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Case study: Risk analysis by overtopping of diversion works during dam construction: The *La Yesca* hydroelectric project, Mexico

H. Humberto Marengo [a,*], Felipe I. Arreguin [b], Alvaro A. Aldama [c], Victor Morales [d]

[a] Coordinator of Hydroelectric Projects, Federal Electricity Commission (CFE), M. ASCE, President, Academy of Engineering of Mexico, Adjunct Professor Graduate School of Engineering, National Autonomous University of Mexico (UNAM), Mexico
[b] Deputy Technical Director General, National Commission of Water, Mexico
[c] Consultant of CFE, M. ASCE, Former President of the Academy of Engineering of Mexico, Adjunct Professor Graduate School of Engineering, UNAM, Mexico
[d] Analyst, CFE, Mexico

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ABSTRACT

A risk analysis-based methodology for the determination of the most economical layout dam–tunnel diversion works is introduced. The aim of the proposed procedure is to identify the least cost layout in terms of the diversion works overtopping risk. The methodology has been built upon the reliability theory advanced first-order second moment approach, and accounts for the probability of the maximum height reached by the upstream water elevation, associated with a design flood (as characterized by its return period), as well as for excavation and lining costs. The proposed procedure has been applied to the *La Yesca* hydroelectric project in Mexico, currently under operation. It is demonstrated that the use of composite roughness, which consists of lining the floor of the diversion tunnels with hydraulic concrete, while the walls and vault of the tunnels are lined with shotcrete, results in an increase in the discharge capacity of the tunnels, thus leading to a reduction of the overall risk of the project. The importance of economic risk assessments is emphasized and the flexibility of the proposed methodology to account for a suite of risk–cost combinations is shown.

1. Introduction

Dam risk analysis has been a topic of much interest, particularly in Australia, Canada, The Netherlands, South Africa, USA and Mexico [1,7,8,17,20,16,3,2,10,15,21].

Statistical data from historic events are of limited utility in risk analysis. The shortcomings of such data have prompted the establishment of new databases, such as the one contained in the US National Performance of Dams Program Report [15], which provides much more reliable estimates of risk.

Marengo and Morales [14], analyzed the risk of failure of the *El Cajón* dam, Mexico, diversion works, and identified significant advantages of employing an economic risk analysis approach.

This paper is organized as follows. First, safety considerations for temporary works during dam construction are presented. Next, a brief description of risk assessment considerations on dam safety are commented and is made the description of La Yesca Hydroelectric Project including the description of risk conditions analysis for the diversion works, like the construction program, the potential damages in case of overtopping, and expected costs due to overtopping failure, are presented. Subsequently, a performance function for the analysis of risk is derived. Thereon, a sensitivity analysis is proposed. The methodology is applied to the case study of the *La Yesca* project, currently under operation in Mexico, with the objective of determining the optimal coffer dam height and the diversion tunnels sizing. Conclusions and recommendations are finally offered.

2. Safety considerations for temporary works during construction

Of 107 catastrophic dam failures worldwide, 61 occurred due to overtopping, and 13 of those cases occurred during construction [10]. On the basis of an analysis of these failures Marengo [12] concluded that "the design return periods required to ensure consistent safety levels in diversion works should have been higher by roughly a factor of ten".

Little attention has been devoted to dam safety during construction [4]. This lack of attention can be predominantly attributed to the following factors:

(a) Safety has traditionally been analyzed by considering only the damage likely to occur downstream from the dam under construction, without any consideration of the damage caused to the structures themselves or of the loss of revenue due to the

* Corresponding author.
E-mail address: humberto.marengo@cfe.gob.mx (H. Marengo).

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delay in commencing power generation. Safety has been treated as a contractor responsibility, regardless of the consequences.

(b) It is generally believed that a large flood is not likely to occur within the (usually short) construction period. However, available hydrologic evidence demonstrates that many destructive floods have occurred during large dam construction (e.g., at *Kariba*, *Oros*, *Aldedavilla*, *Akosombo*, *Cahora Bassa*, *Tarbela*, and *Aguamilpa*). The main lessons of *Aguamilpa's* overtopping were: risk assessment must take into account the specific features of each dam in more detail, and since the causes and consequences of failure are not easily predicted, there is a high degree of uncertainty that ought to be properly handled. Economic risk analysis provides an appropriate framework for analyzing safety during dam construction. Such analysis requires a sequential and conceptually concise approach, with accounts for each phase of the project.

In the *La Yesca* hydroelectric project, analyzed in this paper, the hydrologic risk of the dam construction (including diversion works), is taken by the owner, that is to say, the Federal Electricity Commission (CFE). Thus, the point of view of the owner of the dam is assumed in this paper. In other cases the construction contractor takes the hydrologic risk and some of the conclusions may differ.

3. Risk assessment of dam safety

Assessing the safety of dams requires an analysis of the effects of hypothetical failures and thus of the costs and benefits inherent to project safety.

A full dam failure analysis values the damage caused by lost services, estimates the construction costs of various design alternatives, determines the probability of failure for each alternative, and enables the selection of the design with the lowest risk–cost combination.

In particular, this approach depends on an accurate assessment of the potential risk presented by dam failure. Here, the term "risk" specifically refers to the total annual probability of failure multiplied by the cost of the consequences induced by this failure, including the partial or total loss of water storage at the time of the failure [11].

In addition, a complete risk assessment considers all possible events that could lead to dam failure. The partial risk of each individual event trajectory is equal to the product of the total annual probability of failure of the trajectory event or situation multiplied by the respective magnitude of the consequences of failure valued in monetary terms. By summing the partial risks, the total annual risk for the dam can be obtained as [9]:

$$R = \sum_i P_i C_i \tag{1}$$

where R is the total annual risk of failure of the dam; P_i, the total annual probability of failure for each situation or event i, and C_i is the cost of failure associated with situation or event i. In this study, R represents the actual risk is defined as the expected cost of the failure in the period of the analysis.

For the return period-based approach, the United States Army Corps of Engineers [19] states that the probability of a long-term failure can be estimated as follows:

$$P_f = 1 - \left(1 - \frac{1}{T_r}\right)^N \tag{2}$$

where P_f is the probability of failure, T_r is the return period of the design flood in years, and N is the period of analysis in years. For temporary works, the value of N is small (one or two years).

Table 1
The maximum discharges associated with various return periods used in the design of the diversion works.

Return period (T_r)	Discharge (m^3/s)
10	3686
20	4958
50	6481
100	7578

4. La Yesca hydroelectric project

The La Yesca hydroelectric project is under operation by the Federal Commission of Electricity (CFE), on the border of the Jalisco and Nayarit states in Mexico. The project, with a rockfill dam height of 208.50 m and a dam volume of 12 million m^3, is the second highest concrete face rockfill dam in the world, after *Shibuya* Dam in China.

The layout has an underground hydropower plant with two units, each of 375 MW capacity; such that the total installed power capacity is 750 MW. The annual mean power generation rate is 1228 GWh.

The diversion works were designed using a 50 year return period peak flow rate entrance of 6481 m^3/s, estimated on the basis of the 1953–2003 hydrological record for the dam site. These works comprise two tunnels with lengths of 703 m and 755 m, each with a portal cross-section of 14×14 m.

The coffer dam was built as a 48.5 m high earth and rock structure with an elevation of 435 masl (meters above sea level); Fig. 1 shows the dam, the coffer dam, and the cross section adopted for the tunnels).

4.1. Design floods for the diversion works

Given the hydrologic record for the period (1953–2003), the following probability distribution functions were fitted to the available data: normal, log-normal, exponential, Gamma, Gumbel, and Gumbel for two populations.

The probability distribution that provided the smallest square error was the Gumbel function for two populations and the values of various discharges and their corresponding return periods estimated with such function are shown in Table 1.

4.2. Risk conditions for a deterministic analysis of the diversion works

The risk conditions associated with the return period-based design of the diversion works were calculated for the first year of the project construction because it was assumed that after the second year the dam would achieve sufficient elevation that there would be no further significant risks of overtopping such as occurred in *Aguamilpa* in 1992 [12].

4.3. Diversion works (construction features).

With the goal of determining the optimal combination of the height of the coffer dam and the dimensions of the tunnel cross-section, a flood-routing analysis of the discharges associated with return periods of 20, 50, and 100 years was performed, and the total cost of the diversion works for each cross-section was found. The hydrograph form of the historical maximum flood of August 1973 (Fig. 2) was adopted and every flood was scaled with the discharges associated with the above mentioned return periods.

To determine the optimum height of the coffer dam, it was analyzed the discharge–elevation curves of the tunnel, and the following factors: