



The increase in streamflows and its impact on the probability of failure by sliding of the Santa Clara HPP dam using Monte Carlo method

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Abstract

Rainfall behavior has been affected worldwide, probably because of climate change. In several cases, this modification generated more intense river streamflows. Risk assessment is essential to check the security of existing dams, and it provides guidance for the design of future hydraulic structures. The risk analysis approach helps new projects to comply with safety criteria, or it is a reliable method to guide the need for safety interventions or repairs and to help in the decision to increase their discharge capacity. A case study of the Santa Clara Hydro-Power Plant was carried out to analyze if there were changes in the design flood and the impact that these variations could have on the dam failure probability. The maximum streamflows determined at the time of the dam construction were compared with the streamflows found in the update of the hydrological studies. Analyzing the results, it was possible to find out there was an increase in streamflow rates. The Monte Carlo method was used to establish a curve correlating the affluent streamflow with the probability of failure, allowing to verify the update of the hydrological study of the project implied an increase in the probability of failure of 18.1% for the millennial flood.

Keywords Probability of failure · Stability of dams · Sliding stability · Climate change · Increase in river streamflows

Terminology

Sliding stability

Refers to the ability of the dam to resist sliding or movement along its base or foundation. It is an important factor in determining the overall stability of a dam.

Failure probability

The likelihood or chance of the dam failing to meet its stability requirements or safety standards, expressed as a probability, often calculated using probabilistic methods that consider uncertainties and variability in parameters.

Design flood

The flood that a dam or other infrastructure is designed to withstand, typically based on statistical analysis of historical data or other methods.

Probabilistic method

A method that incorporates uncertainties and variability in parameters, using statistical techniques to quantify and assess risks, such as the probability of dam failure in this case.

Deterministic method

A method that relies on fixed values and assumptions, without considering uncertainties or variability in parameters, providing deterministic outcomes without quantifying probabilities or risks.

Return period

The average time interval within which a specific event, such as a flood, is expected to occur, based on historical data or

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statistical analysis. For example, a 1000-year return period flood is expected to occur on average once every 1000 years.

Introduction

The safety of dams is a function of the maximum load that can be imposed on them and their strength to withstand such application. Since it is very challenging to determine the maximum load that will be applied to a structure during its lifespan, and the exact ability to resist these forces, it is impossible to assure its absolute safety. This can only be ensured in terms of the probability that the structure's capacity is enough to resist the maximum stress that will be imposed (Motta and Malite 2002), always with the possibility that a combination of factors causes an unsatisfactory performance (Perini 2009).

With the failure of the dikes in New Orleans in 2005, it was discovered that the risk levels change over time for reasons like land use and occupation, structural degradation, and climate change (ASCE 2007). In addition, impacts equally vary because of population growth, influencing the number of people directly or indirectly affected by the dam. Therefore, risk analysis needs to be updated as new information becomes available (Environment Agency 2013a).

According to Perini (2009), risk assessment is still in the process of improvement for application in dam safety. However, several organizations have already considered risk-based approaches, supporting decision making, once it reduces the degree of uncertainty of projects and the influence of bias (PMI 2017).

According to Caldeira and Neves (2014), there is now a gap regarding the concepts of structural safety used in dams and those that are applied in other civil engineering works. In the area of dams, the practice of safety analysis remains associated with simple concepts, like the global safety coefficient, using as a reference the factors presented in the Eletrobrás (2003) publication. However, according to Aoki (2008), a safety factor greater than one does not guarantee the structure will not collapse since the applied load and the strength, are variable expressed by probability density functions. Therefore, the simple application of safety factors can lead to an unacceptable likelihood of ruin.

Ditlevsen (1997) presented examples that showed that the adoption of fixed values of safety factors leads to non-uniform levels of reliability. As follows, it was suggested to carry out probabilistic stability analysis that, through the reliability index (β) and the probability of failure or rupture (PF), allow the quantification of the uncertainties that deterministic methods incur, because of the limited number of samples and the considerable variability of the parameters (Gerscovich 2016).

One way to perform probabilistic analysis is through the Monte Carlo method, in which probability density functions are defined for the parameters. Many combinations are generated from them, resulting in a sample that allows the probability of failure of the dam to be calculated (Environment Agency 2013b).

Therefore, because of the relevance of the subject, this article presents a case study that aims to analyze the impact of updating the hydrological series on the probability of failure due to the landslide of the Santa Clara Hydro-Power Plant (HPP) dam.

This research emphasizes the importance of regularly updating hydrological studies for operational hydropower plants, and the potential implications on dam safety resulting from changes in decamillenarian flow patterns. By incorporating updated hydrological data, hydropower projects can be made safer and more cost-effective. Furthermore, the findings of this research can significantly contribute to the development of laws and regulations governing the incorporation of updated hydrological studies in the hydropower industry, benefiting both society and the technical community.

The accuracy, applicability, and reliability of this case study were evaluated based on the previous research. Isensee (2021) identified an increase in extreme precipitation event in Brazil, while Bottini et al. (2018) concluded that 13 out of 14 of Brazil's largest hydroelectric power plants had an increase in decamillenarian streamflow since their construction. Additionally, Souza and Filho (2020) employed a similar Monte Carlo-based methodology to evaluate the probability of failure due to sliding of hydraulic structures. These findings suggests that the results of the current study are reliable and contribute to the existing knowledge in fields of hydrology, climate change, and dam safety.

Material and methods

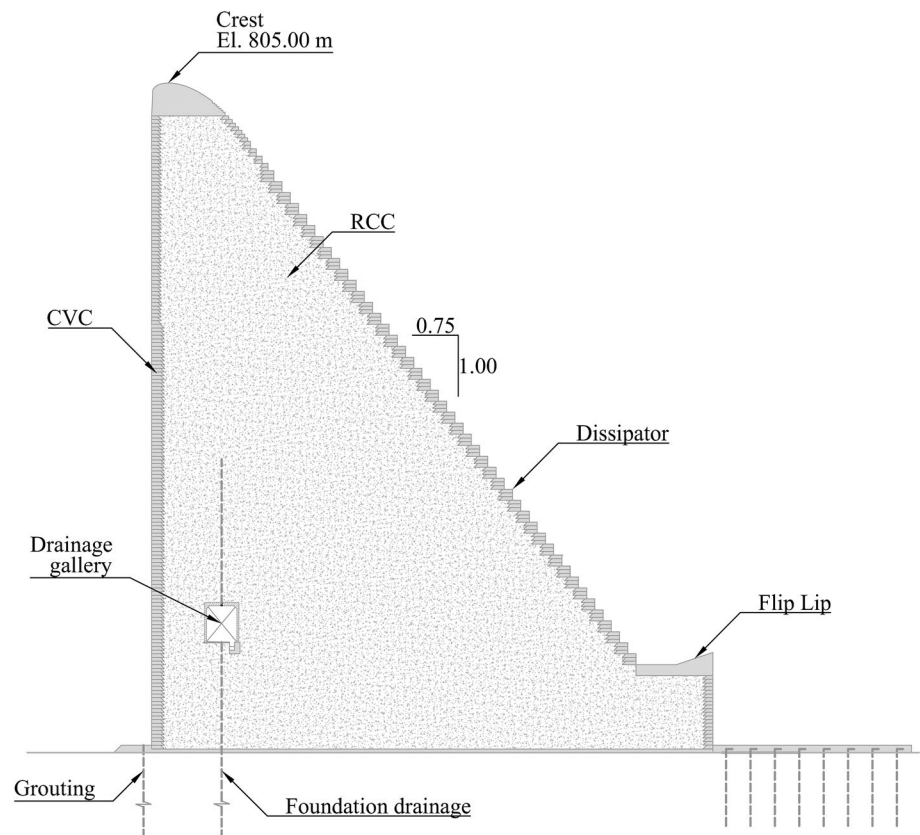
The Santa Clara HPP dam was built on roller compacted concrete (RCC) and conventional vibrated concrete (CVC). The dam is 618-m long and 67-m high and has an uncontrolled central spillway. Its typical cross-section has a vertical upstream face, the warhead-shaped ridge at elevation 805.00 m, and a downstream slope of 0.75 H:1.00 V, as shown in Fig. 1 (COPEL and INTERTECHNE 2000).

The plant is located in southern Brazil, in the State of Paraná between the municipalities of Cândói and Pinhão, and has a drainage area of 3900 km², as shown in Fig. 2.

Hydrology

All the hydrological data used in the study are public domain, obtained from the database of the Brazilian National Water Agency (ANA).

Fig. 1 Dam profile



First, the design flood was recalculated using the streamflow series until 1997, the year in which the hydrological studies of the Santa Clara HPP were prepared. After that, the design flood was calculated using the streamflow series updated until December 2018.

Maximum streamflow study—local analysis

According to the local flood frequency analysis, the maximum annual streamflow rates were taken from Salto Curucaca/Fazenda Taguá and Santa Clara stream gauging stations, which have a catchment area of 2200 and 3913 km², respectively. The average, standard deviation, and asymmetry coefficient of each station, as well as the parameters of scale and position, by the method of moments are listed in Table 1.

According to Eletrobrás (2000) if the Asymmetry Coefficient is less than 1.5, it is recommended to use the Gumbel distribution, (type I extremes) which has an asymmetry coefficient equal to 1.14; if greater than 1.5, the exponential distribution is recommended (estimated by the method of moments) which has an asymmetry coefficient equal to 2.0.

As the series of maximum annual streamflow of the selected stations have an asymmetry coefficient greater than 1.5, the exponential distribution estimated by the method of moments was adopted.

The probability distribution parameters, corrected in Table 1, were determined according to the method of moments (Naghattini and Pinto 2007). The data listed in Table 2 are calculated according to Eq. 1.

$$x(T) = \beta - \alpha \ln \frac{1}{RP} \quad (1)$$

where α is the scale parameter; β is the position parameter; and RP is the return period, in years.

For each return period (RP), a linear equation was established, according to the drainage area and flow in liters per second per square kilometer of the gauging stations of the series until 1997 and until 2018. Based on these equations, the contribution diagram for Santa Clara HPP was defined obtaining the flow corresponding to the drainage area of 3900 km² at the dam's axis, as listed in Table 4. Due to the small difference between the drainage area of the Santa Clara steam gauging station and the dam location, the results obtained in the axis of the plant are similar to those of the gauging station itself.

To determine the maximum instantaneous streamflow, the maximum streamflow coefficient of 1194, determined during the hydrological investigations performed before the dam construction to design the spillway, was used (COPEL and INTERTECHNE 2000). This coefficient was obtained by comparing the average daily streamflow with

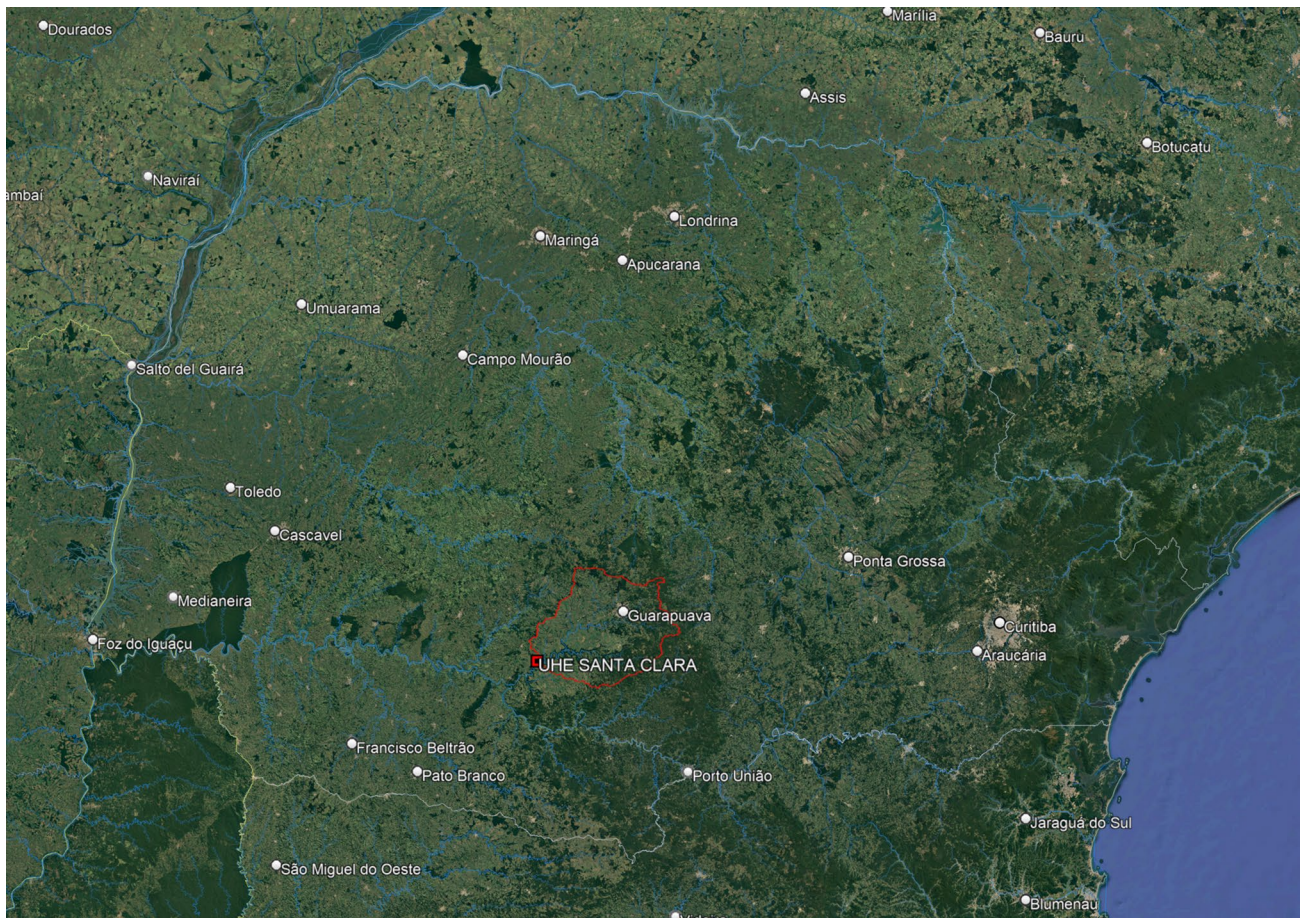


Fig. 2 Location of the Santa Clara HPP drainage area in the State of Paraná

Table 1 Characteristics of the series of maximum annual streamflows

	Available series in 1997		Updated series by 2018	
	Salto Curucaca/ Fazenda Taguá	Santa Clara	Salto Curucaca/ Fazenda Taguá	Santa Clara
Number of years	38 years	48 years	55 years	69 years
Average (m ³ /s)	378	726	419	767
Standard (m ³ /s) deviation	278	515	275	582
Asymmetry coefficient	2.44	3.29	1.83	3.53
Scale parameter (α)	278.22	515.02	275.22	582.10
Position parameter (β)	99.78	210.85	143.77	184.78

the streamflow measured during the peak of the flood in July 1982, according to Table 3.

The maximum streamflow rates calculated based on the series available until 1997 and for the updated series until 2018, are shown in Table 4.

Through the local analysis, we can note that the 10,000-year flood on the Santa Clara HPP axis had an increase of 11.9%. In addition, it is possible to observe that for all return periods above 20 years, the increase was over 10%.

Maximum streamflow study—regional analysis

In the regional flood frequency analysis, the same stations were used as in the basic design, as well as the drainage area and slope data of the stations. There are 17 stream gauging stations, with at least 20 years of observation and drainage area ranging from 65 to 8600 km² (COPEL and INTERTECHNE 2000).

Table 2 Daily average maximum streamflow of local analysis of selected fluviometric stations

RP (years)	Available series in 1997		Updated series by 2018	
	Salto Curucaca/ Fazenda Taguá (m ³ /s)	Santa Clara (m ³ /s)	Salto Curucaca/ Fazenda Taguá (m ³ /s)	Santa Clara (m ³ /s)
2	293	568	335	588
5	548	1040	587	1122
10	740	1397	777	1525
20	933	1754	968	1929
25	995	1869	1030	2058
50	1.188	2226	1220	2462
100	1.381	2583	1411	2865
500	1.829	3412	1854	3802
1000	2.022	3768	2045	4206
10,000	2.662	4954	2679	5546

In the analysis, the generalized extreme value (GEV) distribution was used, and its parameters were estimated using the L-moments method.

As well as in the local analysis, the maximum streamflows in the plant axis for the regional analysis were calculated based on the diagram of contributions of the stream gauging stations, and for the definition of the instantaneous

maximum streamflow, the maximum streamflow coefficient of 1.194, determined in the basic design, was used.

The maximum streamflow rates, calculated based on the series available until 1997 and for the updated series until 2018, are shown in Table 5.

As in the local analysis, in the regional analysis, there was also an increase in the streamflow rates of all the return periods analyzed. According to the regional analysis, the 10,000-year flood on the Santa Clara HPP axis increased by 6.6%.

Maximum streamflow rates adopted

Comparing the results obtained in the local flood frequency analysis with those of the regional analysis, it is possible to verify that for the return periods up to 1000 years, the streamflow rates of the local analysis were higher. In this manner, for return periods of 2–1000 years, the values of the local analysis were adopted, since it is a study of maximum streamflows, the adoption of higher streamflows ends up being a more conservative choice.

For the return period of 10,000 years, that is, for the spillway design flood, the regional analysis streamflow rates were higher, and for the same reason already showed, the data were adopted for the definition of the design flood.

Table 3 Floods analyzed at Santa Clara gauging station

	Floods						
	May/54	June/55	July/82	May/87	Sept/89	May/93	Jan/95
Maximum daily average (m ³ /s)	1065	1008	1110	1413	850	944	1163
Instantaneous maximum (m ³ /s)	1155	1039	1323	1503	942	1035	1188
Instantaneous/daily average (observed)	1.085	1.030	1.192	1.064	1.108	1.096	1.021
Instantaneous/daily average (corrected)	1.115	1.043	1.194	1.074	1.061	1.081	1.037

Table 4 Maximum streamflow rates for the local analysis of the Santa Clara HPP

RP (years)	Available series in 1997		Updated series by 2018		Variations between the series (%)
	Maximum daily averages (m ³ /s)	Instantaneous maximums (m ³ /s)	Maximum daily averages (m ³ /s)	Instantaneous maximums (m ³ /s)	
2	565	675	587	701	+ 3.9
5	1037	1239	1118	1335	+ 7.8
10	1393	1663	1520	1815	+ 9.1
20	1748	2088	1923	2296	+ 10.0
25	1863	2225	2052	2451	+ 10.1
50	2219	2649	2454	2930	+ 10.6
100	2576	3076	2855	3409	+ 10.9
500	3402	4062	3789	4524	+ 11.4
1000	3757	4486	4192	5006	+ 11.6
10,000	4940	5899	5528	6600	+ 11.9

Table 5 Maximum streamflow rates for the regional analysis of HPP Santa Clara

RP (years)	Available series in 1997		Updated series by 2018		Variations between the series (%)
	Maximum daily averages (m ³ /s)	Instantaneous maximums (m ³ /s)	Maximum daily averages (m ³ /s)	Instantaneous maximums (m ³ /s)	
2	762	909	808	965	+6.1
5	1121	1338	1218	1454	+8.7
10	1391	1661	1521	1816	+9.3
20	1678	2004	1839	2196	+9.6
25	1775	2119	1946	2323	+9.6
50	2093	2499	2293	2738	+9.6
100	2447	2922	2553	3048	+4.3
500	3374	4029	3669	4381	+8.7
1000	3843	4588	4163	4971	+8.3
10,000	5753	6869	6132	7321	+6.6

When analyzing the series of maximum streamflows, listed in Tables 4 and 5, it is possible to verify that all return periods had an increase in streamflow.

Hydraulics

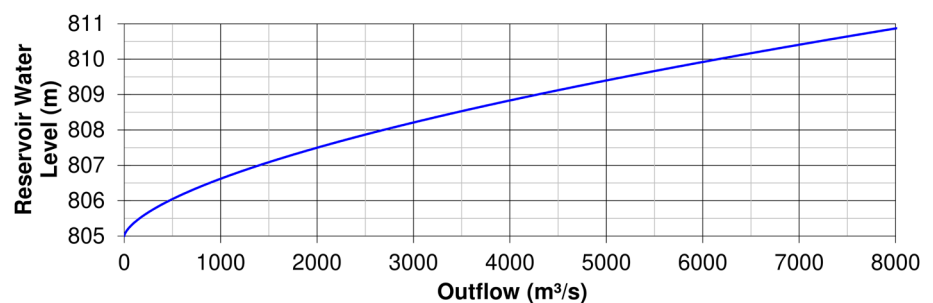
To get the elevation upstream and downstream of the dam due to the increase in the design flood streamflow, it is necessary to determine the respective discharge curves of the spillway.

Spillway discharge curve (reservoir water level)

Santa Clara HPP has a free sill spillway with a Creager profile, which eliminates the need to consider spillway maneuvers. The spillway discharge curve was determined according to Eq. 2, indicated to calculate the discharge over uncontrolled ogee crests, whose results are plotted in Fig. 3 (USBR 1987).

$$Q = C.L.H^{\frac{3}{2}} \quad (2)$$

where Q is the discharge in m³/s; C is the discharge coefficient; L is the effective spillway length, in m; and H is the hydraulic head, in m.

Fig. 3 Discharge curve of the spillway at the Santa Clara HPP

Based on the hydrological studies and the discharge curve, the update of the 10,000-year discharge increased the streamflow from 6869 to 7321 m³/s. This resulted in an increase in the maximum reservoir water level (RWL), from 810.35 to 810.56 m, an increase of 0.21 m.

As the ogee crest is positioned at elevation 805.00 m, the increase in the design head was only 3.9%, with a maximum hydraulic load of 5.56 m. According to USBR (1987), tests have shown that the suction pressures at the crest, during the passage of the maximum flood, do not exceed half of the design hydraulic load if the design load corresponds to 75% of the maximum load. As the design load from the Santa Clara HPP spillway is 4.50 m, this way it can spill flows of up to 6.00 m of maximum hydraulic load. Thus, the increase in RWL does not imply greater risks for the warhead.

Discharge curve on the dam axis (Tailwater)

To define the Tailwater of the dam during the stability calculations, the discharge curve defined during the dam construction projects was adopted, as plotted in Fig. 4 (COPEL and INTERTECHNE 2000).

The update of the hydrological studies resulted in an increase of 0.43 m in the Tailwater, going from 751.63

to 752.06 m, considering streamflow with a 10,000-year return period.

Geotechnical parameters

The geotechnical parameters were adopted according to the literature, and nearby works located on the same geological basis (NVE 2005; Pires et al. 2019; Souza and Filho 2020). The adopted geotechnical parameters are listed in Table 6.

Dam parameters

As well as the geotechnical parameters, the dam parameters were also adopted according to nearby works and the literature, as shown in Table 7 (ABNT 2014; CFBR 2012; JCSS 2001; Oliveira et al. 1998; Pires et al. 2019).

Stability

The stability calculation was performed according to the criteria established by Eletrobrás (2003), using Eq. 3. Therefore, whenever the Factor of Safety for Sliding (FS_s) is less than one, the stability of the dam is not met for the combination of generated variables.

$$FS_s = \frac{\sum N \times \tan \varphi + c \times A}{\sum T} \geq 1 \tag{3}$$

where FS_s is the factor of safety for sliding; c is the cohesive strength, in kPa; φ is the friction angle parameter, in degrees; A is the contact surface area, in m^2 ; $\sum N$ is the sum of normal forces acting at the sliding surface, in kN; and $\sum T$ is the sum of forces parallel to the sliding surface, in kN.

The probability of failure of each of the return periods, of the series until 1997 and of the series updated until 2018, was evaluated through simulations employing the Monte

Fig. 4 Discharge curve on the Santa Clara HPP dam axis

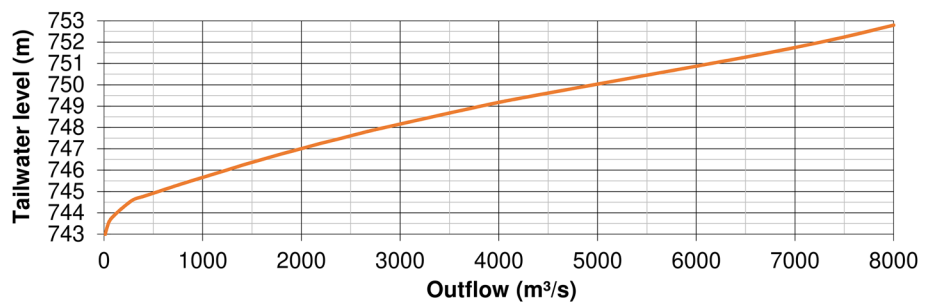


Table 6 Geotechnical parameters

Variable	Unit	Probability function	Parameters			
			Mean/value	Standard deviation	Minimum	Maximum
Cohesion in concrete–foundation interface	kPa	Log-normal	400	225	0	1000
Friction angle in concrete–foundation interface	kPa	Normal	tg(45°)	0.2.tg(45°)	tg(25°)	tg(65°)

Table 7 Dam parameters

Variable	Unit	Probability function	Parameters			
			Mean/value	Standard deviation	Minimum	Maximum
CVC weight	kN/m ³	Normal	24.00	0.40	21	26
RCC weight	kN/m ³	Normal	25.50	0.40	21	26
Effectiveness of drainage system	–	Triangular	0.66	–	0	1.0
Seismic action	–	Yes–No	0.0021	–	–	–

Carlo method and the probability distribution curves for each parameter.

The data obtained in the simulations of the probability of failure were compared by verifying the impacts that the update of the hydrological series had on the probability of failure due to landslide of the dam.

Monte Carlo simulation

For the application of the method, the Crystal Ball software together with the Excel software was used to perform the simulations. The estimate of the probability of failure for the condition being simulated is given by Eq. 4.

$$Pf = \frac{nf}{N} \tag{4}$$

where Pf is the probability of failure; nf is the number of failures; and N is the number of simulations.

In this way, the probability of failure of the series of the basic design and the updated one until 2018 was calculated.

In order to simplify the understanding of the workflow, a schematic diagram of the methodology employed is shown in Fig. 5.

Results and discussions

The update of the hydrological studies from the Santa Clara HPP resulted in higher maximum streamflows for all return periods, according to other studies that found an increasing

trend in the flows of plants located in the Paraná River basins (Bottini et al. 2018; Hirabayashi et al. 2013).

The first gauging stations began to be installed in Paraná in 1930. The first HPPs installed in the Iguaçu River basin were: Salto Osório, Foz do Areia and Salto Santiago, inaugurated in 1975, 1977 and 1980, respectively. Consequently, the hydrological studies carried out had a more limited sample to conclude the behavior of the maximum streamflows than what is currently available. Therefore, hydrological updating can provide benefits to statistical analysis by incorporating elements into the analyzed sample.

In this way, it is important to assess the impact of the increase in the maximum streamflows on the security of the dams because these changes can cause dams to no longer meet acceptable security levels.

The results of all the simulations carried out are presented in Tables 8 and 9, referring to the series up to the years 1997 and 2018, respectively. A million simulations were performed per return period, based on the probability functions defined in Tables 6 and 7, resulting in a sample with the results of Eq. 3. Based on the counting of the number of simulations of each sample in which the FS_s were lower than one, the probability of failure was estimated for each return period through Eq. 4.

It is observed that with the increase of the affluent streamflow, there is an increase in the water levels, and an increase in the probability of failure of the dam, as expected.

Comparing the probability of failure of the two hydrological series for the same return period, it is possible to note that the probability of failure by sliding increased with the update of the hydrological series.

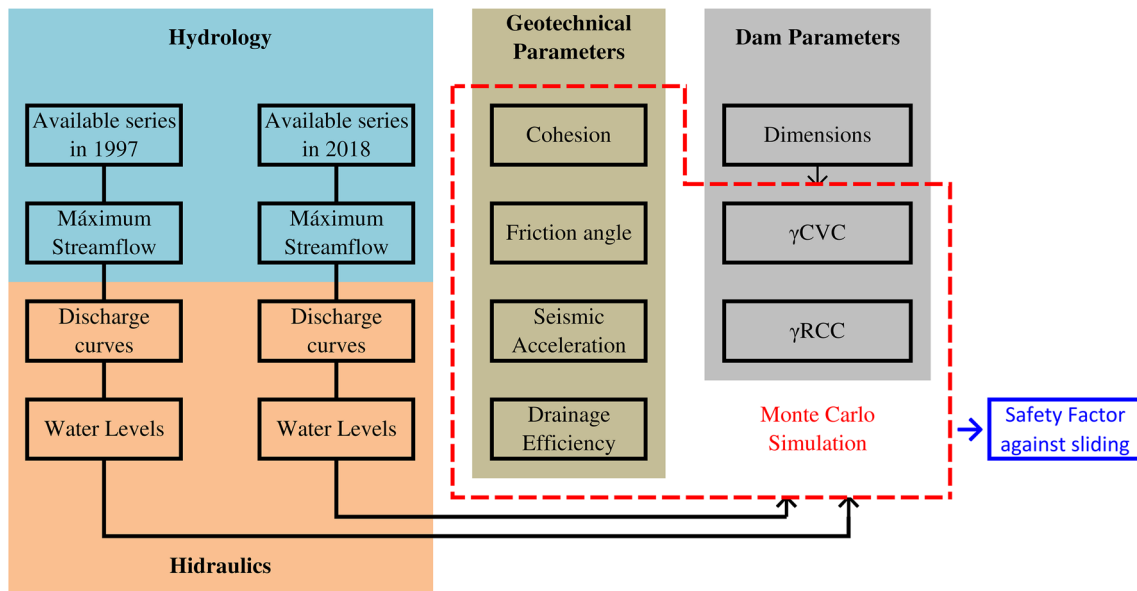


Fig. 5 Schematic diagram of the methodology employed

Table 8 Probability of failure by sliding for the analyzed return periods of the available series in 1997

RP (stream-flow) (years)	Affluent streamflow (m ³ /s)	RWL (msnm)	Tailwater (msnm)	N° of failures	Pf	RP (failure) (years)
2	675	806.26	745.19	13	1.3E-05	76,923
5	1239	806.85	746.00	23	2.3E-05	43,478
10	1663	807.22	746.58	33	3.3E-05	30,303
20	2088	807.56	747.12	41	4.1E-05	24,390
25	2225	807.66	747.29	50	5.0E-05	20,000
50	2649	807.97	747.79	60	6.0E-05	16,667
100	3076	808.26	748.25	79	7.9E-05	12,658
500	4062	808.87	749.23	121	1.2E-04	8264
1000	4486	809.11	749.61	142	1.4E-04	7042
10,000	6869	810.34	751.63	289	2.9E-04	3460

Table 9 Probability of failure by sliding for the analyzed return periods of the updated series by 2018

RP (stream-flow) (years)	Affluent streamflow (m ³ /s)	RWL (msnm)	Tailwater (msnm)	N° of failures	Pf	RP (failure) (years)
2	701	806.29	745.23	15	1.5E-05	66,667
5	1335	806.94	746.14	24	2.4E-05	41,667
10	1815	807.35	746.78	35	3.5E-05	28,571
20	2296	807.72	747.37	51	5.1E-05	19,608
25	2451	807.83	747.56	54	5.4E-05	18,519
50	2930	808.16	748.10	74	7.4E-05	13,514
100	3409	808.47	748.60	86	8.6E-05	11,628
500	4524	809.13	749.64	145	1.5E-04	6873
1000	5006	809.40	750.05	174	1.7E-04	5747
10,000	7321	810.55	752.06	342	3.4E-04	2924

Contributing to data analysis the results of Tables 8 and 9 are plotted in Fig. 6, correlating the streamflow data with the probability of failure. The results of the series updated to 2018 are plotted in red and the results of the series available in 1997 are plotted in blue.

Analyzing Fig. 6, we note the impact that the increase in the affluent streamflow has on the probability of failure due to the landslide of the analyzed dam, but the probability of failure remains acceptable according to the values recommended by ICOLD (2014).

It is equally possible, through Fig. 6, to validate the simulations performed, since none presented outliers and all followed a consistent trend.

As much as the return periods have different streamflows when analyzing the streamflows concerning their failure probability, it was possible to verify they presented a clear tendency of increasing the failure rate with the increase in the streamflows. In addition, the higher the streamflow, the higher the increase in the probability of failure.

Based on the results obtained and plotted in Fig. 6, a fourth-degree polynomial was established, according to Eq. 5.

$$Pf = A4.Q_{aff}^4 + A3.Q_{aff}^3 + A2.Q_{aff}^2 + A1.Q_{aff}^1 + A0 \tag{5}$$

where Pf is the probability of failure; Q_{aff} is the affluent streamflow in m³/s; and A4, A3, A2, A1, A0 are the polynomial coefficients;

The polynomial coefficients in Eq. 5 are listed in Table 10.

As the polynomial generated obtained an R-square value greater than 0.99 and provided a satisfactory adjustment, as shown in Fig. 6, the equation is considered to represent the correlation between streamflow and failure probability.

Through the obtained equation, it is possible to analyze the probability of failure for all inflow, if they are within the range of simulated minimum and maximum streamflows, from 675 to 7321 m³/s, respectively.

Fig. 6 Correlation diagram between streamflow and probability of failure by sliding of the Santa Clara HPP dam

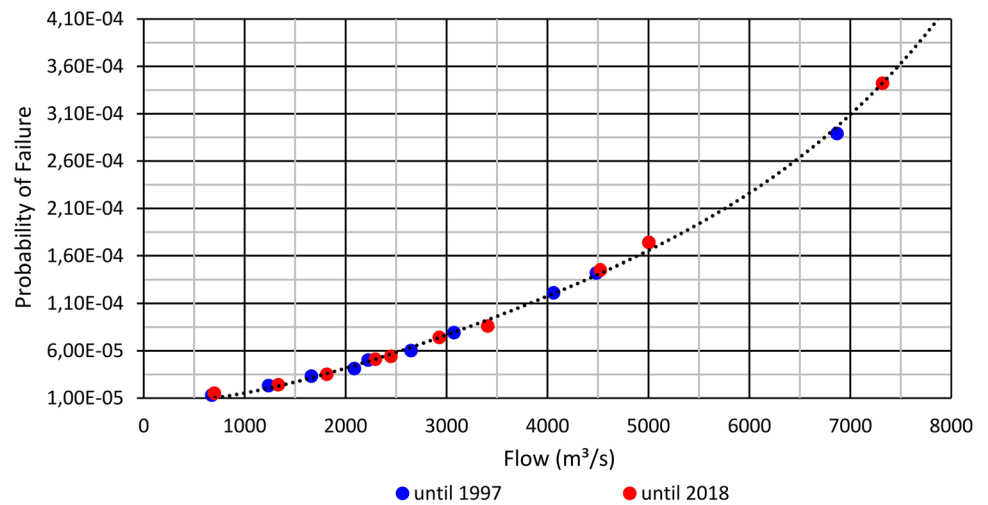


Table 10 Polynomial coefficients between streamflow and probability of failure

R^2	0.99931
A0	2.325841787374550E-05
A1	-2.611358784304000E-08
A2	2.410724477000000E-11
A3	-3.981850000000000E-15
A4	2.700000000000000E-19

Equation 5 was used to calculate the probabilities of failure of the basic design and updated streamflows. This procedure was adopted to obtain a clearer result and to avoid that the result of a simulation that disagrees with the others affects the interpretation of the results.

Thus, the probability of failure for all return periods was recalculated based on the polynomial generated for the two series of streamflows and, on top of these results,

the variation of probability between the two series was verified, as shown in Table 11.

In the index column, the increase in the failure probability was divided by the respective increase in streamflow, establishing a correlation between the streamflow variation and failure probability.

It is noted that the increase in the streamflow of the return periods had an even greater percentage impact in the increase in the probability of failure, as is the case of the 10,000-year flood in which a 6.6% increase in the streamflow increased the probability of failure by 15.6%.

Conclusion

This paper developed a study of the Santa Clara HPP dam, to verify the sensitivity of the variation of the sliding stability failure probability concerning the increase of the design flood generated by its update. It is clear the probabilities obtained are in the order of the magnitude of

Table 11 Failure probability and streamflow variation for the analyzed return periods with the update of the hydrological series

RP (years)	Failure probability		Failure probability variations (%)	Streamflow variations (%)	Index
	Available series in 1997	Updated series by 2018			
2	1.54E-05	1.55E-05	+0.3	+3.9	0.08
5	2.10E-05	2.28E-05	+8.5	+7.8	1.09
10	3.03E-05	3.44E-05	+13.7	+9.1	1.50
20	4.27E-05	4.97E-05	+16.4	+10.0	1.64
25	4.72E-05	5.52E-05	+16.8	+10.1	1.65
50	6.25E-05	7.34E-05	+17.4	+10.6	1.65
100	7.93E-05	9.31E-05	+17.4	+10.9	1.61
500	1.22E-04	1.43E-04	+17.6	+11.4	1.54
1000	1.41E-04	1.67E-04	+18.1	+11.6	1.56
10,000	2.92E-04	3.37E-04	+15.6	+6.6	2.37

the values raised and recommended by the International Commission On Large Dams (ICOLD), that is, less than 1×10^{-4} (ICOLD 2014), and that in this way the risk of the enterprise is under what the literature recommends.

Based on the results of this case study, the following conclusions can be listed:

- (a) When updating the hydrological studies, it was possible to note that the series obtained through local analysis corresponded to higher increases in streamflow rates than the series obtained through regional analysis.
- (b) The hydrological studies of the basic design used the data collected between the years 1960 and 1997, totaling 37 years of observations. By including 21 years to the existing observations, including the data collected up to 2018, an increase in the streamflow rate of 11.9% was obtained by using local analysis and 6.6% by regional analysis, stressing the importance of updating hydrological studies.
- (c) The Santa Clara HPP, inaugurated in 2005, despite having more recent hydrological studies, had a considerable increase in the design flood streamflow with the update of the studies. This reinforces the need for hydrological studies to be updated periodically.
- (d) The water depth in the spillway warhead, during the passage of the 10,000-year discharge, went from 5.35 to 5.56 m. That is, when updating the hydrological studies, there was an increase of 3.9% in the water depth, indicating that the impacts on the profile due to the increased project load are small and that the spillway can discharge higher streamflows than those foreseen in the basic design.
- (e) The probabilistic method, applied in the analysis of stability to the slide of the dam, presented advantages concerning the deterministic method because it considers the standard deviation of the variables, considering the uncertainties present in the parameters, and for providing the probability of failure.
- (f) The update of the design flood increased the probability of failure of the dam. For the 1000-year return period, the increase was 18.1% and for the 10,000-year increase, the increase was 15.6%. Even when dealing with tiny probabilities, the magnitude of the increase was considerable, since it occurred over an interval of 21 years and considering only hydrological variables.

The case study highlighted the importance of reviewing the hydrological studies of existing dams. The development of laws and regulations to regulate the elaboration of updated hydrological studies and to evaluate whether the spillway capacity and dam stability of the existing plants remain adequate will provide benefits to society

and the technical environment, by quantifying a risk that may be disregarded.

Regular updates of historical design flows can provide insights into temporal changes and trends. Additionally, conducting probabilistic stability analysis in other hydropower plants can reveal potential risks associated with increased flows, establishing a link between updated flow data and dam behavior. Such research significantly contributes to water resources management and provides crucial insights for hydropower project planning and operation.

Based on the results and limitations of this study, two potential areas for future research are proposed. Firstly, exploring solutions that can increase the discharge capacity of existing dams through innovative engineering techniques or operational strategies to optimize flow rates. Secondly, examining the impact of changes in land use and land cover on the relationship between precipitation and surface runoff in specific watersheds over an extended period. This could involve studying how alterations in land-use patterns, such as urbanization or deforestation, influence the hydrological cycle and alter runoff dynamics.

This research focused on the global stability analysis, specifically evaluating safety against sliding, and was limited to the interface region between the concrete and the foundation, without considering crack opening upstream. Stresses in concrete structures or at the base of foundations were not analyzed, and the study did not include the analysis of impacts of dam failure.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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