

Advances in Dam Engineering

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The expansion of water resources is the key factor in the socio-economic development of all countries. Dams play a critical role in water storage, especially for areas with unequal rainfall and limited water availability. While the safety of the existing dams, the periodic re-evaluations, and life extension are the primary objectives in developed countries, the design and construction of new dams is the main concern in developing countries. The role of dam engineers has greatly changed over recent decades. Thanks to new technologies, the surveillance, monitoring, design and analysis tasks involved in this process have significantly improved.

Aside from engineering and technical aspects, the nature and existence of dams are highly coupled by concepts such as population growth [1], climate change [2], global warming [3] and water security [4]. While national organizations focus on all their constructed dams, the International Commission on Large Dams (ICOLD) basically focuses on large dams. It is defined as a dam with a height of q_e 15 m from lowest foundation to crest, or a dam between 5 and 15 m impounding more than 3 Mm³ [5]. According to the ICOLD [5]'s most recent update in September 2019, there are about 58,000 registered large dams around the world. Figure 1 shows the global distribution of these dams. It is noted that a significant number of high dams are in China, India and United States.

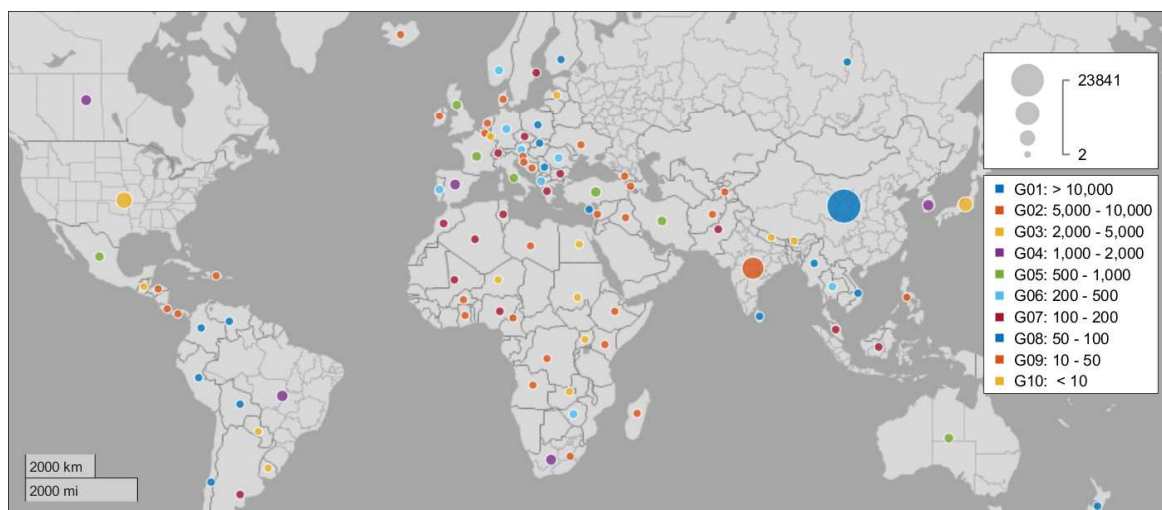


Figure 1. Global distribution of large dams as of 2019.

In national level, many countries have detailed information about the operating dams [6]. For example, as of 2019, over 91,460 dams operate across the United States. The Federal Emergency Management Agency (FEMA) reported a total of 15,500 high-hazard dams as of 2016 in the United States [7]. According to the 2019 USACE National Inventory of Dams (NID), the average age of dams in the United States is 57 years old, and American Society of Civil Engineers (ACSE) reports that by 2025, 70% of dams will be over 50 years old [8]. 74% of high-hazard dams have an emergency action plan. The Association of State Dam Safety Officials (ASDSO) estimates that the nation's non-federal and federal dams will require a combined total investment of \$64 billion for rehabilitation. A very detailed information about all the operating dams in the United States is recently published by NID [9], See Figure 2.

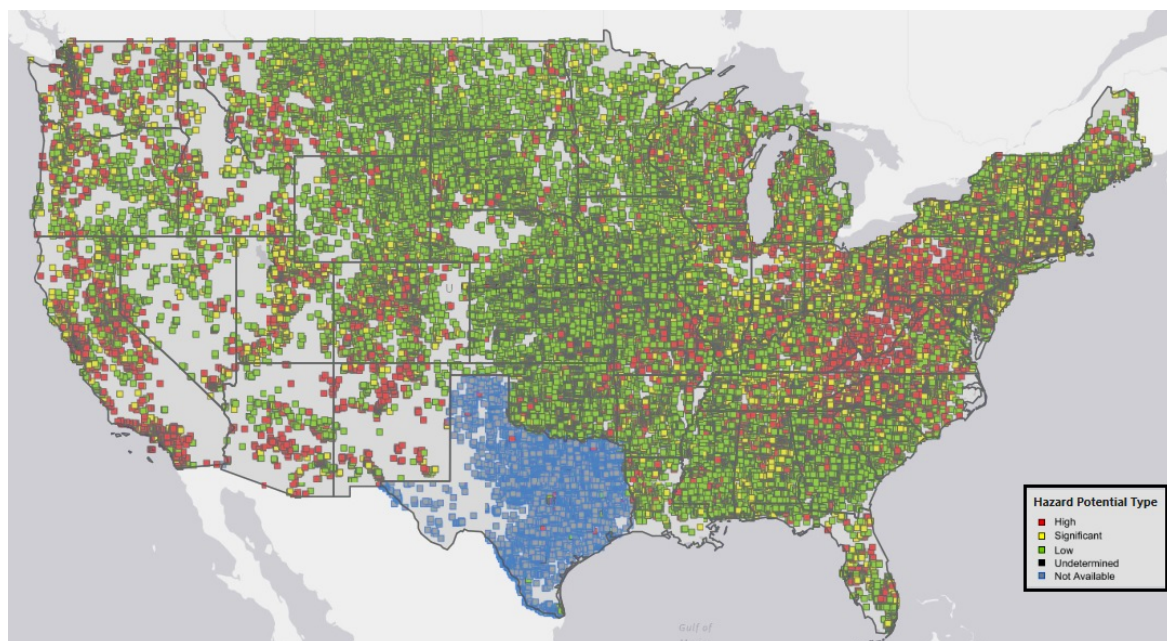


Figure 2. Distribution of dams with potential hazard type in the United States as of 2020; Generated from NID [9].

In December 2018, a team of guest editors specialized in different aspects of dam engineering proposed to launch a special issue “Advances in Dam Engineering” to the journal of “*Infrastructures*”. The special issue aimed to capture the recent increase in research activity in the field of dam engineering due to a series of recent catastrophes such as the 2017 Oroville Dam’s spillway incident [10]. The concept of dam failure, failure frequency and failure probability have been then studied by several researchers [11,12]. Statistical analysis of dam failure was an important topic in recent years [13]. Figure 3 summarizes the statistics of the failed dam as a function of construction year, dam height, reservoir capacity, dam type, and failure context. Data are adapted from ICOLD’s recent draft incident database [14].

Therefore, investigation of the current condition and future risks is a vital task in dam safety [15]. In this Special Issue, we solicit high-quality original research articles focused on the state-of-the-art techniques and methods employed in the design, construction, and analysis of dams. Both the theoretical and applied aspects are important, because they facilitate an awareness of techniques and methods in one area that may be applicable to other areas.

This book includes ten excellent contributions to this special issue published between 2019 and 2020. The overall aim of the collection is to improve modeling, simulation and field measurements in different dam types (i.e., concrete gravity dams, concrete arch dams, and embankments). The articles cover a wide range of topics around dams, and reflect scientific efforts and engineering approaches in this challenging and exciting research field.

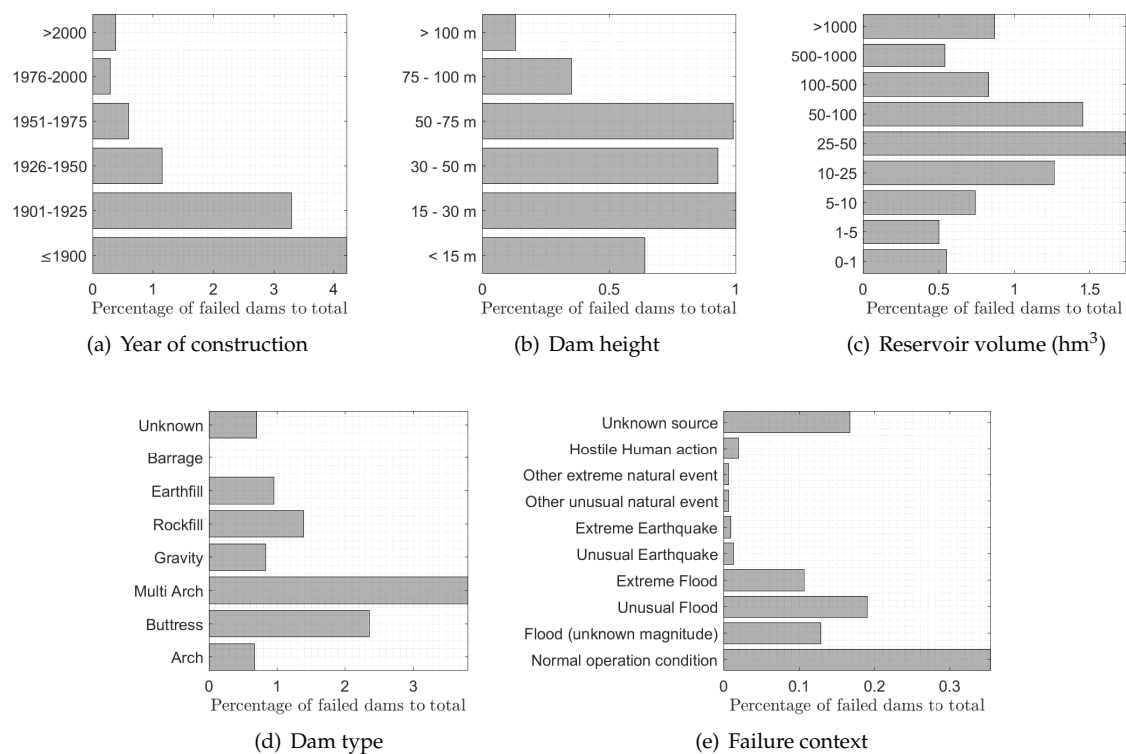


Figure 3. Statistics of large dams failure as a function of different features.

Although many detailed models have been proposed for seismic analysis of a coupled dam-foundation-reservoir system, less focus has been placed on the correlation of actual seismic response of different dams. In the paper by Hariri-Ardebili et al. [16] “Probabilistic Identification of Seismic Response Mechanism in a Class of Similar Arch Dams,” the authors compared the linear and nonlinear seismic performance of two similar high arch dams with relatively different response mechanisms. This paper is, in fact, a complementary to several previous research in this field, among them [11,17]. They found that some engineering demand parameters and seismic intensity measures can reduce the dispersion of the results and increase the correlation. In general, the dam geometry has a direct relation with the deformation and spatial distribution of potential damaged area. However, it is not related to the localized damage at the most critical location. Furthermore, the anticipated crack profile (from nonlinear simulation) has a discrete nature compared to the continuous overstressed/overstrained regions (from linear simulation).

One of the most important challenges in dam engineering field is to determine the maximum dynamic load concrete dams can withstand. In the paper by Furgani et al. [18] “On the Dynamic Capacity of Concrete Dams,” the authors studied seismic capacity of three types of concrete dams (i.e., gravity, buttress and arch). This paper is, in fact, a complementary to several previous research in this field, among them [19,20]. The key topics including the selection of dynamic parameters, the progressive level of detail for the numerical simulations, the implementation of nonlinear behaviors, and the concept of the service and collapse limit states were also discussed. They used the concept of Endurance time analysis to retrieve the capacity curves with minimum computational effort (as opposed to incremental dynamic analysis and cloud analysis technique) [21].

Seismic performance of dams can be assessed by either deterministic or probabilistic approaches. The latter one is required to manage the various sources of uncertainties that may impact the dam performance. Within the context of probabilistic framework, a fragility analysis is a powerful tool to present the likelihood of any desired damage state as a function of seismic intensity level. The concept

of fragility has been studied many times in various dam types [22,23]. Two of the accepted papers in this special issue discuss fragility analysis of gravity dams [24] and arch dams [25].

In the paper by Segura et al. [24] “Modelling and Characterizing a Concrete Gravity Dam for Fragility Analysis,” the authors proposed a methodology for the proper modeling and characterization of the uncertainties to assess the seismic vulnerability of a dam-type structure. This is a follow up research for the authors previous articles [26,27]. They also discussed on all the required verification of the numerical model prior to performing a seismic fragility analysis. The procedure considers the uncertainties associated with the modeling parameters and the randomness in the seismic solicitation.

In the paper by Sevieri et al. [25] “Shedding Light on the Effect of Uncertainties in the Seismic Fragility Analysis of Existing Concrete Dams,” the authors discussed the main issues behind the application of performance-based earthquake engineering to existing concrete dams, with particular emphasis on the fragility analysis. This paper is a follow up for the authors previous contributions in uncertainty quantification of dam responses [28,29]. More particularly, they discussed the impact of epistemic uncertainties on the calculation of seismic fragility curves. They showed that the median of fragility curve is sensitive to epistemic uncertainty and the inter-correlation among random variables.

For many large concrete structures, the load effects that occur from variations in ambient conditions may be the dominating loads that introduce significant stresses in the structure. Dams located in cold areas are subjected to large seasonal temperature variations and subsequent cracks. In the paper by Malm et al. [30] “Lessons Learned Regarding Cracking of a Concrete Arch Dam Due to Seasonal Temperature Variations,” the authors summarized and discussed on the results of the ICOLD Benchmark Workshop to predict the cracking and displacements of an arch dam due to seasonal variations [31]. The theoretical aspects were already discussed in [32–34]. They highlighted several important aspects need to be considered in order to obtain realistic results: (1) the importance of performing transient thermal analyses using robin boundary conditions (i.e., based on convective heat transfer boundaries); (2) the impact of dam-foundation contact formulation; and (3) adapting a realistic nonlinear material model.

Passive rock bolts are commonly used to anchor concrete dams. Although they affect the stability of dams, they are often omitted from dam safety analysis due to uncertainties regarding their condition and the force-displacement relation. In the paper by Hellgren et al. [35] “Progressive Failure Analysis of A Concrete Dam Anchored with Passive Rock Bolts,” the authors addressed the latter question by analyzing the failure process of a small concrete dam anchored with rock bolts. This paper is a follow up for the authors previous contribution [36]. Two approaches were used to model the anchorage of the rock bolts: (1) anchorage using a fixed boundary condition, and (2) anchorage using springs. They showed that the rock bolts contribute 40–75% of the load-carrying capacity of the dam.

Dams and appurtenant structures are usually located on the large foundations or soil medium with heterogeneous properties. Uncertainty in ground datasets often stems from spatial variability of soil parameters and changing groundwater regimes. In the paper by Herridge et al. [37] “A Probabilistic Approach to the Spatial Variability of Ground Properties in the Design of Urban Deep Excavation,” the authors used a probabilistic random set finite element approach to revisit the stability and serviceability of a deep submerged soil nailed excavation built into a cemented soil profile. The validated model is then deployed to test the viability of using independent hydraulic actions as stochastic variables. They found that using cohesion and water level as stochastic variables provides a reasonable response prediction.

The alkali-silica reaction (ASR), more commonly known as concrete cancer, is a swelling chemical reaction that occurs over time in concrete between the highly alkaline cement paste and the reactive silica in aggregates, given sufficient moisture and temperature. It may eventually lead to crack formation in concrete [38], and eventually affect functionality of the structure. Traditionally, there have been many studies to address this phenomenon in concrete dams [39–42]. In the paper by Colombo and Comi [43] “Hydro-Thermo-Mechanical Analysis of an Existing Gravity Dam Undergoing Alkali-Silica Reaction,” the authors investigated the impact of ASR on damage response of a gravity dam using a

two-phase isotropic damage model. The impact of both temperature and humidity were considered through two uncoupled diffusion analyses. This paper which was a follow up for the author's previous research [44,45] showed a reasonable predicted crest displacement compared with the real monitoring data.

Aside from numerical simulations, the field measurement is an essential source for safety assessment of dams. In the paper by Seyed-Kolbadi et al. [46] "Instrumented Health Monitoring of an Earth Dam," the authors evaluated the stability of a large earth dam by monitoring its long-term performance and interpreting the measured data. Various quantities such as pore water pressure, water level, and internal stress ratios were measured. The piezometers showed efficient drainage. Other instruments also showed a reasonable horizontal stress in dam body. Overall, the failure risk was evaluated to be low, and the dam operates in normal condition. This field investigation was a complementary to the author's previous research on numerical slope stability analysis [47].

Although the empirical models can predict the normal dam behavior, they do not account for changes due to recurring extreme weather events. On the other hand, the numerical models provide insights into this, but results are affected by the chosen material properties. In the paper by Pytharouli et al. [48] "From Theory to Field Evidence: Observations on the Evolution of the Settlements of an Earthfill Dam, over Long Time Scales," the authors analyzed the recorded settlements for one of the largest earthfill dams in Europe. They compared the evolution of the settlements to the reservoir level, rainfall, and the occurrence of earthquakes for over 31 years. They reported that the clay core responds to the reservoir fluctuations with an increasing (from 0–6 months) time delay. This paper is a follow up for the authors previous research [49,50].

We hope that this special issue would shed light on the recent advances and developments in the area of dam engineering, and attract attention by the scientific community to pursue further research and studies on simulation, testing, and field measurement of dams and appurtenant structures.

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