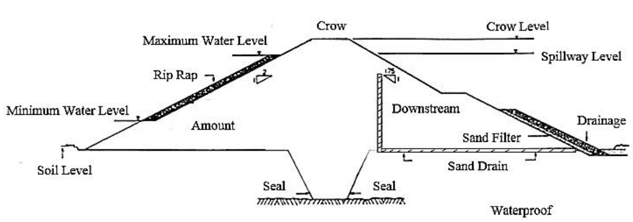

Figure 1. Typical profile of a homogeneous dam.
Source: adapted, Stephens, 2011.

The stability evaluation of the upstream slope of earth dams during rapid drawdown of the reservoir is necessary not only for existing dams but also in the phases of inventories, feasibility studies, and basic and executive design of future homogeneous earth dams.

When the slope is partially or totally submerged, the internal and external forces (water pore pressure and external water load) are equalized with medium saturation, varying with NW changes. However, this equalization occurs in a longer or shorter period of time according to the permeability of the porous medium. For slopes comprised of high permeability soils, these NW variations are reflected almost instantaneously in pore pressures and do not represent a risk of slope instability.

In the case of soils with low permeability, pore pressure changes are not likely to dissipate in the same proportion as the variations in the external water level and, in this way, totally or partially undrained behavior of the slope soil can occur.

Figure 2 illustrates flow behavior in a slope of low permeability with the lowering of the NW of the reservoir, where the existence of pore pressure in the upstream embankment, without the stabilizing counterpart of the reservoir, can be observed.

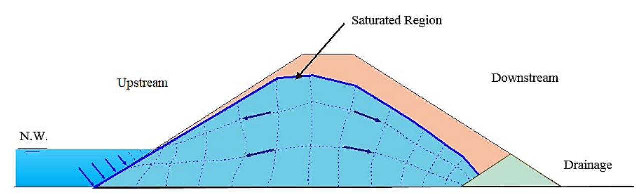

Figure 2. Flow behavior in U/S dam slope of low permeability with rapid drawdown N.W.
Source: Authors

The rapid lowering of U/S water level stability can lead to failure, according to different case studies of natural and artificial slopes. Many authors have dealt with the evaluation of slope stability during rapid drawdowns (Morgenstern, 1963; Lane and Griffiths, 2000; Berilgen, 2007; Alonso and Pinyol, 2009, 2016; Fattah, M. Y., Omran, H. A., and Hassan, M. A., 2015, 2017, Fattah, M. Y., Al-Labban, S. N. Y., and Salman, F. A., 2014) making use of classical stability analysis, slope stability limit approach or numerical solutions.

Pre-dimensioning of the upstream slopes of dams, according to the U.S. Bureau of Reclamation (2002), does not take into account the level of stresses acting on the mass due to the height of the dam, which may result in oversized projects for small dams and undersized design for higher dams. One of the aspects discussed in this work is the influence of the magnitude of the dam on the stability of the upstream slope in rapid drawdown conditions, considering the transient flow and the suction that is generated inside the body of the dam.

In this work, the transient flow behavior in the dam, associated with the water level lowering of the reservoir, is simulated by the finite element method, coupled with several slope stability evaluations of the upstream slope through limit equilibrium methods for different stages of water level in the reservoir.

Pre-dimensioning of slopes of an earth dam

Pre-dimensioning of slopes depends largely on the type of dam (homogeneous or heterogeneous) and the nature of the materials used in its construction. Table 1 presents the recommendations of the U.S. Bureau of Reclamation (2002) for slopes of homogeneous dams, considering or not the possibility of rapid drawdown, for different types of soils.

Table 1. Recommended slopes for small homogenous earth dams with stable foundation

Case	Type	Object	Subject to rapid drawdown(1)	Soil Type(2)	Upstream	Down stream
A	Homogeneous or modified homogeneous	Retention or storage	No	GW, GP, SW, SP	No waterproof	
				GC, GM, SC, SM	2,5:1	2:1
				CL, ML	3:1	2,5:1
				CH, MH	3,5: 1	2,5:1
B	Modified homogeneous	Storage	Yes	GW, GP, SW, SP	No waterproof	
				GC, GM, SC, SM	3:1	2:1
				CL, ML	3,5:1	2,5:1
				CH, MH	4:1	2,5:1

(1) Speed of water level lowering of 15 cm or more per day, after a prolonged situation with high reservoir level.

(2) Soils OL and OH are not recommended for zones in large homogeneous earth dams.

Source: adapted, Bureau of Reclamation, 2002.

Safety factors in slope stability studies

Considering all the aspects presented above, the Brazilian standard of slope stability (NBR 11.682, 2009) proposes safety factors according to the associated risk conditions.

However, U.S. Corps of Engineers (2003) recommended, specifically for dam structures, the safety factor values presented in Table 2 that range from 1.0 to 1.2 for upstream slopes subjected to the rapid lowering condition.

Table 2. Safety factors according to U.S. CORPS OF ENGINEERS

Situation	Safety factor
End of Construction	1,3
Long-term permanent flow	1,5
Rapid drawdown	1,0 a 1,2

Source: U.S. Corps of Engineers, 2003.

The safety factor associated with rapid drawdown may be the smallest figure among all the requirements regarded as critical to the stability of an earth dam, because it reflects the consequences of rupture in this kind of situation, once the mass of water stored in the lowered reservoir is reduced and the possible collapse of the dam causes less damage than in a full storage situation.

Methodology used in the analysis

Description of the studied hypothetical dam

The work consisted in simulating the transient flow induced by the lowering of the reservoir and performing stability analysis of the upstream slope at several stages of the transient analysis for different heights of a dam (from 10 m to 50 m), different inclinations of the upstream slope (1V: 1.1 H to 1V:2.5 H) as well as different materials in the dam embankment (SM, SM-SC, SC, ML, ML-CL, CL, MH and CH) according to the Unified Soil Classification System (USCS).

The typical section studied is shown in Figure 3, consisting of a dam with 5.0 m wide crest, 1.0 m thick rip-rap, Brazilian section (homogeneous compacted embankment with vertical filter associated to an horizontal downstream drainage mat) resting on a permeable foundation layer 3.0 m thick, in which a cut-off was implanted down to the bedrock.

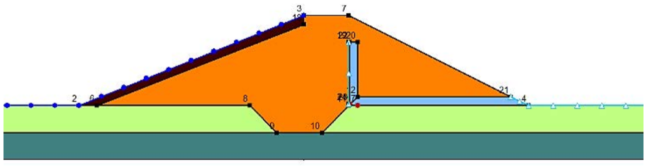

Figure 3. Typical section homogeneous dam: H=10 m, upstream slope 1V:2.5 H.
Source: Authors

Analysis of flow in transient conditions during the lowering of the water level

The bidimensional transient simulations were performed on the SEEP/W platform, considering that the lowering of the NW occurs at a limit speed of 15 cm/day as indicated by the USBR (2002), which is necessary to consider the rapid drawdown in slope stability assessments of an homogeneous dam.

In the SEEP/W platform, two functions were employed: the soil characteristic curve (volumetric water content x suction) and the permeability variation curve (hydraulic conductivity x suction). In the case of SC soil, those curves came from laboratory tests, while characteristic curve for volumetric moisture, evaluated by Fredlund and Xing (1994), was adopted for the other soil types.

In the present work, the hydraulic conductivity function was developed in an unsaturated context, where voids filled by air increased the tortuosity of the flow passage, thus reducing permeability in relation to saturated conditions. The permeability curves were defined by providing to the software the saturated permeability values, obtained from conventional tests, and the volumetric water content.

In order to adequately simulate the transient phenomenon and its impacts on the suction in the upstream slope, the transient flow analyses considered daily time intervals, being the total period of analysis proportional to the height of the dam, that is:

- Up to 30m = 180 days / time intervals;
- 35m = 240 days / time intervals;
- 40m = 260 days / time intervals;
- 45m = 290 days / time intervals;
- 50m = 330 days / time intervals;

Table 3. Results of 1500 trials carried out by U.S. Bureau of Reclamation

	Soil properties						
USCS Soil type	Compactation			Permeability	Strength parameters		
	maximum unit weight γ_g (KN/m^3)	optimum moisture content h (%)	wet unit weight γ_w (KN/m^3)	(m/day)	C′ (kPa)	C′ sat(kPa)	$\phi^{(\circ)}$
GW	>19,0	<13,3	>21,53	2,33E+07 ± 1,12E+07	(x)	(x)	>38,3
GP	>17,6	<12,4	>19,78	5,53E+07 ± 2,94E+07	(x)	(x)	>36,5
GM	>18,2	<14,5	>20,84	>2,59E-04	(x)	(x)	>33,8
GC	>18,4	<14,7	>21,10	>2,59E-04	(x)	(x)	>31,0
SW	19,0 ± 0,8	13,3 ± 2,5	21,53 ± 0,82	*	40 ± 4,0	(x)	38,6 ± 1,2
SP	17,6 ± 0,3	12,4 ± 1,0	22,03 ± 0,30	>1,30E-02	23 ± 6,0	(x)	36,5 ± 1,2
SM	18,2 ± 0,2	14,5 ± 0,4	20,80 ± 0,20	6,48E-03 ± 4,15E-03	52 ± 6,0	20 ± 7,0	33,8 ± 1,2
SM-SC	19,0 ± 0,2	12,8 ± 0,5	21,40 ± 0,20	6,91E-04 ± 5,18E-04	51 ± 2,0	14 ± 6,0	33,4 ± 4,0
SC	18,4 ± 0,2	14,7 ± 0,4	21,10 ± 0,20	2,9E-04 ± 1,73E-04	76 ± 2,0	11 ± 6,0	31,0 ± 4,0
ML	16,5 ± 0,2	19,2 ± 0,7	19,70 ± 0,20	5,10E-04 ± 1,73E-05	68 ± 1,0	09 ± (x)	31,8 ± 2,3
ML-CL	17,4 ± 0,3	16,8 ± 0,7	20,30 ± 0,30	1,12E-04 ± 6,05E-05	64 ± 2,0	22 ± (x)	31,8 ± 3,4
CL	17,3 ± 0,2	17,3 ± 0,3	20,30 ± 0,20	6,91E-05 ± 2,59E-05	88 ± 1,0	13 ± 2,0	28,4 ± 2,3
MH	13,1 ± 0,6	36,3 ± 3,2	17,90 ± 0,62	1,38E-04 ± 8,64E-05	36,3 ± 3,2	20 ± 9,0	25,2 ± 2,9
CH	15,0 ± 0,3	25,5 ± 1,2	18,80 ± 0,30	4,32E-05 ± 4,32E-05	25,5 ± 1,2	11 ± 6,0	19,3 ± 5,1

The resistance parameter ϕ_b considered was the average value of $\phi'/2$ as suggested by Kranh (2004).

Source: U.S. Bureau of Reclamation, 2002.

Analysis of stability during the lowering of the water level

Stability analyses of upstream slopes were performed on the SLOPE/W platform with the Morgenstern-Price method (1965), which is based on the limit equilibrium of rupture surfaces comprising both equilibrium of moments and forces. It also considers efforts between the slices.

The pore pressures considered in the stability analyses were obtained from the results of transient reservoir water level lowering analyzes performed every 30 days, until the complete depletion of the reservoir.

Geotechnical parameters used in the analysis

The analyses contemplated only the materials of reduced permeability, for which the rapid lowering of the NW represents a risk of destabilization. These materials are highlighted in blue in Table 3 of USBR (2002) whose recommended parameters were used in the performed analyses.

For the analyzes with suction, in addition to the drained parameters, saturated specific gravity, and Mohr Coulomb rupture criterion, a resistance parameter (ϕ_b) was used, as suggested by Kranh (2004), to consider the suction effect on the material shear strength.

For SC soil, the parameters were determined in laboratory tests with materials from an experimental dam with similar geometric characteristics to the model proposed in Figure 3, located in the Lavoura Seca Experimental Farm, in the municipality of Quixadá, belonging to the Federal University of Ceará. For the other soil types, the parameters presented by the U.S. Bureau of Reclamation (2002) were used.

Physical Characterization of the soil (SC)

Table 4 presents the summary of the geotechnical properties obtained in laboratory tests for SC soil of the experimental dam:

Table 4. Geotechnical Properties of Soil SC

Granulometry	Gravel	Sand	Silt	Clay
	3%	59%	10%	28%
Atterberg Limits (%)	LL	PL	PI	
	26	17	9	
Specific Gravity	2,62			
Soil Classification	USCS		HRB	
	SC		A-2-4	
Proctor Normal	W optimum (%)		γ_d (g/cm^3)	
	14,7		1,84	
Resistance Parameters	c′(kPa)		$\phi(\circ)$	$\phi b(\circ)$
	11,7		26,6	12,0

Source: Authors

Hydraulic properties of SC soil

The saturated hydraulic conductivity was obtained in laboratory tests performed in deformed samples, according to the NBR 14545/2000 standard for variable load tests, resulted in a permeability coefficient (k) of 2,6 x 10^{-7} m/s for the studied sample.

Soil characteristic curve

The filter paper method, according to ASTM Standard D5298-03 (2003), is generally accepted to be an inexpensive, technically simple, and reasonably accurate method that could be used to measure soil suction to a great extent. The method, however, is dependent of the accuracy of the calibration curve that relates filter paper water content to soil suction. Additionally, applying contact stress to the filter papers significantly influences this curve.

This is the basic approach, suggested by the American Society for Testing and Materials (ASTM) standard D5298-03 for the measurement of either matric suction using the contact filter paper technique or total suction using the non-contact filter paper technique. This standard employs a single calibration curve that has been used to infer both total and matric suction measurements, and it recommends the filter papers to be initially oven-dried (for 16 h or overnight) and then allowed to cool to room temperature in a desiccator. Its calibration curve is a combination of both wetting and drying curves. However, because of the marked hysteresis on its wetting and drying, the calibration curve for initially dry filter paper is different from that of the initially wet one.

Some publications present calibration for the wetting path, with the paper initially air dry (Chandler and Gutiérrez, 1986; Chandler et al., 1992; Ridley, 1993; and Marinho, 1994). Marinho and Oliveira (2006) shows that the calibration for the particular type of paper is unique in relation to the type of suction (i.e., total or matric).

Figure 4 shows the characteristic curve for SC soil, where the determination of soil suction was performed through the filter paper technique consisting of placing a soil sample in contact with a known calibration filter paper in a hermetically sealed environment until the system was balanced, while carefully handling the tools used in the test.

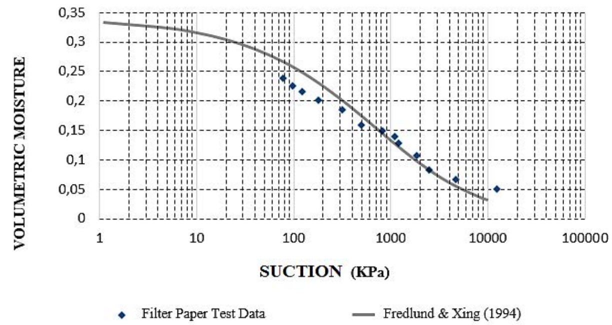

Figure 4. Relation matric suction and moisture (core) for SC soil
Source: Authors

Results of stability analysis in transient regime

The results of the stability analyses, carried out considering the transient behavior of the flow during the lowering of the reservoir and the effect of the suction on the stability of the upstream slope of a homogeneous dam, are presented in the graphs of Figure 5, relating the minimum safety factor with the inclination of the upstream slope for different dam heights, and in Figure 6, relating the minimum safety factor with the dam heights for different upstream slope inclination.

As expected, the influence of the permeability coefficient was observed in the results; in general, more permeable soils result in higher values of the minimum safety factor, keeping the due influence of the shear strength of the materials.

A linear relationship between the minimum safety factor for the rapid drawdown situation and the inclination of the upstream slope was found for practically all soil types according to the dam height, as well as an exponential relationship between the safety factor and the height of the dam for a given inclination of the upstream slope.

Except for 10 m dams, all results present excellent correlation for the adjusted equations to the minimum safety factor points obtained.

Using such equations and considering a safety factor of 1,1 a minimum slope and maximum height of the dam were determined for all types of material studied, which are presented in Tables 5 and 6, respectively.

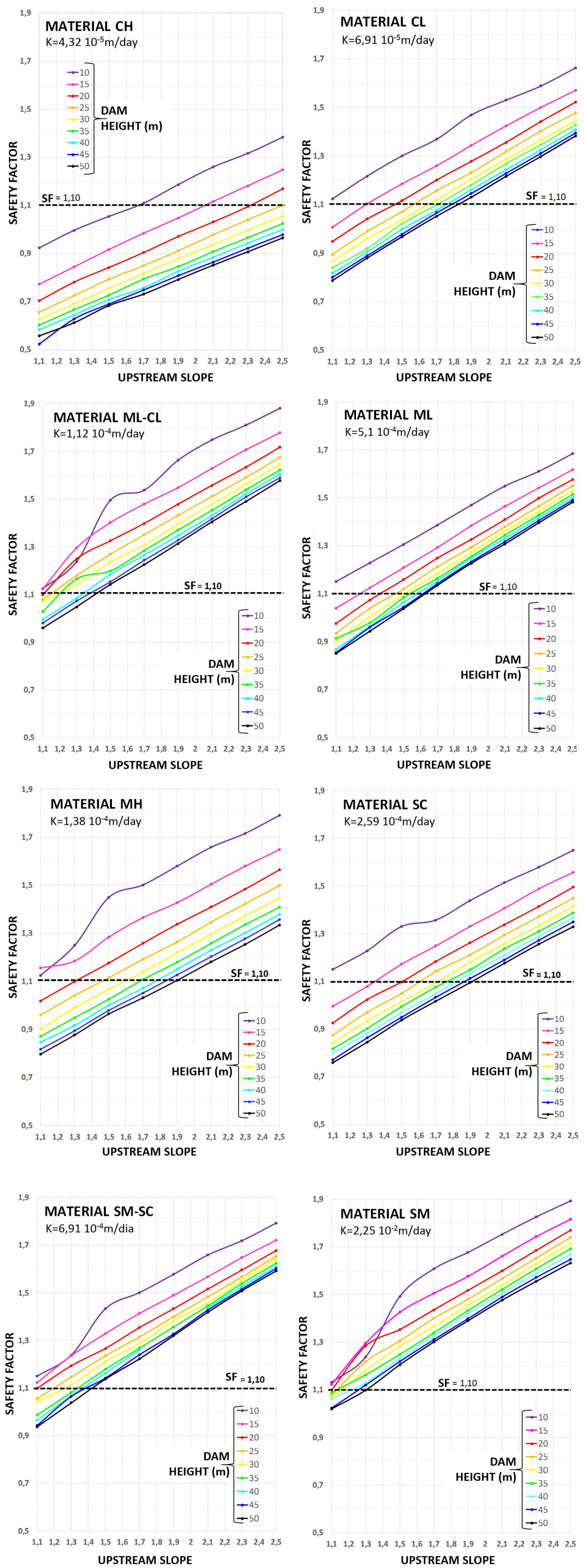

Figure 5. Safety Factor x Upstream Slope.
Source: Authors

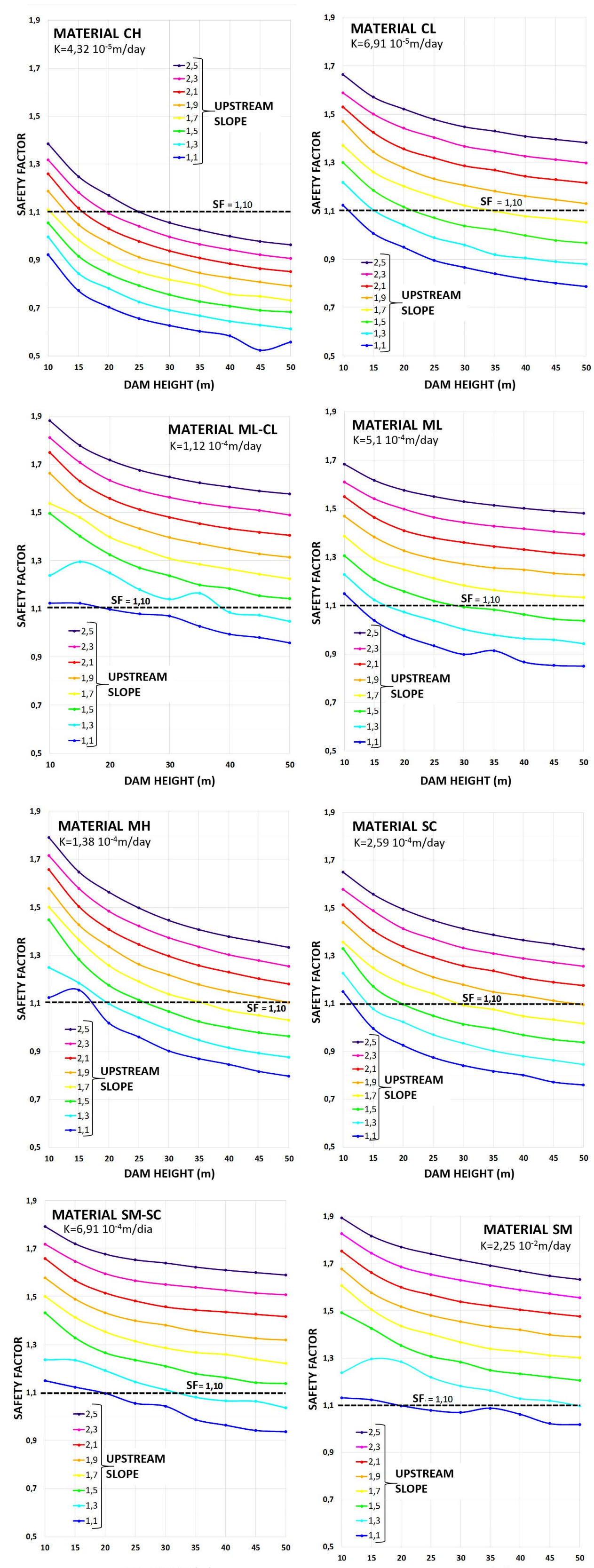

Figure 6. Safety Factor x Dam Height.
Source: Authors

Table 5. Minimum U/S Slope for a SF = 1,1

Minimum U/S Slope - SF = 1.10								
H (m)	CH	CL	ML-CL	ML	MH	SC	SM-SC	SM
10	1,64	1,05	0,54	0,96	0,91	0,93	0,58	0,44
15	2,05	1,30	0,70	1,24	1,00	1,34	0,99	0,67
20	2,30	1,46	0,93	1,31	1,30	1,51	1,09	0,87
25	2,49	1,57	1,12	1,46	1,46	1,63	1,19	1,02
30	2,63	1,65	1,18	1,53	1,59	1,72	1,25	1,10
35	2,74	1,71	1,27	1,55	1,69	1,78	1,34	1,15
40	2,83	1,76	1,33	1,59	1,77	1,83	1,37	1,20
45	2,86	1,79	1,37	1,62	1,83	1,88	1,41	1,25
50	2,96	1,82	1,41	1,64	1,89	1,92	1,43	1,27
USBR	4,0	4,0	3,5	3,5	3,5	3,0	3,0	3,0

Source: Authors

In Table 5 above, it can be observed that all the values of minimum upstream slope obtained with the consideration of the transient flow and suction are well below the values recommended by the USBR (2002); as expected, it is quite conservative.

This suggests that, eventually, the final construction situation may be the determining factor for the upstream slope of a homogeneous dam.

Table 6. Maximum dam height for a SF = 1,1

Maximum Dam Height (m)								
SLOPE	CH	CL	ML-CL	ML	MH	SC	SM-SC	SM
2,5	26,35	351,51	1328,76	1982,70	138,44	200,38	8665,68	4058,20
2,3	20,47	176,58	599,55	701,76	95,02	121,66	2324,12	1756,41
2,1	16,26	97,64	290,42	254,62	67,93	73,20	646,45	807,99
1,9	12,61	55,71	162,91	122,41	48,73	47,17	239,57	365,99
1,7	9,79	35,38	102,36	57,25	36,18	30,85	114,13	166,91
1,5	7,80	23,18	60,09	30,29	27,65	21,63	58,73	93,20
1,3	6,46	15,47	37,77	17,78	18,98	14,77	33,23	49,03
1,1	5,31	10,33	23,70	11,27	13,87	10,69	18,75	33,13

Source: Authors

Table 6 shows that CH soils are the least recommended for upstream slopes, because they have lower maximum heights for each analyzed slope -as explained below in the comparison of results- while the others are quite adequate.

Comparison results

In order to provide a basis for comparison, simplified stability analyses were carried out, considering instantaneous drawdown conditions without taking into account the transient flow and suction effect in the upstream slope.

The pore pressure for such simplified analyses came from a water table along the upstream slope associated to the permanent regime water table inside the embankment.

The analyses were carried out only for SC soil with the same effective resistance parameters and without the suction plot.

In addition, analyses were also performed without the foundation layer in order to evaluate the effect of the presence of this material on the stability of the upstream slope. Figure 7 shows the adopted geometric model.

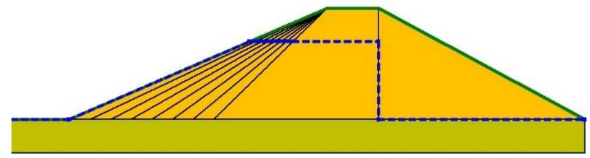

Figure 7. Simplified Analysis Model.
Source: Authors

The simplified analysis results are presented in Table 7 for both geometries, along with the ones from the analyses considering transient flow regime and suction, the latter highlighted in red.

It can be seen that CH-type soils, among the evaluated ones, are the least adequate for upstream slopes of dams where rapid drawdown is expected because safety factors greater than the unit are obtained solely for dam heights equal to or less than 20 m and 25 m, respectively with and without the foundation layer. While safety factors considering transient flow and suction are greater than 1,0 for slopes as steep as 1V: 1,7 H., using this type of soil would result in a greater use of soil volumes, which in turn would mean higher costs and execution times.

The SF curves versus upstream slope and SF versus height of the dam present a similar behavior to those obtained from analyses considering transient flow regime and suction, but with much lower safety factors, as shown in Figure 8.

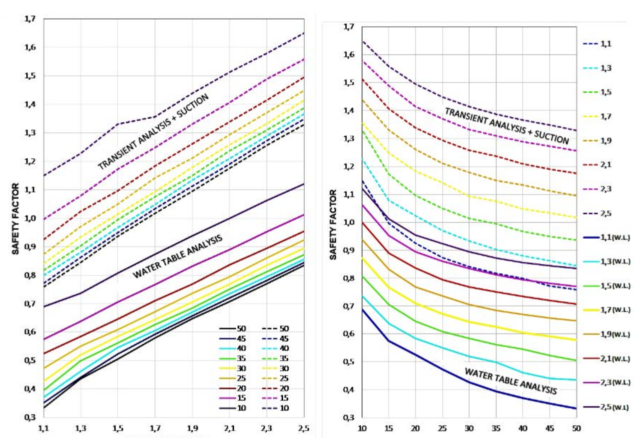

Figure 8. Simplified Analysis Model.
Source: Authors

Applying the same, previously adopted concept, it was possible to define analogous equations for the analyses with water table by defining the minimum slope and maximum height for a safety factor of 1,1.

Table 7. Results Analysis with Instant Drawdown

H(m)		Soil Type SC – Safety Factor Upstream Slope Rapid Drawdown							
		1V:1,10H	1V:1,30H	1V:1,50H	1V:1,70H	1V:1,90H	1V:2,10H	1V:2,30H	1V:2,50H
50	Transient analyze W/foundation	0,759	0,845	0,937	1,017	1,095	1,176	1,256	1,329
	W/foundation	0,334	0,436	0,506	0,579	0,648	0,707	0,770	0,835
	Out/foundation	0,331	0,435	0,505	0,585	0,662	0,734	0,807	0,879
45	Transient analyze W/foundation	0,771	0,863	0,949	1,033	1,112	1,190	1,272	1,349
	W/foundation	0,351	0,440	0,523	0,592	0,657	0,720	0,781	0,845
	Out/foundation	0,350	0,438	0,522	0,603	0,681	0,755	0,826	0,900
40	Transient analyze W/foundation	0,800	0,880	0,968	1,048	1,133	1,209	1,289	1,366
	W/foundation	0,371	0,461	0,545	0,605	0,670	0,735	0,794	0,856
	Out/foundation	0,371	0,459	0,543	0,624	0,703	0,779	0,851	0,924
35	Transient analyze W/foundation	0,817	0,902	0,994	1,076	1,149	1,237	1,310	1,388
	W/foundation	0,395	0,498	0,562	0,626	0,685	0,705	0,812	0,872
	Out/foundation	0,394	0,486	0,562	0,651	0,730	0,809	0,881	0,955
30	Transient analyze W/foundation	0,841	0,934	1,014	1,094	1,179	1,258	1,333	1,414
	W/foundation	0,427	0,519	0,584	0,644	0,706	0,769	0,835	0,895
	Out/foundation	0,427	0,520	0,606	0,688	0,766	0,846	0,923	0,996
25	Transient analyze W/foundation	0,874	0,970	1,049	1,141	1,211	1,294	1,371	1,449
	W/foundation	0,473	0,551	0,609	0,672	0,736	0,795	0,860	0,923
	Out/foundation	0,473	0,567	0,654	0,738	0,817	0,897	0,979	1,055
20	Transient analyze W/foundation	0,925	1,023	1,097	1,183	1,262	1,338	1,414	1,495
	W/foundation	0,525	0,584	0,646	0,710	0,769	0,836	0,894	0,955
	Out/foundation	0,539	0,634	0,724	0,809	0,894	0,976	1,056	1,138
15	Transient analyze W/foundation	0,996	1,079	1,172	1,249	1,331	1,407	1,489	1,558
	W/foundation	0,575	0,638	0,705	0,767	0,832	0,890	0,953	1,012
	Out/foundation	0,647	0,748	0,840	0,930	1,017	1,107	1,190	1,273
10	Transient analyze W/foundation	1,150	1,228	1,330	1,357	1,439	1,514	1,579	1,650
	W/foundation	0,689	0,736	0,807	0,873	0,938	0,999	1,062	1,120
	Out/foundation	0,866	0,972	1,076	1,175	1,272	1,369	1,464	1,557

Source: Authors

Table 8 shows the adjusted equations, the minimum slopes for each height and type of analyses, as well as the percentual relationship between the volume with the water table alternative and the volume considering transient analysis and suction.

This allows for the evaluation of the impact on the embankment volume of the upstream slope for each one of the approaches, considering a SC-type material.

The volume corresponding to the analysis with water table ranges from 161% to 262% of the volume from the transient analyses with suction, thus demonstrating the economy that represents a more sophisticated analysis of the problem.

Table 8. Comparison available of amount volume

H(m)	Water Table Analysis			Transient Analysis + Suction			V_{WT}
	SF = f(slope)	Correlation Coefficient	Minimum Slope (SF = 1,1)	SF = f(slope)	Correlation Coefficient	Minimum Slope (SF = 1,1)	V_{TRANS}
50	y = 0,3482x - 0,0248	R^2 = 0,9944	3,09	y = 0,4071x + 0,3189	R^2 = 0,9992	1,92	161%
45	y = 0,3464x - 0,0098	R^2 = 0,9951	3,15	y = 0,4103x + 0,3288	R^2 = 0,9993	1,88	167%
40	y = 0,339x + 0,0194	R^2 = 0,9947	3,19	y = 0,4057x + 0,3564	R^2 = 0,9997	1,83	174%
35	y = 0,3293x + 0,0573	R^2 = 0,9943	3,17	y = 0,4071x + 0,3764	R^2 = 0,9991	1,78	178%
30	y = 0,3258x + 0,086	R^2 = 0,997	3,11	y = 0,4061x + 0,4023	R^2 = 0,9995	1,72	181%
25	y = 0,3165x + 0,1327	R^2 = 0,9993	3,06	y = 0,4068x + 0,4376	R^2 = 0,9989	1,63	188%
20	y = 0,3089x + 0,1839	R^2 = 0,9999	2,97	y = 0,4016x + 0,4942	R^2 = 0,9991	1,51	197%
15	y = 0,3127x + 0,2336	R^2 = 0,9997	2,77	y = 0,403x + 0,5597	R^2 = 0,999	1,34	207%
10	y = 0,3148x + 0,3364	R^2 = 0,999	2,43	y = 0,3505x + 0,7749	R^2 = 0,9943	0,93	262%

Source: Author

Conclusions

The results demonstrated the advantages of considering the actual flow and suction conditions of the upstream slope for a rapid drawdown context. The equations correlating the minimum slope with the height of the dam represent the lower limit, to be considered once the velocity adopted in the analyses corresponds to the lower velocity defined by the USBR. It can be a valuable aid in the definition of dam geometry as much as in the construction process or schedule, and the selection of borrowing areas. As an example of the proposal, graph 9 shows the curves for the SC material, highlighting the application range.

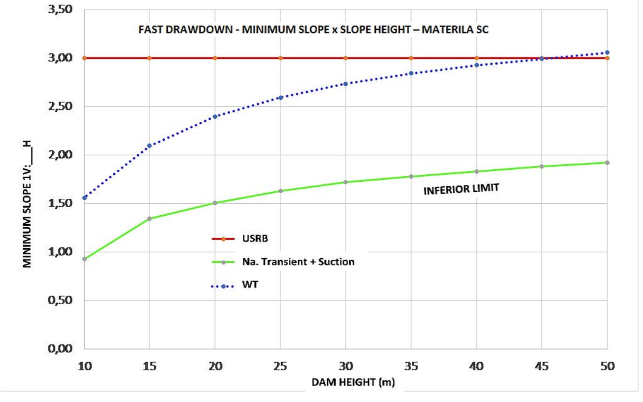

Figure 9. Safety factor x Dam height (m) – Inferior limit.
Source: Authors

A rapid drawdown transient analysis, along with a better representation of the phenomena, incorporates the apparent increase on the shear strength of the material according to its degree of saturation.

The comparison with the usual simplified analysis, presented in Figure 8, shows, for a same safety factor and dam height, much steeper inclination for the transient analysis, which means smaller volumes of material in the upstream slope and therefore a more desirable economic scenario.

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