Quantitative Risk Analysis to inform safety investments in Jaime Ozores Dam (Spain)

Manuel Setrakian-Melgonian[1,a], Ignacio Escuder-Bueno[2,b], Jesica T. Castillo-Rodriguez[2,c], Adrián Morales-Torres[3,d], Dolores Simarro-Rey[4,e]

[1]*Junta de Extremadura, Mérida, Spain*
[2]*Universitat Politècnica de València & iPresas, Valencia, Spain*
[3]*iPresas Risk Analysis, Valencia, Spain*
[4]*PAYMACOTAS, Mérida, Spain*

[a]manuel.setrakian@gobex.es
[b]iescuder@hma.upv.es
[c]jecasrod@upvnet.upv.es
[d]adrian.morales@ipresas.com
[e]dsimarro@getinsapayma.com

ABSTRACT

Jaime Ozores dam is a concrete gravity dam, 28 m high, located in the province of Badajoz (Spain). It has a spillway with two gates and a bottom outlet and it was built in 1962. This reservoir is used to supply water to the downstream population. In 2000, a flood produced overtopping over the crest of the dam. For this reason, a lower maximum operating level was set in the reservoir. In this context, a complete risk informed process was started focused on overtopping and sliding failure modes, including a detailed fault tree analysis of the two gates in the spillway. The outcomes of the risk informed process are presented in this paper, showing how it has been used to analyze the effect of improving flood operating rules, changing the operation of the bottom outlet and improving warning systems in the downstream Water Treatment Plant. The outcomes of the risk informed process are presented in this paper and they are compared with the risk results of Membrio and El Horcajo dams, presented in previous ICOLD conferences, showing how robust and transparent information has been develop to support safety governance in the portfolio of dams from the Junta de Extremadura.

1. INTRODUCTION

Jaime Ozores dam is located in the province of Badajoz (Spain) and it was built in 1982. It is a concrete gravity dam (Figure 1), 28 m high and it has a spillway and a bottom outlet. The spillway outflow is controlled by two bottom-hinged flap gates. This reservoir is used to supply water to the downstream population.

Figure 1. Jaime Ozores Dam

In 2000, a flood produced overtopping over the crest of the dam (Figure 2), while the flap gates of the spillway were raised. For this reason, a lower maximum operating level was set in the reservoir. Hence, an equilibrium is considered between maximum water levels in the reservoir for safety reasons and urban water demands downstream.

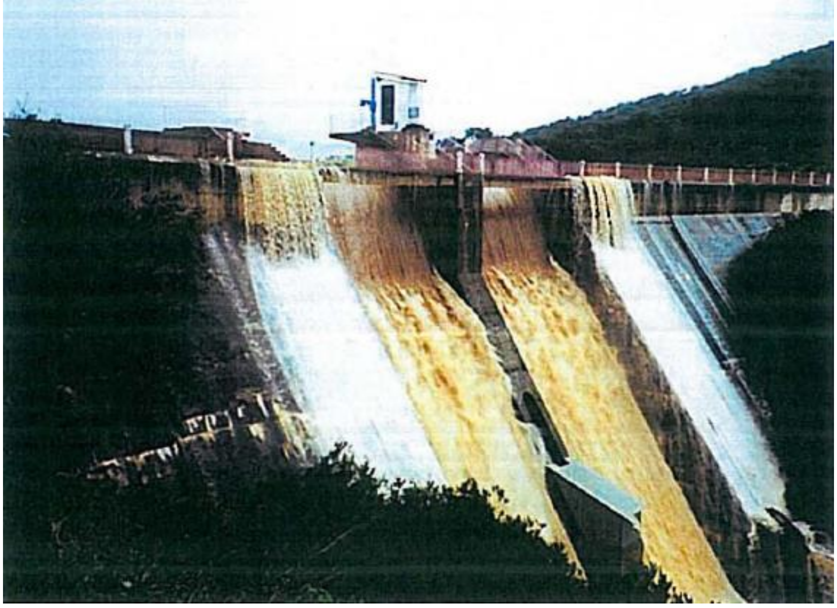

Figure 2. Overtopping in Jaime Ozores dam in 2000.

In this context, a complete risk informed process was started by the owner, Junta de Extremadura, the consultant on conservation, maintenance and operating support for the dam, Paymacotas, and iPresas, a spin-off company from Universitat Politècnica de València (UPV) providing the overall risk framework. This paper presents the main findings and conclusions of this process.

This risk informed process is the third one made by the Junta de Extremadura in the recent years, after the analysis of El Horcajo and Membrio dams. Therefore, it is a third step in a journey towards risk informed dam safety governance in the Junta de Extremadura Portfolio. This process is inspired by the application of the SPANCOLD Guidelines for Risk Analysis (SPANCOLD 2013). The structure of the process followed in the three dams is shown in Figure 3.

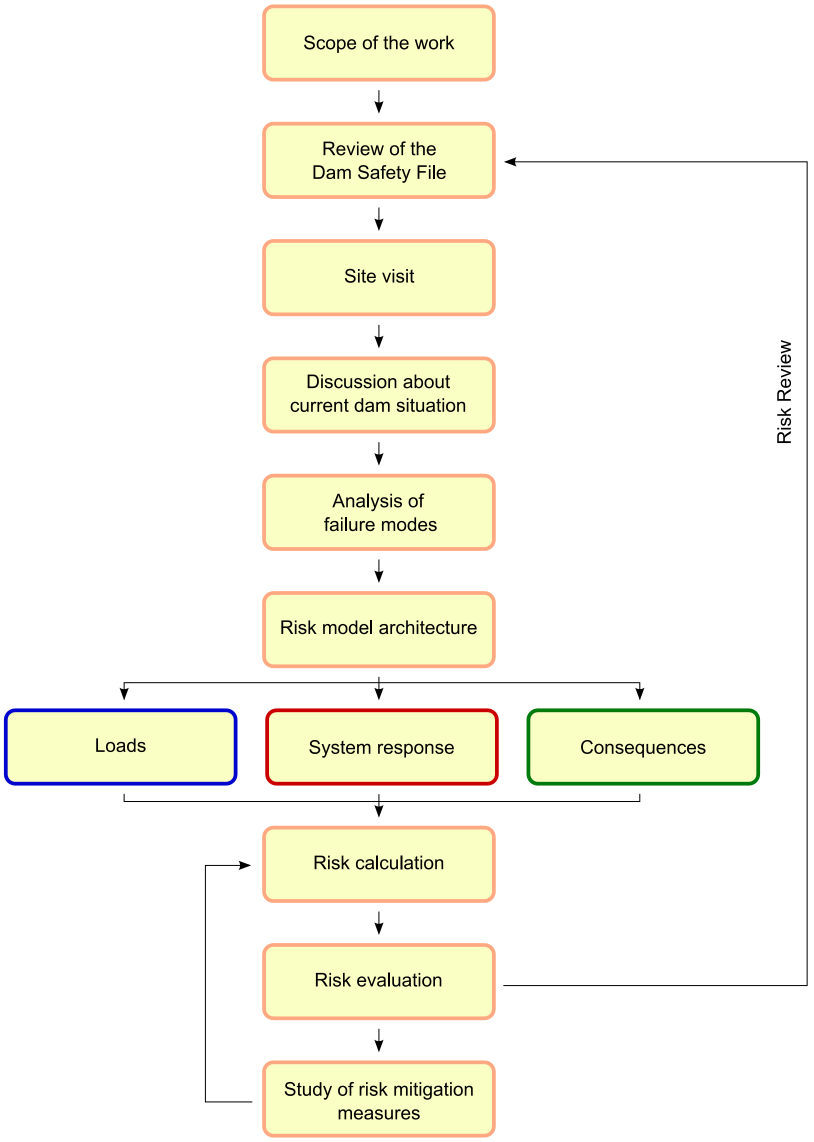

Figure 3. Steps of the risk analysis process (SPANCOLD 2013)**.**

2. FAILURE MODES IDENTIFICATION

After a detailed discussion of the available information and the site visit to the dam, it was decided to include two failure modes in the quantitative risk model (Figure 4):

- FM1: Sliding failure due to water pressure and high uplift pressures in the foundation.
- FM2: Overtopping failure in a flood event.

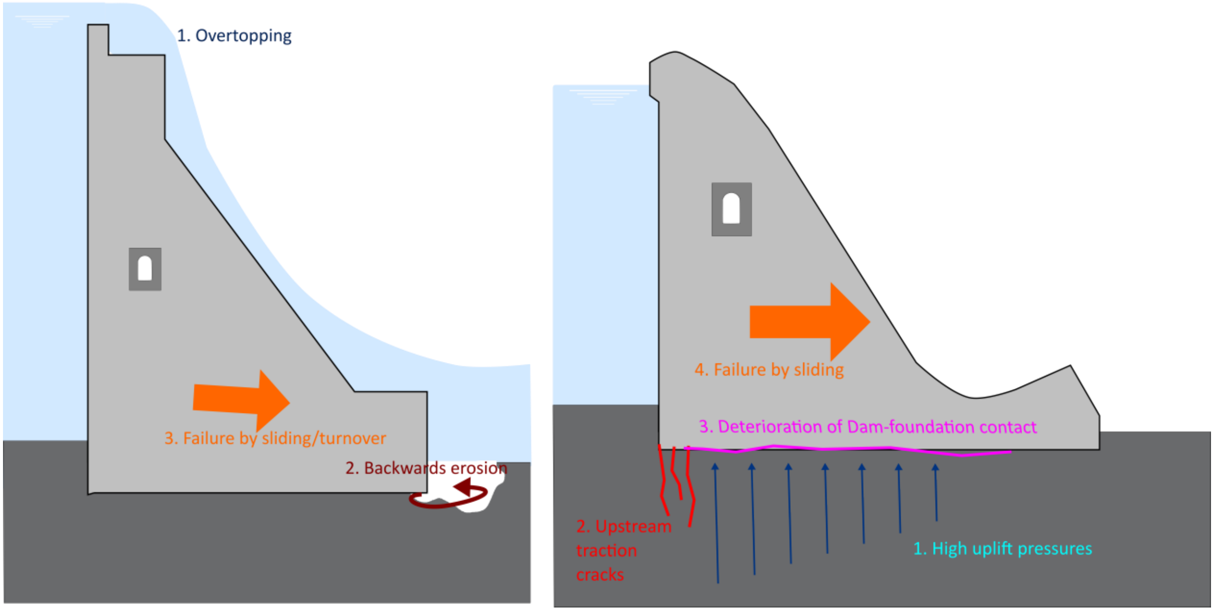

Figure 4. Failure modes introduced in the risk model: Overtopping (left) and sliding (right).

3. BASELINE RISK CHARACTERIZATION AND EVALUATION

In order to carry out a quantitative risk analysis, a risk model of the dam was set up including the loads of the system (in this case, water levels in the reservoir), the system response (for the three failure modes) and the consequences (economic and loss of life). The structure of the risk model is shown in Figure 5.

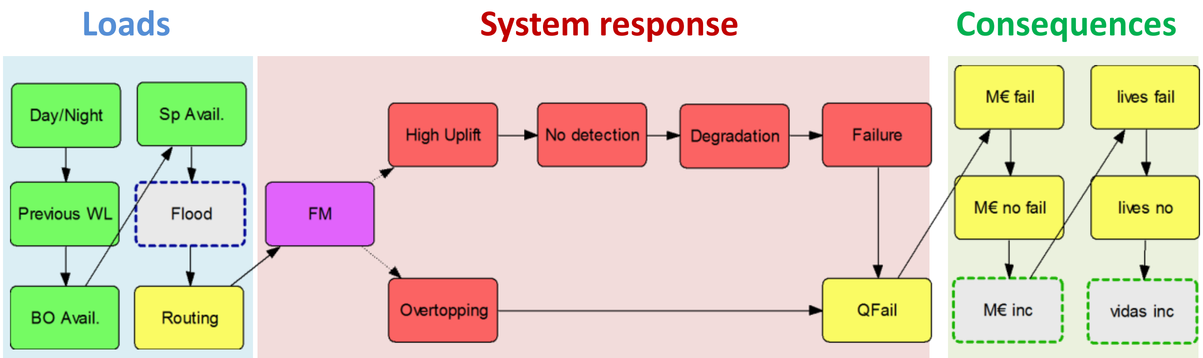

Figure 5. Risk model architecture elaborated with iPresas Calc.

Risk model architecture was developed with iPresas Calc software (iPresas 2014). This software uses influence diagrams and event trees to compute failure probability and risk. This software can model any type of loads (hydrologic, seismic, etc.), failure modes and consequences (loss of life, economic, total, incremental, etc.). In addition, it can be combined with software iPresas Manager to help to design, visualize and evaluate different strategies for safety investment prioritizations.

The first nodes of the risk model are focused on the loads, in this case they are defined by the water pool levels in the reservoir, the availability of the bottom outlet and the spillway for flood routing and the maximum pool levels that could be reached during a flood event.

In this case, the 2000 event showed that the water pool level in this reservoir is very sensitive to the position of the spillway flap gates during the flood event. When these gates are raised, the overtopping probability is clearly higher. For this reason, it was decided to build a fault tree to analyze the behavior of these gates, following international recommendations. (SPANCOLD 2013; USBR and USACE 2015). The structure of this tree is shown in Figure 6. This fault tree analyzes the causes that can lead to being unable to operate the flap gates during a flood event. It is not limited to mechanical failures since it also includes human mistakes and energy supply problems. As a result of this tree, the probability of being able to operate the gates during a flood event is obtained.

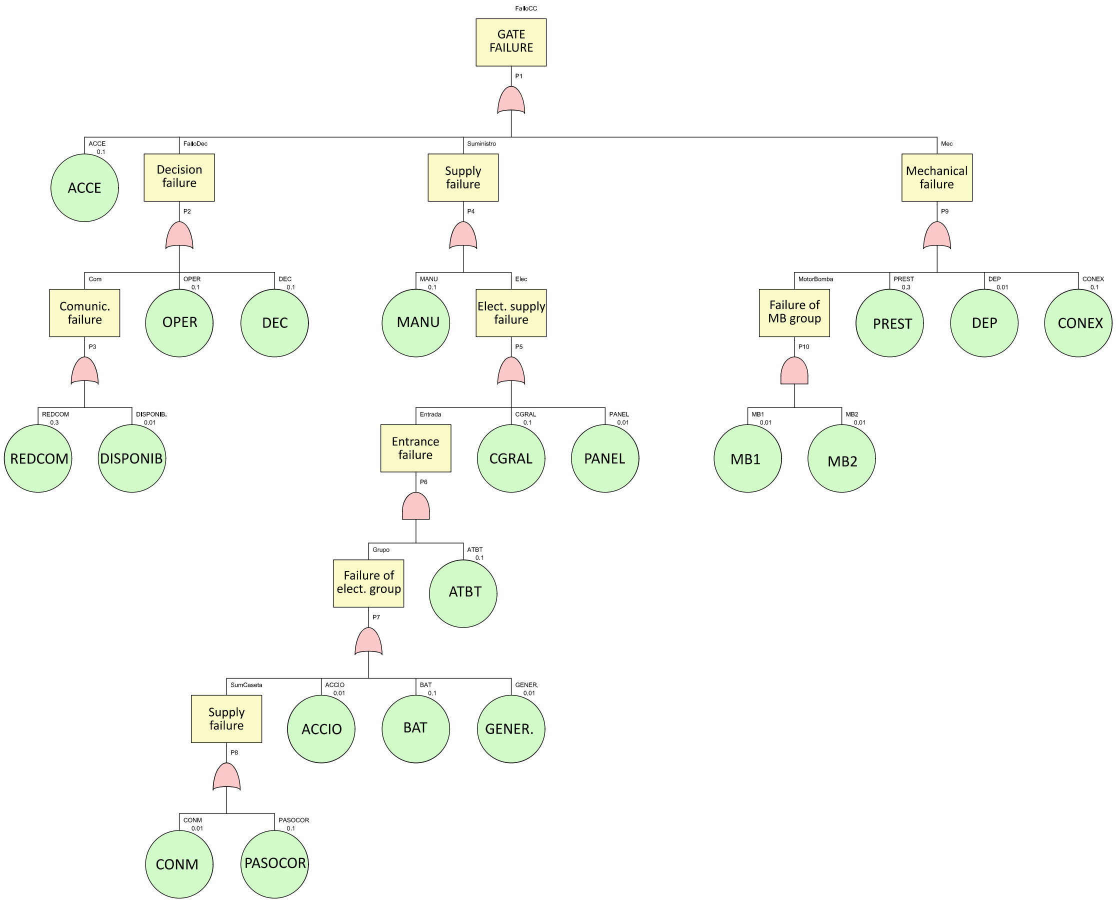

Figure 6. Fault tree architecture of Jaime Ozores spillway gates.

Next, the nodes of the system response are used to introduce the probability of each failure mode, which are divided in different events. In each node, a conditional probability is introduced based on the data available about the dam and international recommendations (Altarejos García et al. 2014; USBR and USACE 2015). In addition, in the failure node of the sliding failure mode, a Montecarlo analysis was made using two random variables related to the foundation resistance capacity: friction angle and cohesion. The detailed process used to make this analysis is described in (Altarejos-García et al. 2012; Morales-Torres, Escuder-Bueno, et al. 2016).

Finally, dam failure consequences are estimated based on the data available in the Emergency Action Plan, which estimates the flood characteristics of dam failure and the populations affected. In this case, there would not be large urban areas affected by the dam failure. The most important damage from the loss of life point of view is the water treatment plant located downstream of the dam.

With all the input variables of the risk model in place, the calculation of the risk was performed for the initial situation. With regard to the calculation itself, the procedure is conceptually simple. The probability of each branch of the event tree is obtained as the multiplication of all the conditional probabilities of the sub-branches that compose it. Failure probability and total risk can be determined by adding up the results of all the branches.

Risk results were plotted in the USBR tolerability graphic (USBR 2011). USBR tolerability guidelines are based on fN graphs, that represent the relation between failure probability and societal risk (Figure 7). A first limit is put on a failure probability of 10^{-4}. This value is related to individual risk, to the public responsibility of the dam owner and to protecting the image of the organization. A second limit is put on societal risk, suggesting maximum values of 10^{-3}. These limits define two areas. On the upper area, the further away you are from the limit lines, the more justified risk reduction measures will be. On the lower area, the further away you are from the limit lines, the less justified risk reduction measures will be.

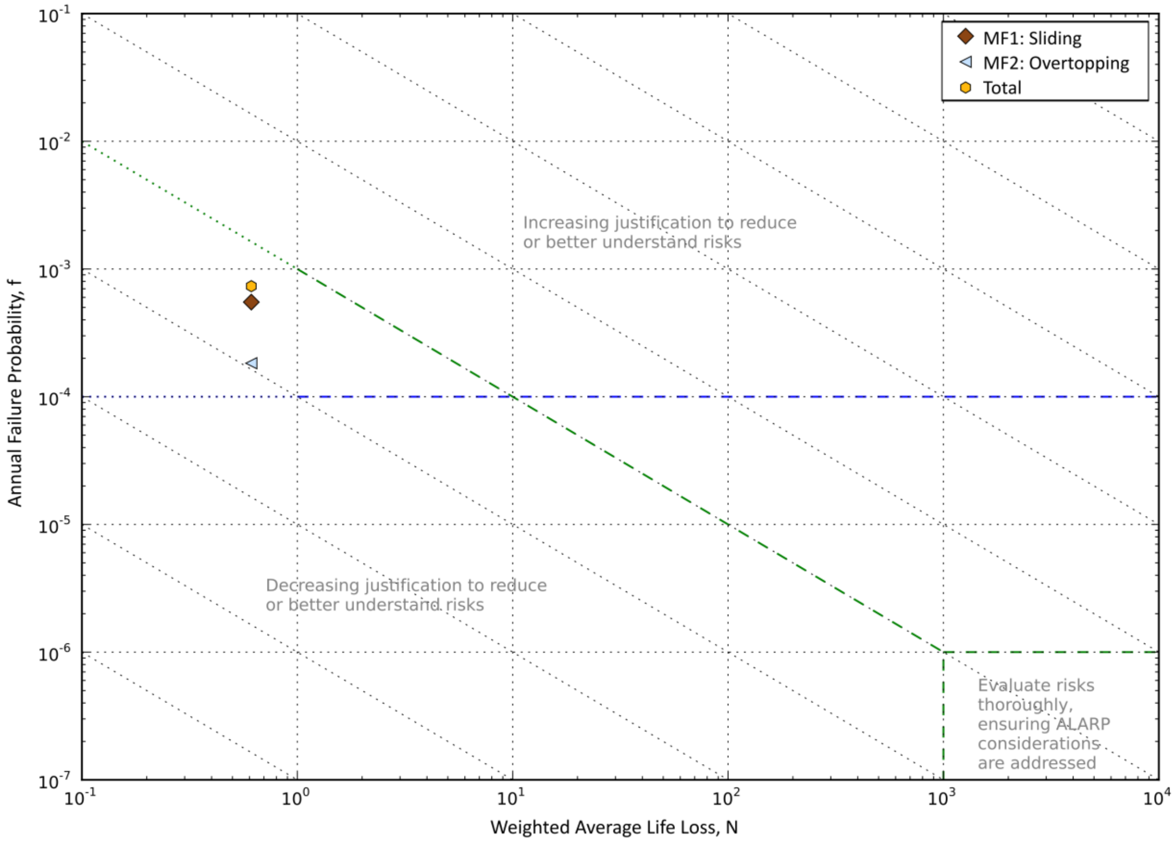

Figure 7. Current risk estimates plotted versus USBR (2011) tolerability guidelines.

As can be inferred from Figure 7, Jaime Ozores dam would not be aligned with a sufficiently low risk values since its failure probability is higher than 10^{-4}, thus action is supported to reduce such risk. The two failure modes have a similar failure probability, being the sliding failure probability half order of magnitude higher.

In addition, different analyses were made to check the sensitivity of risk results to the data introduced in the different nodes of the risk model. The highest sensitivity of risk results was obtained for the position of the spillway flap gates during the flood event. When these gates are completely raised, the overtopping failure probability is clearly higher, as it was observed during the flood event in 2000. Nowadays, the maximum level of the gates is 428 m.a.s.l. (risk results for current situation). The results of this sensitivity analysis are shown in Figure 8.

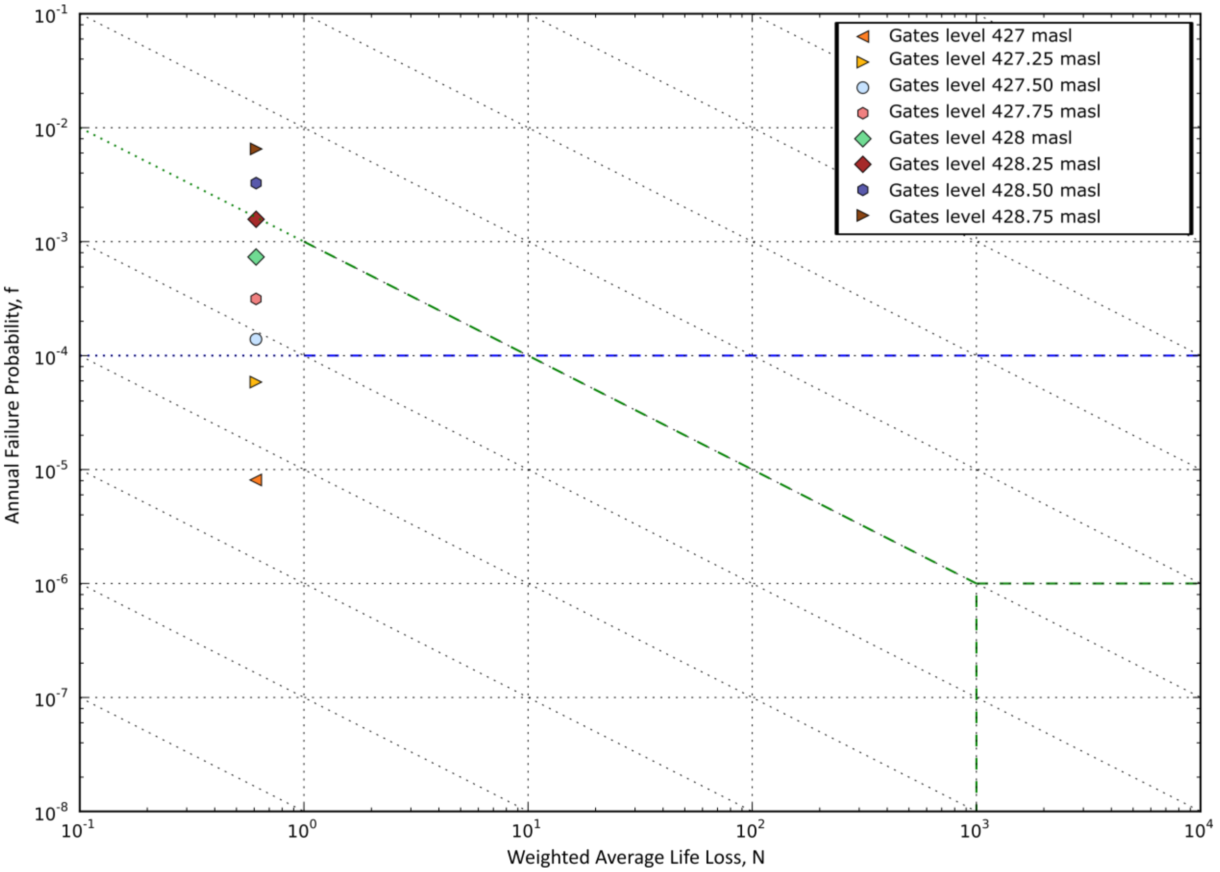

Figure 8. Sensitivity analysis of risk results as a function of the spillway flap gates level.

4. EVALUATION OF RISK MITIGATION MEASURES

The alternatives were first analysed and later prioritized in accordance with the so called Equity Weighted Adjusted Cost per Statistical Life (EWACSLS), a risk indicator whose components and formulation are included in the SPANCOLD Guidelines and combines equity and efficiency risk reduction principles (Serrano-Lombillo et al. 2016; SPANCOLD 2013). Namely, they were:

1. Emergency Action Plan implementation.
2. Surveillance improvement of foundation uplift pressures with piezometers.
3. Small changes in gates mechanisms and actuators to improve its reliability.
4. Drainage system improvement under the spillway.
5. Emergency Plan focused on the downstream water treatment plant.
6. Remote spillway gates operation.
7. New gates operation rules during flood events.
8. Reinforce parapet wall to increase the dam crest level.

Once risk is recomputed for each measure and EWACSLS is evaluated, a sequence of measures implementation is obtained following the procedure detailed in (Morales-Torres, Serrano-Lombillo, et al. 2016). The obtained sequence of measures for this dam is shown in Figure 9. As it can be observed, the first measure is the definition of new operation rules for the spillway gates. This result is reasonable due to the high sensitivity of risk results to how these gates are operated during flood events. Hence, the operation of these gates is one of the keys for safety management in this dam. In addition, when this measure is combined with the improvement of the gates reliability, the estimated failure probability of the dam is lower than 10^{-4}. Other measures that are also efficient to reduce risk are the emergency plan for the downstream treatment plant (since most of the social consequences are concentrated there) and the improvement of the drainage system (which is very effective to reduce sliding failure probability).

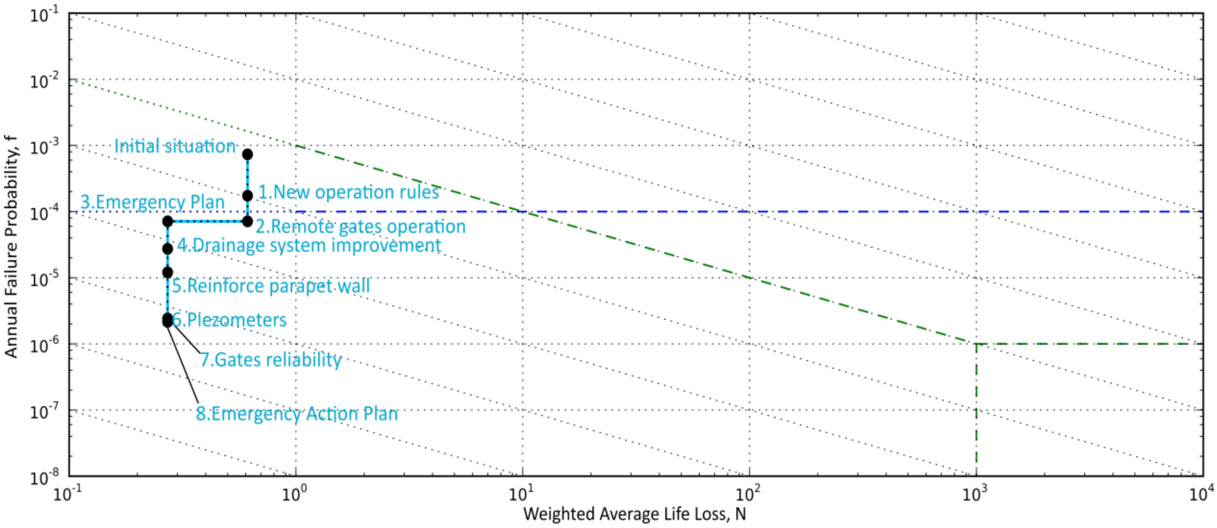

Figure 9. Prioritized sequence of risk mitigation measures.

5. RISK MANAGEMENT IN THE PORTFOLIO OF THE GOBIERNO DE EXTREMADURA

Finally, in order to illustrate how risk results could inform dam safety management for the whole portfolio of the Junta de Extremadura, risk results and mitigation measures of the Jaime Ozores dam were combined with the results obtained the previous year for the El Horcajo concrete dam (Setrakian et al. 2015, 2016) and the Membrio embankments (Figure 10). Therefore, a new prioritization sequence was obtained combining the risk mitigation measures of the three dams, as explained in (Morales-Torres, Serrano-Lombillo, et al. 2016). The results obtained are shown in Figure 9.

As it can be observed in this sequence, the proposed measures for the three dams are combined to obtain single sequences of measures implementation for the whole portfolio, thanks to the use of quantitative risk results and risk indicators. Therefore, risk analysis provides a clear opportunity to support an integrated management of the dams' safety, allowing prioritizing among different risk mitigation strategies.

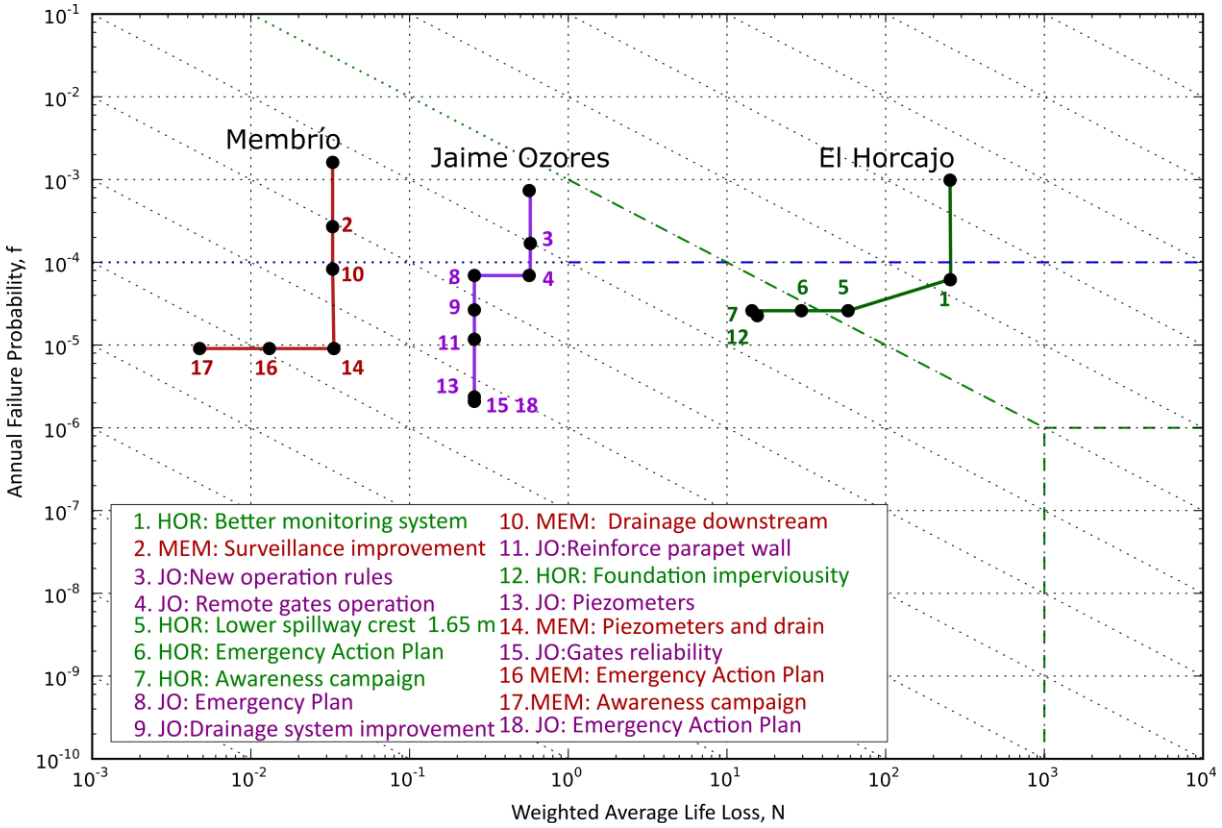

Figure 10. Prioritized sequences of risk mitigation measures of Jaime Ozores, Membrío and El Horcajo dams.

6. REFERENCES

Altarejos-García, Luis, Ignacio Escuder-Bueno, Armando Serrano-Lombillo, and Manuel Gómez de Membrillera-Ortuño. 2012. “Methodology for Estimating the Probability of Failure by Sliding in Concrete Gravity Dams in the Context of Risk Analysis.” *Structural Safety* 36–37:1–13.

Altarejos García, Luis et al. 2014. *Metodología Para La Evaluación Del Riesgo Hidrológico de Presas Y Priorización de Medidas Correctoras*. edited by I. Escuder-Bueno and J. González-Pérez. Madrid: Colegio de Ingenieros de Caminos, Canales y Puertos.

iPresas. 2014. “iPresas Calc. User Guide.” Retrieved (http://www.ipresas.com).

Morales-Torres, Adrián, Ignacio Escuder-Bueno, Luis Altarejos-García, and Armando Serrano-Lombillo. 2016. “Building Fragility Curves of Sliding Failure of Concrete Gravity Dams Integrating Natural and Epistemic Uncertainties.” *Engineering Structures* 125:227–35. Retrieved (http://linkinghub.elsevier.com/retrieve/pii/S0141029616303340).

Morales-Torres, Adrián, Armando Serrano-Lombillo, Ignacio Escuder-Bueno, and Luis Altarejos-García. 2016. “The Suitability of Risk Reduction Indicators to Inform Dam Safety Management.” *Structure and Infrastructure Engineering* 12(11):1465–76.

Serrano-Lombillo, Armando, Adrián Morales-Torres, Ignacio Escuder-Bueno, and Luis Altarejos-García. 2016. “A New Risk Reduction Indicator for Dam Safety Management Combining Efficiency and Equity Principles.” *Structure and Infrastructure Engineering*.

Setrakian, Manuel, Ignacio Escuder-Bueno, Adrian Morales-Torres, and Dolores Simarro. 2016. “Application of Risk Analysis in Membrío Dam (Spain) to Inform Safety Investments.” in *84th ICOLD Annual Meeting. Johannesburg*.

Setrakian, Manuel, Ignacio Escuder-bueno, Adrián Morales-Torres, Dolores Simarro Rey, and Dolores Simarro. 2015. “Safety Investments in Horcajo Dam (Spain): A Process Informed by the Application of SPANCOLD Guidelines on Risk Analysis.” in *XXV ICOLD Congress, Stavanger, Norway, Q99*. Stavanger, Norway: ICOLD.

SPANCOLD. 2013. *Technical Guide on Operation of Dams and Reservoirs. Volume 1. Risk Analysis Applied to Management of Dam Safety*. Professional Association of Civil Engineers. Spanish National Committe on Large Dams. Retrieved (http://www.spancold.es/Archivos/Monograph_Risk_Analysis.pdf).

USBR. 2011. *Dam Safety Public Protection Guidelines - A Risk Framework to Support Dam Safety Decision-Making*. United States Bureau of Reclamation. Retrieved (http://www.usbr.gov/ssle/damsafety/documents/PPG201108.pdf).

USBR and USACE. 2015. *Best Practices in Dam And Levee Safety Risk Analysis. United States Bureau of Reclamation and United States Army Corps of Engineers*. Denver: United States Bureau of Reclamation and United States Army Corps of Engineers.