Rapid Drawdown in Homogeneous Earth Dam Considering Transient Flow and Suction

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

Grover Romer Llanque Ayala¹, Francisco Chagas da Silva Filho², Rosiel Ferreira Leme³, Maria do Carmo Reis Cavalcanti⁴, and Claudio Fernando Mahler⁵

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 taludes 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

Received: May 30th, 2019
Accepted: February 28th, 2020

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.
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.](image)

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 | Soil Type(2) | Upstream | Downstream |
|-----------|----------------------------------|--------------|----------|------------|
| 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 to 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

| USCS Soil type | Compaction | Permeability | Strength parameters |
|----------------|------------|--------------|---------------------|
|                | maximum unit weight γ_1 (KN/m³) | optimum moisture content h (%) | wet unit weight γ_w (KN/m³) | (m/day) | C’ (kPa) | C’ sat(kPa) | ϕ’(°) |
| 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 ± 1,2 |
| SP             | 17,6 ± 0,3 | 12,4 ± 1,0   | 22,03 ± 0,30        | >1,30E-02          | 23 ± 6,0 | (x) | 36 ± 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 | 12,6 ± 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_h considered was the average value of ϕ’/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_h) 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 | PL |
| 26 | 17 | 9 |
| Specific Gravity | 2.62 |
| Soil Classification | USCS | HRB |
| SC | A-2-4 |
| Proctor Normal | W optimum (%) | ρ_d (g/cm³) |
| 14.7 | 1.84 |
| Resistance Parameters | c'(kPa) | φ(°) | φb(°) |
| 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 on 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

| 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| 1,04| 1,14| 0,90  | 0,67|
| 20    | 2,30| 1,46| 0,93  | 1,31| 1,20| 1,31| 0,99  | 0,87|
| 25    | 2,49| 1,57| 1,12  | 1,46| 1,42| 1,46| 1,09  | 1,02|
| 30    | 2,63| 1,65| 1,18  | 1,53| 1,49| 1,52| 1,24  | 1,10|
| 35    | 2,74| 1,71| 1,27  | 1,55| 1,50| 1,54| 1,34  | 1,15|
| 40    | 2,83| 1,76| 1,33  | 1,59| 1,55| 1,58| 1,44  | 1,20|
| 45    | 2,86| 1,79| 1,37  | 1,62| 1,58| 1,59| 1,44  | 1,23|
| 50    | 2,96| 1,82| 1,41  | 1,64| 1,59| 1,69| 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

| SLOPE | CH | CL | ML-CL | ML | MH | SC | SM-SC | SM |
|-------|----|----|-------|----|----|----|-------|----|
| 2,5   | 26,35| 35,51| 1328,76| 1982,70| 138,44| 200,38| 8665,68| 4058,20|
| 2,3   | 20,47| 175,58| 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   | W/foundation | 0,759 | 0,845 | 0,937 | 1,017 | 1,095 | 1,176 | 1,256 | 1,329 |
|      | Out/foundation | 0,334 | 0,436 | 0,506 | 0,579 | 0,648 | 0,707 | 0,770 | 0,835 |
| 45   | W/foundation | 0,771 | 0,863 | 0,949 | 1,033 | 1,112 | 1,190 | 1,272 | 1,349 |
|      | Out/foundation | 0,351 | 0,440 | 0,523 | 0,592 | 0,657 | 0,720 | 0,781 | 0,845 |
| 40   | W/foundation | 0,800 | 0,880 | 0,968 | 1,048 | 1,133 | 1,209 | 1,289 | 1,366 |
|      | Out/foundation | 0,371 | 0,461 | 0,545 | 0,605 | 0,670 | 0,735 | 0,794 | 0,856 |
| 35   | W/foundation | 0,817 | 0,902 | 0,994 | 1,076 | 1,149 | 1,237 | 1,310 | 1,388 |
|      | Out/foundation | 0,394 | 0,486 | 0,562 | 0,626 | 0,685 | 0,705 | 0,812 | 0,872 |
| 30   | W/foundation | 0,841 | 0,934 | 1,014 | 1,094 | 1,179 | 1,258 | 1,333 | 1,414 |
|      | Out/foundation | 0,427 | 0,519 | 0,584 | 0,644 | 0,706 | 0,769 | 0,835 | 0,895 |
| 25   | W/foundation | 0,874 | 0,970 | 1,049 | 1,141 | 1,211 | 1,294 | 1,371 | 1,449 |
|      | Out/foundation | 0,473 | 0,551 | 0,609 | 0,672 | 0,736 | 0,795 | 0,860 | 0,923 |
| 20   | W/foundation | 0,925 | 1,023 | 1,097 | 1,183 | 1,262 | 1,338 | 1,414 | 1,495 |
|      | Out/foundation | 0,525 | 0,584 | 0,646 | 0,710 | 0,769 | 0,836 | 0,894 | 0,955 |
| 15   | W/foundation | 0,996 | 1,079 | 1,172 | 1,249 | 1,331 | 1,407 | 1,489 | 1,558 |
|      | Out/foundation | 0,575 | 0,638 | 0,707 | 0,776 | 0,832 | 0,890 | 0,953 | 1,012 |
| 10   | W/foundation | 1,150 | 1,228 | 1,330 | 1,357 | 1,439 | 1,514 | 1,579 | 1,650 |
|      | Out/foundation | 0,689 | 0,736 | 0,807 | 0,873 | 0,938 | 0,999 | 1,062 | 1,120 |

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 | \( V_{WT} \) | \( V_{TRANS} \) |
|------|----------------------|-----------------------------|----------------|-----------------|
|      | \(SF = f(\text{slope})\) | Correlation Coefficient | Minimum Slope | Correlation Coefficient | Minimum Slope |
| 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   | \( y = 0.3399x + 0.0194 \) | \( R^2 = 0.9947 \) | 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   | \( y = 0.3258x + 0.086 \) | \( R^2 = 0.9974 \) | 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 | \( y = 0.4016x + 0.4942 \) | \( R^2 = 0.9999 \) | 1.51 | 197% |
| 15   | \( y = 0.3127x + 0.2336 \) | \( R^2 = 0.9997 \) | 2.77 | \( y = 0.403x + 0.5597 \) | \( R^2 = 0.9999 \) | 1.34 | 207% |
| 10   | \( y = 0.3148x + 0.3364 \) | \( R^2 = 0.9999 \) | 2.43 | \( y = 0.3505x + 0.7749 \) | \( R^2 = 0.9993 \) | 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.

References

ASTM D2487-11 (2011). Standard practice for classification of soils for engineering purposes (unified soil classification system). West Conshohocken, PA ASTM International. 10.1520/D2487-11

ASTM D5298-03 (2003). Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. West Conshohocken, PA ASTM International. 10.1520/D5298-03

Alonso, E. and Pinyol, N. (2009). Slope stability under rapid drawdown conditions. Barcelona: Universidad Politecnica de Catalunya. https://upcommons.upc.edu/bitstream/handle/2117/11200/01_IWL2009_Alonso-Pinyol.pdf

Alonso, E. and Pinyol, N. (2016). Numerical analysis of rapid drawdown: Applications in real cases. Water Science and Engineering. 9(3), 175-182. 10.1016/j.wse.2016.11.003

Berligen, M. M. (2007). Investigation of stability of slopes under drawdown conditions. Compute Geotechnics 34(2), 81-91. 10.1016/j.compgeo.2006.10.004

Chandler, R. J., Crilly, M. S., and Montgomery-Smith, G. (1992). A low-cost method of assessing clay desiccation for low-rise buildings. Proceedings of the Institution of Civil Engineers-civil Engineering, 92, 82–89. 10.1680/icen.1992.18771

Chandler, R. J. and Gutierrez C. I. (1986). The filter-paper method of suction measurement. Geotechnics, 36(2), 265-268. 10.1680/geot.1986.36.2.265

Cruz, P. T. (1996). 100 Barragens Brasileiras: Historic Cases, Materiais de Construção e Projeto. São Paulo: Oficina de Textos.

Fredlund, D. G. and Rahardjo, H. (1993a). Soil mechanics for unsaturated soils. New Jersey: John Wiley and Sons.
Fredlund, D. G. and Xing, A. (1994). Equations for the Soil-Water Characteristic Curve. *Canadian Geotechnical Journal*, 521-532. 10.1139/t94-061

Fredlund, D. G., Xing, A., and Huang, S. (1994). Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. *Canadian Geotechnical Journal*, 31(4), 533-546. 10.1139/t94-062

Fattah, M. Y., Omran, H. A., and Hassan, M. A., (2017). Flow and Stability of Al-Wand Earth Dam during Rapid Drawdown of Water in Reservoir. *Acta Montanistica Slovaca*, 22(1), 43-57.

Fattah, M. Y., Omran, H. A., and Hassan, M. A., (2015). Behavior of an Earth Dam during Rapid Drawdown of Water in Reservoir – Case Study. *International Journal of Advanced Research*, 3(10), 110 -122.

Fattah, M. Y., Al-Labban, S. N. Y., and Salman, F. A. (2014). Seepage Analysis of a Zoned Earth Dam by Finite Elements. *International Journal of Civil Engineering and Technology (IJCIET)*, 5(8), 128-139.

Geostudio International. (2007a). *Seepage Modeling with SEEP/W*. 2007. Calgary, Alberta, Canadá.

Geostudio International. (2007b). *Seepage Modeling with SLOPE/W*. 2007. Calgary, Alberta, Canadá.

Kranh, J. (2004). *Stability modelling with SLOPE/W - An Engineering Methodology*. Alberta, Canada: GEO-SLOPE/W International Ltd.

Lambe, T. W., and Whitman, R. (1969). *Soil Mechanics*. Spanish version of the English edition of 1969, Madrid: Limusa.

Lane P. A. and Griffiths D. V. (2000). Assessment of stability of slopes under drawdown conditions. *Journal of Geotechnical and Geoenvironmental Engineering*, 126, 443-450. 10.1061/(ASCE)1090-0241(2000)126:5(443)

Leme Ferreira, R. (2015). *Avaliação de uma metodologia para projeto de pequenas barragens de terra no semiárido: construção, ensaios e modelagem numérica*. (Doctoral dissertation), Universidade Federal do Ceará, Fortaleza, Brasil. http://www.repositorio.ufc.br/handle/riufc/16525

Llanque, G. R. A. (2018). *Verificação da estabilidade do talude de montante em barragem de terra submetida a rebaixamento rápido realizada com ensaios em solos não saturados e modelagem numérica*. (Master’s thesis), Universidade Federal do Ceará, Fortaleza, Brasil. http://www.repositorio.ufc.br/handle/riufc/31763

Marinho, F. A. M. (1994). Shrinkage behavior of some plastic clays. PhD Thesis, Imperial College, University of London.

Marinho, F. A. M., and Oliveira, O. M. (2006). The filter paper method revised. *ASTM geotechnical testing journal*, USA, 29(3), 250–258.

Morgenstern, N. R. (1963). Stability charts for earth slopes during rapid drawdown. *Geotechnique*, 13, 121-131. 10.1680/geot.1963.13.2.121

Morgenstern, N. R. and Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Geotechnique*, 15, 79-93. 10.1680/geot.1965.15.1.79

NBR 11.682 (2009). *Estabilidade de taludes*. ABNT, Associação brasileira de normas técnicas.

NBR 14.545 (2000). *Solu de Determinação do coeficiente de permeabilidade de solos argilosos a carga variável*. ABNT, Associação brasileira de normas técnicas.

Pinyol, N. M., Alonso, E. E., and Olivella, S. (2008). Rapid drawdown in slopes and embankments. *Water Resources Research*, 44, W00D03. 10.1029/2007WR006525

Ridley, A. M. (1993). *The measurement of soil moisture suction*. PhD thesis, University of London.

Sherard, J. L. (1953). *Influence of Soil Properties and Construction Methods on the Performance of Homogeneous Earth Dams*. Technical Memorandum 645. Denver, CO: Bureau of Reclamation.

Stephens, T. (2011). *Manual on small earth dams - Guide to the location, design and construction*. Roma: Food and Agriculture Organization of the United Nations.

Teixeira, R. S. and Vilar, O. M. (1997). *Shear Strength of a Compressed Soil not Saturated*. Proceedings of the 3rd Brazilian Symposium on Unsaturated Soils, 1,161-169. Rio de Janeiro.

U.S. ARMY CORPS OF ENGINEER (2003). *Engineer and design Slope Stability*. Washington, D.C.: U.S. Government.

U.S. BUREAU OF RECLAMATION (2002). *Design of Small Dams, A Water Resources Technical Publication*. Washington, D.C.: U.S. Government.

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 5(44), 892–898. 10.2136/sssaj1980.03615995004400050002x

Wang, J. J., Zhang, H. P., Zhang, L., and Liang, Y. (2012). Experimental study on heterogeneous slope responses to drawdown. *Engineering Geology*, 147-148, 52-56. 10.1016/j.enggeo.2012.07.020

Yan Z. L., Wang, J. J., Chai, H. J. (2010). Influence of water level fluctuation on phreatic line in silty soil model slope. *Engineering Geology*, 113(1-4), 90-98. 10.1016/j.enggeo.2010.02.004