Encyclopedia

Reviewing Arch-Dams' Building Risk Reduction

Created by: Jose-luis Molina
Version received: 8 January 2020

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%

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.

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 [[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. 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.

Regarding the obtained results, it is worthy to highlight that this entry addresses and comprises critical aspects that are summarized as follows: (i) to show innovative approaches respecting to the enormous quantities of variables that are involved for concrete arch-dams; (ii) to provide numerical values of parameters to design concrete arch-dams; (iii) to show the project phases a,nd methodologies; (iv) to estimate different scenarios respecting to the main actions on the dam system; (v) to contribute to the knowledge of the state-of-the-art about concrete arch dams.
The first results are shown in terms of new estimated data provided in the Appendix A. Other results concern the parameters of the interaction between dam–foundation–reservoir–sediments with respect to the area of rigid foundations under the dam (~ 3.0 Hd2), the contribution of each sub-system damping ratio respect to the system damping ratio (8.5%), and the contribution of each sub-system vibration period respect to the system vibration period (0.393 s). These values are useful to estimate some general relations that can be used to aid design. Moreover, the maximum elastic and elasto-plastic displacements are of the order of ~ 0.10–0.20m that, in relation to the maximum damheight, is Hd/1000, in accordance with the literature.
Furthermore, the sustainability assessment demonstrates that the mean probability of failure of the stability of dam body and its deformation is about 32%. In particular, that for stability is 34%, which is higher than for the deformation at 29%. These mean percentages are quite large because unstable actions have been taken. When the intersection point between the stable and unstable line rises, the pf increases, and so the “no safety” state is more probable. However, this raises the level of attention during the design of a monitoring method for concrete arch-dams, and in this sense, risk management can be carried out satisfactory.

References

1. Inventory of Dams and Reservoirs (SNCZI). . SNCZI. Retrieved 2020-1-13
2. Spanish Association of Dams and Reservoirs (SEPREM) . SEPREM. Retrieved 2020-1-13
3. Huang, H.; Chen, B.; Liu, C.; Safety monitoring of a super-high dam using optimal kernel partial least squares. *Math. Probl. Eng* **2015**, *2015*, 571594.
4. Shi, Z.; Gu, C.; Qin, D; Variable-intercept panel model for deformation zoning of a super-high arch dam. *SpringerPlus* **2016**, *5*, 898–917.
5. Zhang, Q.L.; Wang, F.; Gan, X.Q.; Li, B; A field investigation into penetration cracks close to dam-to-pier interfaces and numerical analysis. *Eng. Fail. Anal* **2015**, *57*, 188–201.
6. Hariri-Ardebili, M.A.; Saouma, V.E.; Seismic fragility analysis of concrete dams: A state-of-the-art review.. *Eng. Struct* **2016**, *128*, 374–399.
7. Hariri-Ardebili, M.A.; Risk, reliability, resilience (R3) and beyond in dam engineering: A state-of-the-art review.. *Int. J. Disaster Risk Reduct* **2018**, *31*, 806–831.
8. Altarejos-García, L.; Escuder-Bueno, I.; Serrano-Lombillo, A.; De Membrillera-Ortuño, M.G; Methodology for estimating the probability of failure by sliding in concrete gravity dams in the context of risk analysis. *Struct. Saf.* **2012**, *36–37*, 1–13.
9. Savage, J.L.; Houk, I.E.; Checking arch dam design with models. *Civ. Eng* **1931**, *1*, 695–699.
10. U.S. Army Corps of Engineers (USACE). Arch Dam Design, Manual; USACE, Eds.; USACE: Washington, DC, USA, 1994; pp. 1110-2-2201.
11. U.S. Army Corps of Engineers (USACE).. Theoretical Manual for Analysis of Arch Dams; Technical Report; USACE, Eds.; USACE: Washington, DC, USA, 1993; pp. ITL-93-1.

12. International Commission on Large Dams (ICOLD).. Selecting Seismic Parameters for Large Dams; Guidelines, Bulletin; ICOLD:, Eds.; ICOLD:: Paris, 2016; pp. 148.
13. Federal Guidelines for Dam Safety (FEMA).. Earthquake Analyses and Design of Dams; FEMA, Eds.; FEMA: Washington, DC, USA, 2005; pp. NC.
14. International Commission on Large Dams (ICOLD).. Dam Safety Management: Operational Phases of the Dam Life Cycle; ICOLD, Eds.; ICOLD: Paris, 2017; pp. NC.
15. Pouraminian, M.; Ghaemian, M; Multi-criteria optimization of concrete arch dams. *Sci. Iran* **2017**, *24*, 1810–1820.
16. Kaveh, A.; Ghaarian, R.; Shape optimization of arch dams with frequency constraints by enhanced charged system search algorithm and neural network.. *Int. J. Civ. Eng* **2015**, *13*, 102–111.
17. Seyedpoor, S.M.; Gholizadeh, S.; Optimum shape design of arch dams by a combination of simultaneous perturbation stochastic approximation and genetic algorithm methods. *Adv. Struct. Eng* **2008**, *11*, 500–510.
18. Seyedpoor, S.M.; Salajegheh, J.; Salajegheh, E.; Gholizadeh, S; Optimal design of arch dams subjected to earthquake loading by a combination of simultaneous perturbation stochastic approximation and particle swarm algorithms. *Appl. Soft Comput* **2011**, *11*, 39–48.
19. Mahani, A.S.; Shojaee, S.; Salajegheh, E.; Khatibinia, M.; Hybridizing two-stage meta-heuristic optimization model with weighted least squares support vector machine for optimal shape of double arch dams. *Appl. Soft Comput* **2015**, *27*, 205–218.
20. Zhang, X.F.; Li, S.Y.; Chen, Y.L.; Optimization of geometric shape if Xiamen arch dam. *Adv. Eng. Softw* **2009**, *40*, 105–109.
21. Akbari, J.; Ahmadi, M.T.; Moharrami, H.; Advances in concrete arch dams shape optimization. *Appl. Math. Model* **2011**, *35*, 3316–3333.
22. Shouyi, L.; Lujun, D.; Lijuan, Z.; Wei, Z.; Optimization design of arch dam shape with modified complex method.. *Adv. Eng. Softw* **2009**, *40*, 804–808.
23. Gholizadeh, S.; Seyedpoor, S.M.; Shape optimization of arch dams by metaheuristics and neural networks for frequency constraints.. *Sci. Iran* **2011**, *18*, 1020–1027.
24. Mirzabozorg, H.; Varmazyari, M.; Ghaemian, M; Dam-reservoir-massed foundation system and travelling wave along reservoir bottom.. *Soil Dyn. Earthq. Eng* **2010**, *30*, 746–756.
25. Lamea, M.; Mirzabozorg, H; Simulating structural responses of a generic AAR-aected arch dam considering seismic loading. *Sci. Iran* **2018**, *25*, 2926–2937.
26. Wang, J.T.; Jin, A.Y.; Du, X.L.; Wu, M.X.; Scatter of dynamic response and damage of an arch dam subjected to artificial earthquake accelerograms.. *Soil Dyn. Earthq. Eng* **2016**, *87*, 93–100.
27. Hariri-Ardebili, M.A.; Furgani, L.; Meghella, M.; Saouma,V.E.; Anew class of seismic damage and performance indices for arch dams via ETA method. *Eng. Struct* **2016**, *110*, 145–160.
28. García, F.; Aznárez, J.J.; Padrón, L.A.; Maeso, O.; Relevance of the incidence angle of the seismic waves on the dynamic response of arch dams.. *Soil Dyn. Earthq. Eng.* **2016**, *90*, 442–453.
29. Furgani, L.; Imperatore, S.; Nuti, C; Analisi sismica delle dighe a gravità: Dal semplice al complesso, se necessaio.. *Proceedings of the XIV Convegno ANIDIS, L'Ingeneria Sismica* **2011.**, *Bari, Italy, 18–22 September*, NC.
30. Hariri-Ardebili, M.A.; Kianoush, M.R; Integrative seismic safety evaluation of a high concrete arch dam. *Soil Dyn. Earthq. Eng.* **2014**, *67*, 85–101.
31. Hariri-Ardebili, M.A.; Mirzabozorg, H.; Kianoush, R; Comparative study of endurance time and time history methods in seismic analysis of high arch dams.. *Int. J. Civ. Eng* **2014**, *12*, 219–236.
32. Chen, B.F.; Yuan, Y.S; Nonlinear hydrodynamic pressures on rigid arch dams during earthquakes. *Proceedings of the 12 WCEE 2000, 12th World Conference on Earthquake Engineering* **2000.**, *New Zeland, 30 January–4 February*, NC.
33. Schultz, M.; Huynh, P.; Cvijanovic, V.; Implementing nonlinear analysis of concrete dams and soil-structure interaction under extreme seismic loading. *Proceedings of the 34th AnnualUSSDConference* **2014.**, *San Francisco, CA, USA, 7–11 April*, NC.
34. Khosravi, S.; Heydari, M.M.; Modelling of concrete gravity dam including dam-water-foundation rock interaction. *World Appl. Sci. J.* **2013**, *22*, 538–546.
35. Alegre, A.; Oliveira, S.; Ramos, R.; Espada, M.; Resposta sísmica de barragens abobada. Estudo numérico sobre a influência da cota de água na albufeira.. *Proceedings of the Encontro Nacional Betão Estrutural* **2018**, *BE2018*, NC.
36. Seyedpoor, S.M.; Salajegheh, J.; Salajegheh, E; Shape optimal design of arch dams including dam-water-foundation rock interaction using a grading strategy and approximation concepts. *Appl. Math. Model.* **2010**, *34*, 1149–1163.
37. Mirzabozorg, H.; Kordzadeh, A.; Hariri-Ardebili, M.A.; Seismic response of concrete arch dams including dam-reservoir-foundation interaction using infinite elements. *Electron. J. Struct. Eng.* **2012**, *12*, 63–73.
38. Proulx, J.; Paultre, P.; Experimental and numerical investigation of dam-reservoir-foundation interaction for a large gravity dam. *Can. J. Civ. Eng* **1997**, *25*, 90–105.
39. Akköse, M.; Adanur, S.; Bayraktar, A.; Dumano˘ glu, A.A.; Elasto-plastic earthquake response of arch dams including fluid-structure interaction by the Lagrangian approach. *Appl. Math. Model* **2008**, *32*, 2396–2412.
40. Hariri-Ardebili, M.A.; Seyed-Kolbadi, S.M.; Seismic cracking and instability of concrete dams: Smeared crack approach. *Eng. Fail. Anal.* **2015**, *52*, 45–60.
41. Demirel, E.; Numerical simulation of earthquake excited dam-reservoirs with irregular geometries using an immersed boundary method. *Soil Dyn. Earthq. Eng.* **2015**, *73*, 80–90.
42. Li, Q.; Guan, J.; Wu, Z.; Dong,W.; Zhou, S.; Equivalent maturity for ambient temperature eect on fracture parameters of site-casting dam

concrete.. *Constr. Build. Mater.* **2016**, *120*, 293–308.

43. Shi, N.; Chen, Y.; Li, Z; Crack risk evaluation of early age concrete based on the distributed optical fiber temperature sensing. *Adv. Mater. Sci. Eng.* **2016**, *2016*, 4082926.
44. Jin, F.; Chen, Z.; Wang, J.; Yang, J.; Practical procedure for predicting non-uniform temperature on the exposed face of arch dams.. *Appl. Therm. Eng* **2010**, *30*, 2146–2156.

Keywords

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