Arch-Dams' Building Risk Reduction

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The are thousands of large dams over the globe. The importance of dams is rapidly increasing due to the impact of climate change on increasing hydrological process variability and on water planning and management need. This study tackles a review for the concrete arch-dams' design process, from a dual sustainability/safety management approach. On one hand, Sustainability is evaluated through a design optimization for dams´ stability and deformation analysis. On the other hand, safety is directly related to the reduction and consequences of failure risk. For that, several scenarios about stability and deformation, identifying desirable and undesirable actions, were estimated. More than 100 specific parameters regarding dam-reservoir-foundation-sediments system and their interactions have been collected. Also, a summary of mathematical modelling was made, and more than 100 references were summarized. The following consecutive steps, required to design engineering (why act), maintenance (when to act) and operations activities (how to act), were evaluated: individuation of hazards, definition of failure potential and estimation of consequences (harm to people, assets and environment). Results show that the area to model the dam–foundation interaction is around 3.0 Hd2, the system-damping ratio and vibration period is 8.5% and 0.39 s. Also, maximum elastic and elasto-plastic displacements are ~0.10–0.20 m. The failure probability for stability is 34%, whereas for deformation it is 29%

concrete arch-dams | stability scenarios | deformation scenarios | safety management | sustainability assessment

1. Introduction

There are many factors, largely controlled by the structures size, that hinder sustainability in the field of dam engineering. In this sense, the height of the blocks can reach more than 100 m and the crown length can reach more than 500 m [1][2]. Dams with these dimensions are called "super-high dams" [3][4]. Then, the presence of structural elements [5], and their interactions, with different functions that increase the difficulty of calculation and modelling, e.g., the cantilevers that support and distribute the vertical loads and the arches that distribute the horizontal loads. Finally, the interaction of dam, foundation, sediments and reservoir sub-systems, requires not only the knowledge of the structural and hydraulic engineering, but also, other engineering areas are involved.

2. Reviewing Arch-Dams' Building Risk Reduction

Three aspects, namely geometry, behaviour, and materials, comprise the internal and intrinsic actions, which exclude the external actions and their uncertainties of probability and occurrence. These uncertainties are called

"random" and are related to the magnitude of variability and inherent randomness. Besides these types of uncertainties, there are the "epistemic" uncertainties that are related to the lack of knowledge of materials and models [6]. Random and epistemic uncertainties are studied in stochastic analyses, which are used to solve problems that cannot be deterministically solved because models are not known, or data are not available.

Due to the doubts of the input data, analyses, methodologies, and results, the concept of "risk" and quantitative risk assessment (QRA) is introduced through the following equation:

$$\text{Risk} = \int [P(L,E) \times P(R|L) \times C(L,R)] \quad (1)$$

where L = loads, E = events, and R = responses. P[R|L] is the conditional probability that R is true, given that L is true, and C stands for the consequences [7][8].

This integral is a measure of risk quantification based on the occurrence and probability of L, E and R, regarding the variability of extreme events, e.g., flooding, hurricanes, earthquakes, explosions. The interest of the concrete arch-dams is proven by the fact that several studies have been published since 1931 [9]. This interest has generated several codes/manuals/reports [10][11][12][13][14]. Furthermore, several academic works with the following goal have been published. First, there are researches about the definition of the shape (volume and area of concrete) optimization, aimed to minimize the cost and the impact of the dam body on the environment [15][16][17][18][19][20][21][22][23]. Then, publications addressing the analysis of the dam behaviour under seismic actions accounting the enormous importance of the structure [24][25][26][27][28][29][30][31][32][33]. Finally, there are studies that consider the fact that the dam body is linked with the foundation base, water reservoir, and soil sediments [34][35][36][37][38][39].

However, there are some aspects, described as follows, that are not well studied either synthetized or published in the literature. In this sense, the response estimation of arch-dams are not well studied or categorized, for example the effects of the non-uniform temperature variation due to the solar radiation and convective heat [30],[40][41][42][43][44]. Furthermore, a good calibration between the theoretical and practical data is often difficult to obtain. In this sense, there is a lack of experimental tests made in the laboratory, which allow verifying the analytical and computational models. Also, there is a lack of practical experience of researchers and technical engineers do not easily accept the insights of researchers. In this sense, some cases about real concrete arch-dams are listed in supplementary materials (see Appendix Table A1). Finally, but not least, there is a clear lack of academic papers that synthetize, integrate, and summarize most of the aspects involved in sustainability of concrete arch dam building. This review paper mainly aims to cover this deficiency, which comprises its main novelty too. This is performed herein by reviewing the existent knowledge on the development of sustainability and safety assessment through the study of structural stabilities/deformations and failure risk, respectively.

The rest of this paper is organized as follows: Section 2 shows a background about the data and mathematical modelling. Section 3 describes some main key findings about an operating system and the project variables in a managerial context [7,12,14]. Section 4 is dedicated to the materials and methodologies followed in this research,

describing the structure gand content of the different stages. Regarding materials, Random Variables (RVs) are showed; on the other hand, methods such as Monte Carlo Simulation (MCS), sustainability assessment framework and seismic hazard assessment are described. Then, section 5 comprises the description of results, largely addressing the sustainability assessment of structural stability and deformations. Finally, section 6 is dedicated to show the main conclusions drawn from this research.

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