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Safety assessment in dams due to downstream slope anomalies

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ABSTRACT

Recent cases of tailings dam failure in Brazil have demonstrated in the current methods of safety assessment of these structures. One of the most employed methods is the evaluation through routine inspections and audits, but this method is considered non-deterministic and affected by the expertise of the evaluator. This paper presents the results of numerical simulations of anomalies commonly found in safety inspections to measure the impact of these anomalies on the dam safety factor. The study was limited to numerical simulations of five types of dams (three downstream and two upstream dams), with varying embankment and tailings strength parameters, simulating different magnitudes of downstream slope anomalies (cracks, scour, and resurgence), totaling a sample space of 270 analyses. The results show that there were average reductions in safety ranging from 4% to 10% for scour simulations, 8% to 25% for resurgence, and 9% to 24% for cracking. The sample standard deviation of the analyses ranged from 8 to 12%. It was also observed that the combined effect of the anomalies showed proportional overlapping effects in reducing the range of safety. It was concluded that the simulated failures are important variables to be evaluated in inspections, not only for demonstrate deviations in the operation and maintenance of structures, but also to predict the magnitude of these failures in dam designs.

Keywords: Anomalies, cracks, scour, resurgence, factor of safety (FS).

1. Introduction

With the recent disasters resulting from dam failures, such as the Mount Polley dam in Canada in 2014, the Fundão dam in 2015, and dam B1 (both in Brazil), a discussion began regarding the safety assessment system of existing dams. Although rare, dam ruptures can be catastrophic, thus advances in safety assessment that mitigates possible risks of failures are critical (Zhang et al. 2016).

In Brazil alone, as presented in the dam safety report (ANA 2017), the country has 22,920 dams registered in its database, of which only 4,159 are classified concerning potential damage associated with rupture. Of the dams with a potential damage classification, 49% have high potential damage associated with rupture, indicating that 2,053 dams have the potential to cause loss of human life in case of rupture.

Recent studies have proposed alternatives or evolutions to existing dam safety assessment methods, such as Bowles et al. (1999), Bowles (2000), Fell et al. (2000), Hartford and Baecher (2004), ICOLD (2009), Jeon et al. (2009), Schultz et al. (2010), Curt et al. (2011), Zhang et al. (2016), and Morgenstern (2018). According to these authors, the main methods of assessing and ensuring dam safety are (1) deterministic limit equilibrium analyses; (2) probabilistic analyses; (3) portfolio analyses; (4) risk analyses or portfolio risk analyses.

The aforementioned methods have pros and cons: risk analyses point out vulnerable points of a structure and their failure triggers, but do not return results in the form of a safety number; deterministic analyses calculate a safety factor for each possible failure mode, but analyze a design or simulated condition, not describing the real situation with the presence of anomalies; portfolio analyses measure anomalies identified in the field, but the weights assigned depend on the method adopted, as well as on the assessor's interpretation/expertise.

In this context, this paper presents the results of simulations of downstream slope anomalies in dams (cracks, scour, and resurgence) to establish the influence of these anomalies on dam safety deterministically. Furthermore, this paper presents the results of combined simulations of anomalies to validate the effect of superposition of effects. Finally, the results presented aim to establish a form of portfolio analysis that can assist dam managers in ensuring the stability and reliability of these structures.

2. Methodology

2.1. Analysed Models

This study simulated anomalies to quantitatively verify the change in dam safety due to these anomalies. Therefore, a comparison was made between the Factor of Safety (FS) for the design condition and conditions containing anomalies considering the same section (height and batter) and the same geotechnical parameters. The FS for each of the models was the one obtained as a result of the analyses from the adopted geotechnical parameters, that is, the result is a reference for comparison of the failures only in its respective model.

To simulate the reduction of safety due to anomalies, dam models were proposed to cover small, medium, and large dams, as well as dams, elevated downstream and upstream. Fig. 1 shows the type section of the dams used for the simulations, being named B1, B2, and B3 the small, medium, and large downstream dams, respectively, and B4 and B5 the medium and large upstream dams, respectively.

The geometric characteristics of the type dams are presented in Table 1, while Table 2 presents the geotechnical parameters of the materials used in the simulations. The geotechnical parameters were selected aiming to cover a range of strength parameters typically found in dams in Brazil. It is noteworthy that for the downstream dams typically undrained tailings (undrained strength) were chosen, while for the upstream dams fine sand tailings (low friction and cohesionless) were chosen.

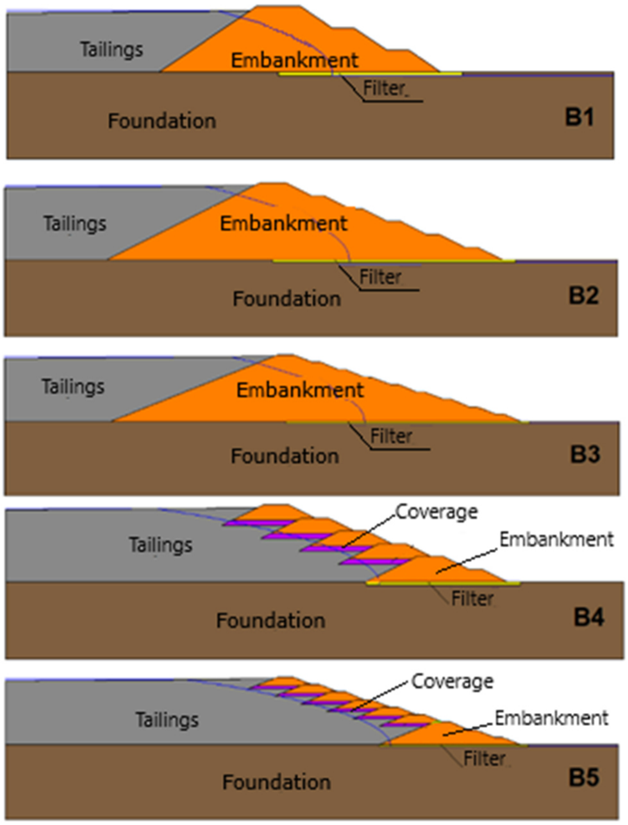


Figure 1. Type section of the type dams used in the simulations.

Both the embankment friction angle and the tailings resistance (friction angle or undrained strength) were varied by 4 lower and upper values in the type dams (B1 to B5) so that each of these models represented 18 dams, for a total sample field of 90 simulated dams.

The geometric characteristics were based on typical slopes of dam designs in Brazil. Geotechnical parameters were defined from previous studies that consider usual coefficient of variation values in soils, such as:

- Effective angle of friction in sands (φ): 2 to 15% (Kulhawy, 1992; Duncan, 2000);
- Angle of friction in clays (φ): 12 to 56% (Lumb, 1974);

Table 1. Geometric characteristics of the models used in the analyses.

Dam	Height (m)	Slope inclination (V:H)	Width of berms (m)	Raising method
B1	15	1:1,5	5	Downstream
B2	30	1:2,0	5	Downstream
B3	45	1:2,5	5	Downstream
B4	30	1:2,0	5	Upstream
B5	45	1:2,5	5	Upstream

Table 2. Geotechnical parameters used in the analyzed models.

Material	Specific weight (kN/m^3)	Cohesion (kPa)	Friction angle	Undrained strength (kPa)
Foundation	20	10	32°	-
Embankment	18	10	18° a 34°	-
Tailings[1]	16	-	0°	12 a 28 + 4 kPa/m
Tailings[2]	16	0	16° a 24°	-
Coverage	16	10	20°	-
Filter	18	0	30°	-

[1] Tailings used in downstream dams with undrained strength increasing with depth. [2] Tailings used in upstream raised dams.

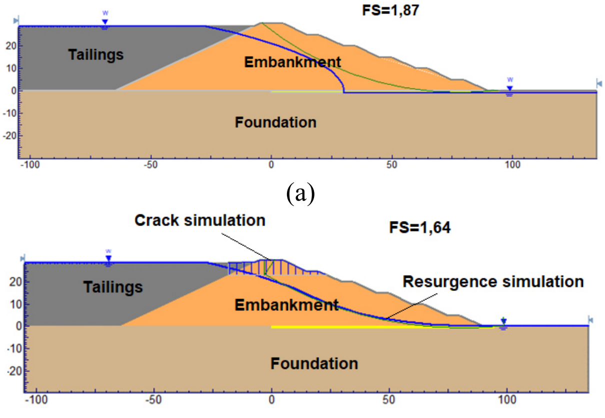
2.2. Method of Evaluation

The safety analyses of the models were executed by calculating the FS of the downstream slope using the Slide 6.0® software. Analyses were considered in the ideal design condition (without the presence of anomalies), as well as simulating analyses of resurgences, surface scour, and small, medium, and large transverse cracks, as well as their respective combinations:

- Small-sized resurgence (magnitude 1): considers the clogging of the internal drainage, resurgence located at the bottom of the structure, and with normal water level near the dam center;
- Medium-sized resurgence (magnitude 2): considers the internal drainage to be clogged, the resurgence to be located above the first berm, the water level to be slightly elevated near the dam center, and the water level to be normal near the dam center;
- Large-sized resurgence (magnitude 3): considers the clogging of the internal drainage, resurgence located above the second berm, and with considerably elevated water level near the dam center;
- Small-sized scour (magnitude 1): isolated, superficial, and located on only one berm of the section;
- Medium-sized scour (magnitude 2): numerous, up to 2 m deep, and located on up to two sides of the section;

- Large-sized scour (magnitude 3): numerous, up to 4 m deep, and located on several of the section's berms;
- Small size cracks (magnitude 1): transverse, saturated, located on the crest and with a depth of up to 5% of the dam height;
- Medium-sized cracks (magnitude 2): transverse, saturated, located on the crest or reservoir and with a depth of up to 10% of the dam height;
- Large-sized cracks (magnitude 3): transverse, saturated, located on the crest or reservoir and with a depth of up to 25% of the dam height.

Fig. 2 shows as an example the result of one of the analyses considering the model for the normal operating condition (Fig. 2a) and considering the combined condition of medium-sized resurgence and cracks (Fig. 2b) for B2 model dam.



(a)

(b)

Figure 2. Type section of the type dams used in the simulations.

The previous analysis was conducted to define the sections and geotechnical parameters of the ideal design condition whose simulations resulted in an FS higher than 1.5, but not higher than 2.2. After the ideal design sections were defined, the FS for this design condition (simulating variations of the embankment and tailings parameters) was calculated, as well as calculated the FS for the anomaly conditions.

In addition, the FS was calculated for combinations of resurgence, scour, and cracking always with the same magnitude to check the combined effect and the hypothesis of validity of the superposition of the effects. The comparison between the FS of the design condition and the anomaly condition was done by fixing the geotechnical parameters so that they would not interfere with the results.

The stability analyses were carried out considering the Mohr-Coulomb failure criterion, circular failure surfaces, and Morgenstern-Price analysis method that satisfies, simultaneously, the equilibrium of forces and moments between slices.

To evaluate the loss of safety due to anomalies, we started from the definition margin of safety (MS) present in Schultz et al. (2010), given by the difference between strength forces (R) and loading forces (C), according to Eq. 1. Knowing that the FS is defined by the ratio between those between R and C (Eq. 2), we defined MS as a function of FS according to Eq. 3.

$$MS = \frac{R-C}{C} \tag{1}$$

$$FS = \frac{R}{C} = \frac{MS+C}{C} \tag{2}$$

$$MS=FS-1 \tag{3}$$

The relative magnitude of the effect of anomalies (scours and cracks) was determined from the concept of relative loss margin of safety (ΔMS), according to Eq. 4, given by the difference between the initial design FS (FS_0) and the FS containing some anomaly (FS_A).

$$\Delta MS = \frac{FS_0 - FS_A}{MS} \tag{4}$$

Considering that the FS_A is the real dam safety condition, in Portuguese real condition of safety (CRS) itself for a dam when an anomaly is considered, we define CRS calculated by FS_0, MS, and ΔMS, according to Eq.s 5 and 6.

$$CRS = FS_0 - MS \cdot \Delta MS \tag{5}$$

$$CRS = FS_0 - MS \sum \Delta MS \tag{6}$$

It is important to note that Eq. 6 will only be valid if the effect of superposition of anomaly effects on the MS is verified. In this case, the anomaly effect may be represented by the simple addition of ΔMS.

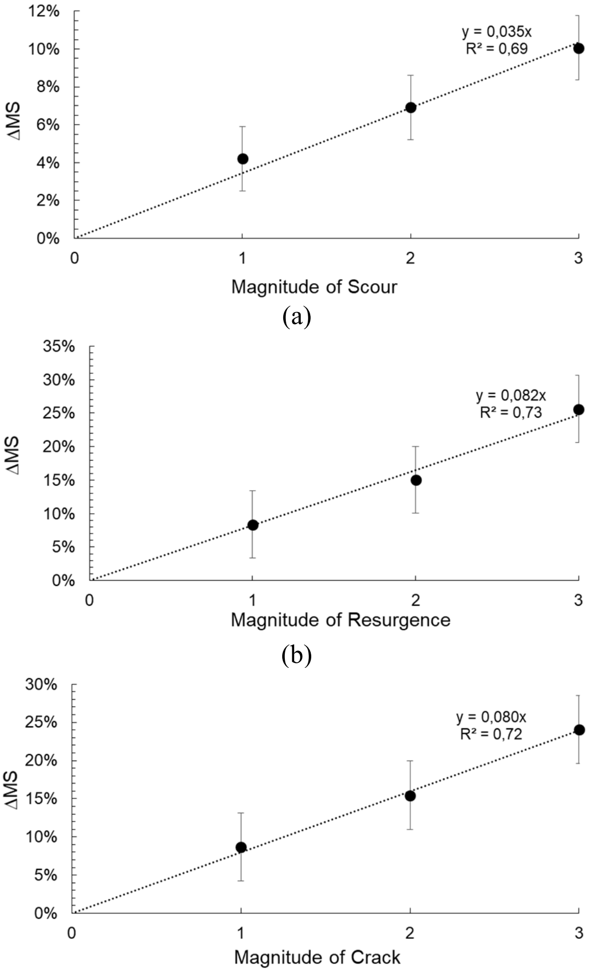
3. Results and Discussions

In general, the results presented a reduction in safety proportional to the magnitude of the simulated anomalies, as shown in the following Figs. There was little variation from the mean (most analyses were within the standard deviation limits), suggesting that the anomalies have a relatively uniform reduction in the safety of the dams, regardless of their size and type of raising. Fig. 3 shows the results of the fits for scours (Fig. 3a), resurgence (Fig. 3b), and cracks (Fig. 3c).

Important to note that their simulations considered the materials to be uniform and homogeneous. However, in real cases, dam size with greater susceptibility to heterogeneity could result in an increase in uncertainty and variability of the parameters.

Overall, magnitude 1 scour resulted in ΔMS at about 4%, magnitude 2 scour at about 7%, and magnitude 3 scour at about 12%. As for crack analyses, it was observed that magnitude 1 cracks resulted in ΔMS by about 9%, magnitude 2 cracks by about 15%, and magnitude 3 cracks by about 24%. As for resurgence, it was observed that magnitude 1 resurgence resulted in ΔMS by about 8%, magnitude 2 resurgences by about 14%, and magnitude 3 resurgence by about 25%. This result was consistent in both the variation of the embankment friction and the variation of the tailings strength parameters.

By analyzing the possible differences between the simulation results the slip surfaces did not follow a rule but were quite varied in both depth and location. This behavior was expected due to the large variation in geotechnical parameters and anomalies. In any case, despite this variation in the slip surface, a relative linear trend of the results was observed.



(a)

(b)

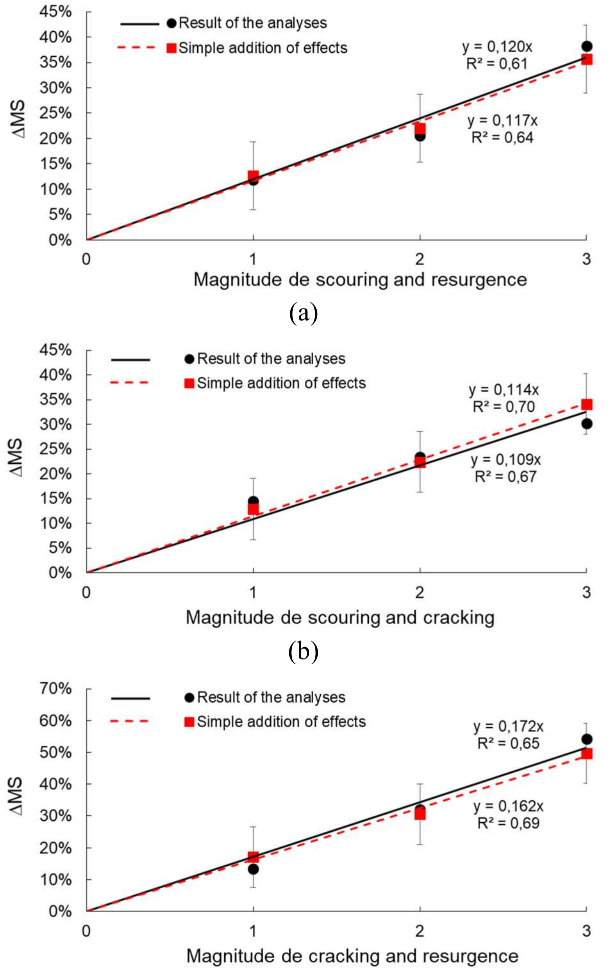
(c)

Figure 3. Linear fits of the simulation results for scour (a) resurgence (b) and cracking (c).

Specifically for the evaluation of scouring (Fig. 3a), the linear fit obtained a coefficient of determination of 69% and a standard deviation of ±2.1% for the sample field evaluated, indicating a satisfactory linear model between the magnitude of scour and relative loss of dam safety. Similarly, a good linear fit can also be observed between the magnitude of resurgence and cracks (Fig.s 3b and 3c) and ΔMS, obtaining respectively a coefficient of determination of 73% and a standard deviation of ±4.6%, and a coefficient of determination of 72% and a standard deviation of ±4.2% for resurgence and cracking.

Comparing the simulated anomalies, it can be inferred from the results obtained that resurgence and cracks have a greater reduction in safety compared to scour. However, it can be affirmed that none of the simulated anomalies can be neglected, with results that can reach a 25% reduction in the margin of safety. As an example, a dam with a design FS of 1.5 presenting a large magnitude resurgence (ΔMS=25%±4.6%), would have this FS reduced to a range between 1.35 and 1.40. Furthermore, this result could be even more significant for the case of verification of more than one anomaly.

In addition to simulations of the anomalies analyzed in isolation, combinations of anomalies were also evaluated in order to verify the reduction in safety and validation of the effect of superposition of the effects. Fig. 3 shows the results of the settings for scouring and resurgence (Fig. 3a), scouring and cracking (Fig. 3b), and cracking and resurgence (Fig. 3c).



(a)

(b)

(c)

Figure 4. Linear fits of the results from the combined simulations of scouring and resurgence (a) scouring and cracking (b) and cracking and resurgence (c).

It is observed, as expected, that the combined effect of anomalies increased the ΔMS for all analyses and all simulated magnitudes, both for isolated model evaluations and on average. A proportionality is seen in the linear fits in Fig. 4 between the combined anomaly magnitude and the relative loss of margin of safety.

The reliability of the modeling can be seen by observing that the coefficient of determination and standard deviation results for both the combined anomaly analysis results (solid line) and the sum of ΔMS values from the isolated anomaly analyses (dashed line). The coefficient of determination values ranged between 61% and 70% considering the standard deviation presented.

This result brings an important reflection on the effect of anomalies on the safety of dams: there is a tendency to investigate irregularities in isolation during an inspection, but it was found that the combined anomalies can add up to the effect of decreasing the safety, especially if these anomalies are identified in the same section of the dam.

Specifically for the analysis of the combination of scouring and resurgence (Fig. 4a), the results of the analyses returned ΔMS at about 12% for magnitudes 1, 22% for magnitudes 2, and for magnitudes 3, and 38% for magnitudes 3. For the combination of scouring and cracking (Fig. 4b), a ΔMS was observed at about 15% for magnitudes 1, 23% for magnitudes 2 and for magnitudes 3, and 31% for magnitudes 3. Whereas for the combination of cracking and resurgence (Fig. 4c), a ΔMS was observed at about 14% for magnitudes 1, 30% for magnitudes 2 and for magnitudes 3, and 53% for magnitudes 3.

Another important finding was that despite the good linear fit for the combined effect of anomalies, it is observed in Fig. 4b that the combined effect of scouring and cracking tends to decrease for high magnitudes (the magnitude 3 points below the trend line is observed). This observation can be explained by the fact that both scouring and cracking are geometry-changing anomalies, and for high magnitudes, erosion can interfere with the area of cracks or vice versa. This observation can also be explained by a possible subtle change of the slip surface between one analysis and another. Furthermore, this observation was not verified in the evaluation of scouring and resurgence (Fig. 4a) and cracking and resurgence (Fig. 4c) which show a point above the tendency line for magnitude 3, showing the potentiating effect of resurgence (high water level) on the anomalies that change the geometry of the section.

Finally, the results presented in this paper indicate that it is possible to evaluate the actual safety condition of dams by measuring anomalies. However, for this purpose, the results of this study should be complemented with evaluations of other boundary conditions, such as upstream slope evaluations, stress-strain analysis, as well as the evaluation of other failure modes that can reduce the safety of a dam.

4. Conclusions

From the results presented in this paper, the following conclusions can be listed:

1. A safety reduction proportional to the magnitude of the simulated anomalies was observed for all anomalies tested, as well as a linear tendency of safety reduction with increasing anomaly magnitude was verified;
2. Resurgences and cracks have a greater effect in reducing the safety margin (about 8% for each magnitude level) compared to scouring (about 4% for each magnitude level). Also, resurgence and cracks had a higher standard deviation of the results (respectively 4.6% and 4.2%) compared to the standard deviation of those obtained for scouring (2.1%);
3. When evaluated separately, the reduction in safety can reach 25%, indicating a large decrease in the design safety factor of a dam;
4. The combined effect of the anomalies demonstrated that the superposition of effects is valid. This finding demonstrates that the reduction in safety can be obtained by adding the effect of the anomalies evaluated separately within an acceptable error;
5. The effect of the combined evaluation was lower for the analyses containing scour, and the worst-case scenario in terms of safety reduction was obtained for the combinations of cracking and resurgence;
6. It was demonstrated that it is possible to measure the reduction of the safety of a dam from the survey of anomalies routinely performed during inspections and audits.

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