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Seismic risk prioritization of a large portfolio of dams: Revisited

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Abstract

The development of potential failure mode analysis and risk analysis has greatly improved the state-of-practice for the safety of dams. Risk analysis are well developed in many industries (such as building design, medicine, and insurance) and has greatly advanced in the dams industry over the last 40 years. Engineers and scientists are now deeply investigating and thinking about failure mechanisms associated with operating dams and the probabilities of dam failures. As such, the condition of dams and the risks associated with their operation are now being portrayed better than ever before to dam safety officials and decision-makers. Accurate and adequate risk analyses for a portfolio of dams is extremely important in today's environment to manage limited budgets and potentially save (or redirect) expensive rehabilitations to identified and critical needs. The goal is to reduce risks of a portfolio of dams in an efficient and cost-effective manner. This article provides a review on risk-based dam terminology and bridging the semi-quantitative and numerical simulation. Moreover, a review of the current state-of-practice for prioritizing a large portfolio of dams subjected to seismic loadings and potential risks is provided. As a potential application, the seismic risk of the 18 dams (which have been experienced relatively large earthquakes) all over the world is evaluated. The semi-quantitative approach is contrasted with finite element model for one of the selected dams.

Keywords

Dams, semi-quantitative method, risk analysis, finite element, seismic, portfolio, uncertainty

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Introduction

As of 2017, more than 90,580 dams operate across the United States, which makes hydropower the biggest source of renewable energy. The US Army Corps of Engineers (USACE) National Inventory of Dams (NID) defines three hazard category for dams: low, significant, and high. Figure 1 illustrates this classification for all the country's dams. It also shows the fast growth of high-hazard dams in need of remediation from 2001 to 2009. Moreover, the Federal Emergency Management Agency (FEMA) reported a total of 15,500 high-hazard dams as of 2016 in the United States.[2]

According to the 2017 American Society of Civil Engineers (ACSE), the average age of dams in the United States is over 56 years old, and by 2025, 70% of dams will be more than 50 years old. 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 US$64 billion for rehabilitation. Given the limited budget for repair and maintenance, national infrastructures require a comprehensive emergency action plan for assessment of dam safety.[3,4]

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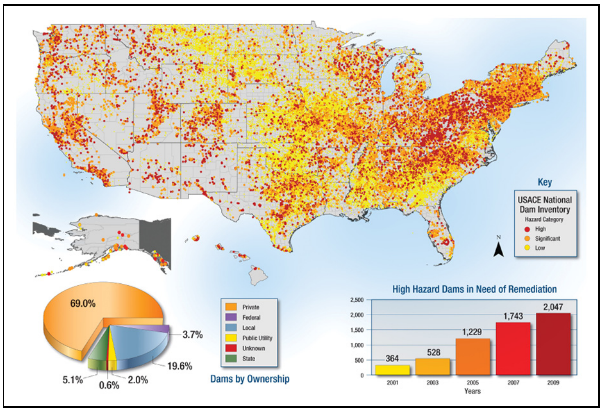

Figure 1. Classification of US dams by how hazardous they are; adopted from Federal Emergency Management Agency.[1]

There have been already several attempts in order to prioritize the decision-making methodologies in dam safety. For example, Harrald et al.[5] categorized a series of methods as follows: (1) preliminary hazard analysis, (2) preliminary risk analysis, (3) what-if/checklist analysis, (4) failure modes and effects analyses, (5) hazard and operability analysis, (6) fault tree analysis, (7) event tree analysis, (8) relative ranking/risk indexing, (9) coarse risk analysis, (10) Pareto analysis, (11) root cause analysis, (12) change analysis, (13) common cause failure analysis, and (14) human error analysis.

Different levels of risk assessments can be implemented on a portfolio of dams. A portfolio is a group of dams for which a single owner or regulator is responsible for.[6] Qualitative, semi-quantitative, and fully quantitative techniques have been introduced for dam safety risk management.

A semi-quantitative method is introduced by International Commission on Large Dams (ICOLD)[7] and Bureauand and Ballentine[8] which is mainly based on a statistical model on the historical data. They compiled the performance of the dams during the past earthquakes between 1900 and 2001. The information of over 350 dams worldwide were gathered mainly from US Committee on Large Dams (USCOLD)[9,10] (note that the 3rd volume of this report is published as US Society on Dams (USSD)[11] which can be used to update the data and empirical models). This method quickly rates the total seismic risk of the dam at a particular site. This method was originally used for the dams in South Carolina (in United States) and its neighbor states.[12] Due to its simplicity, it is adopted by different researchers to provide a general (yet comprehensive) evaluation of dams in different countries such as Turkey,[13,14] India,[15] South Africa,[16] and Argentina.[17] Moreover Chen and Lin,[18] developed a method for total risk analysis of dams under the flood hazard. All the steps are similar to the seismic hazard proposed by Bureauand and Ballentine;[8] however, they altered all the parameters properly for the flood hazard.

On the other hand, there have been proposed many techniques for quantification of risk in dam failure analysis. Cheng et al.[19] recommended using the probabilistic methods for safety analysis of US dams. Bowles[20] advocated for employing the quantitative risk analysis (QRA) to solve the dam safety problems. Furthermore Bowles et al.,[21] compared the standard- and risk-based dam safety evaluations in the context of comprehensive risk management. Kostov and colleagues[22,23] developed a model for quantitative seismic risk of two concrete gravity dams and one arch dam using a detailed finite element model (FEM).

Bowles and colleagues[6,24] explored the concept of portfolio risk assessment (PRA) of dams. This method is based on the overall business context and objectives for PRA, agreement on the business requirements, engineering and risk assessment of dams, evaluating the risk reduction alternatives, and integrating dam safety results into business risk. Chauhan and Bowles[25] proposed a framework for uncertainty analysis in dam safety risk assessment including some useful features such as the confidence level associated with meeting tolerable risk guidelines.

Different computer programs were developed to facilitate dam safety risk analysis: risk assessment methodology dams (RAM-D)^{SM} by Matalucci,[26] risk analysis and prioritization of dams in Italy by Meghella and Eusebio,[27] LIFESim by Bowles and Aboelata,[28] and DAMRAE-U by Srivastava et al.[29]

Smith[30] developed a technique for dam risk analysis based on Bayesian networks, which allows to account for the inter-relations between the failure mechanisms, the uncertainties, and the expert judgments. Serrano-Lombillo et al.[31] developed a model to calculate the incremental risks at the dams in the context of an event tree analysis. Su and Wen[32] combined the risk analysis with fuzzy mathematics to evaluate the stability of concrete dams. Cloete et al.[33] proposed the rational quantitative optimal approach, which was a robust risk evaluation model to produce a definitive result for the risk mitigation at dam site. Finally, Serrano-Lombillo et al.[34] proposed a risk reduction indicator which allows to prioritize the sequences of investments while maintaining an equilibrium between equity and efficiency principles.

In this review article, a semi-quantitative technique is reviewed and revised for seismic risk prioritization of a large portfolio of dams. All the dam- and reservoir-dependent parameters as well as the downstream risk parameters are accounted for. The parameters involved in damage and loss analysis are contrasted with those recommended in performance based earthquake engineering (PBEE),[35] and the necessary adjustments are

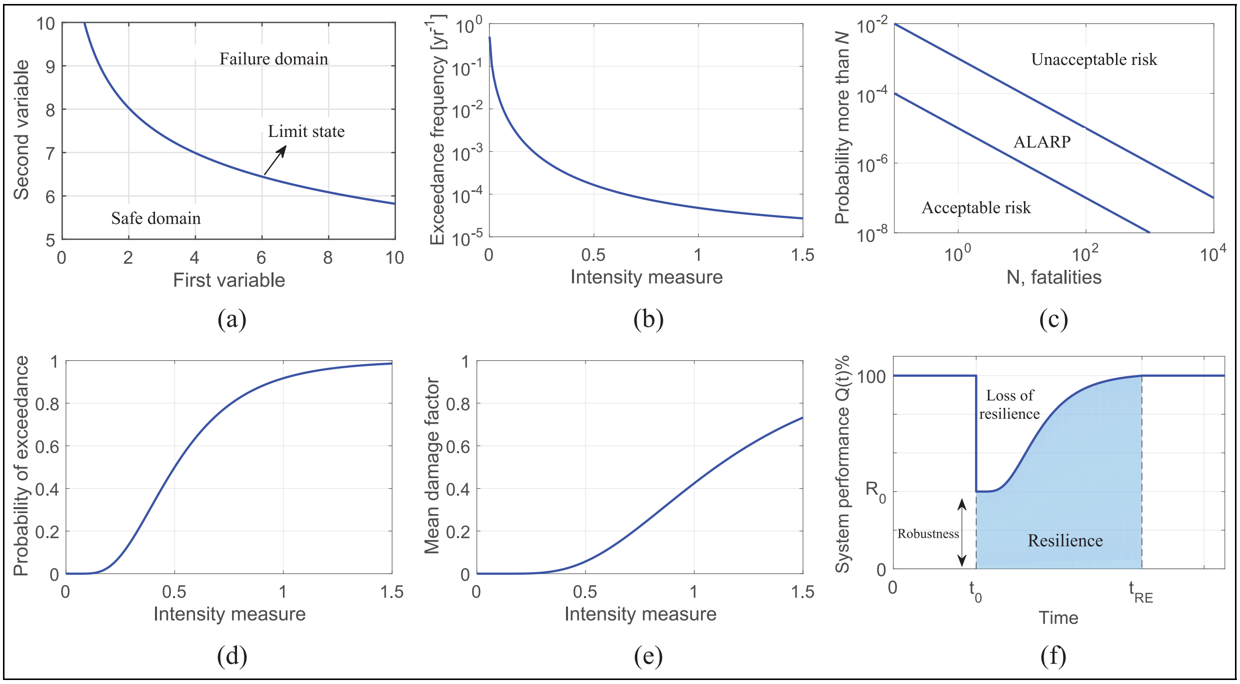

Figure 2. Comparison of different terminologies involved in safety assessment of concrete dams: (a) reliability, (b) hazard, (c) risk, (d) fragility, (e) vulnerability, and (f) resilience.

applied. Subsequently, a hierarchical review is provided on the different numerical simulation techniques for high-hazard dams.

Review of dam safety terminology

The first step in any state-of-the-art review article is to define a unified terminology.[36] This section briefly discusses the differences and similarities among six widely-used concepts in seismic analysis of infrastructures. Some of these concepts have a root in Pacific Earthquake Engineering Research (PEER) Center PBEE methodology,[37] some others in potential failure mode analysis (PFMA),[38] and others in general earthquake engineering.

Reliability

In reliability analysis, the failure probability, P_f (in terms of limit state (LS) function, $G(\boldsymbol{X}) = R(\boldsymbol{X}) - S(\boldsymbol{X})$) can be expressed as[39–42]

$$P_f = \mathbb{P}[R(\boldsymbol{X}) \leqslant S(\boldsymbol{X})] = \int_{G \leqslant 0} f_R(R) f_S(S) dR dS \quad (1)$$

where R and S are resistance and stressor, respectively; $\boldsymbol{X} \subset \mathbb{R}^M$ is a random vector of K basic variables $\boldsymbol{X} = X_1, X_2, \ldots, X_K$; the randomness of R and S is expressed by probability density functions (PDFs) f_R and f_S. In this context, $G(\boldsymbol{X}) \leqslant 0$ corresponds to failure.

Hazard

Seismic hazard refers to an uncertain relationship between some level of seismic intensity measure (IM) and the frequency or probability of a particular location experiencing at least that level of excitation.[43] Usually, a probabilistic seismic hazard analysis (PSHA) is performed to derive the hazard curve. It expresses a plot where the horizontal axis is the IM at a site, and the vertical one is annual frequency of exceedance, λ_{IM}, (inverse of the return period, T_R), refer Figure 2. λ_{IM} is usually determined from Poisson probability model[44]

$$\lambda_{\mathrm{IM}} = -\frac{\ln(1 - P_E)}{t} \quad (2)$$

where P_E is the occurrence (at least one) probability during life time t (usually assumed to be 100 years for dams and 50 year for the buildings). P_E might be 2%–5% for the rare events.

Risk

In the context of the dam safety, risk can be defined as "Measure of the probability and severity of an adverse effect to life, health, property, or environment. In the general case, risk is estimated by the combined impact of all triplets of scenario, probability of occurrence and the associated consequence."[45] Risk can be quantified as[46]

$$\text{Risk} = \int \mathbb{P}\,[\text{LoadEvents}] \times \mathbb{P}\,[\text{Responses}|\text{Loads}] \times \mathbb{C}[\text{Loads, Responses}] \quad (3)$$

where $\mathbb{P}[A|B]$ is the conditional probability that A is true given that B is true, and $\mathbb{C}$ stands for the consequences.

Risk assessment is the process of deciding whether existing risks are tolerable and if not, whether alternative risk control measures are justified or will be implemented.[47] Tolerable risk means different things to different people and organizations. Some focus on economic risks to their company or organization (e.g. insurance, offshore oil, and gas) while others focus on loss of life.[4] Most of the technical codes[4,47–49] use a so-called "risk curve" (either in the form of f-n or F-N chart).[50] An example of Canadian Dam Association (CDA),[49] societal risk guideline is shown in Figure 2(c) (where ALARP stands for "as low as reasonably practicable").

Fragility

Fragility is a continuous function showing the probability of exceedance of a certain LS for a specific level of ground motion IM, *im*,[51,52] Figure 2(d)

$$\text{Fragility} = \mathbb{P}[D \geqslant C_{\text{LS}}|\text{IM} = im] \quad (4)$$

where D is the demand parameter and C_{LS} is the capacity associated with the given LS.

Fragility analysis is one of the main steps in PBEE[37] and can be derived from analytical simulations, experimental data, or expert opinion. The fundamentals of fragility analysis of concrete dams can be found in the work of Hariri-Ardebili[53] with a comprehensive state-of-the-art literature review by Hariri-Ardebili and Saouma.[54]

Vulnerability

Vulnerability is different from fragility.[43] The former measures loss (in terms of dollars, deaths, and downtime), while the latter measures probability. A vulnerability curve expresses the loss as a function of IM. Three major types of vulnerability curves are

- Measuring repair cost: in such a case the repair cost is normalized by the replacement cost new and is called damage factor. The expected value of damage factor conditioned on IM parameter is called mean damage factor, Figure 2(e).
- Measuring life safety: in such a case, the number of casualties is normalized by the number of indoor occupants and expressed as a function of IM parameter.
- Measuring downtime: it is measured in terms of fraction of a year during which the structure cannot be used.

Resilience

Community resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to actual or potential adverse events.[55] Cimellaro et al.[56] define resilience as a normalized function indicating capability to sustain a level of functionality or performance, $Q(t)$, for a given building, dam, lifeline, or community over a period of time, t_{LC}, (life cycle time). t_{LC} includes the structure recovery time, t_{RE}, and the business interruption time, t_{BI} (usually negligible). t_{RE} is the time necessary to restore the functionality of a critical infrastructure system (and usually is a random variable with high uncertainties). Resilience can be defined as[57]

$$\text{Resilience} = \int_{t_0}^{t_{RE}} \frac{Q(t)}{t_{RE}}\,dt \quad (5)$$

where t_0 is the earthquake occurrence time. Resilience and loss of resilience, the complementary part, are usually shown through a so-called "recovery function," Figure 2(f). A comprehensive report on resilience of dams and levees can be found in the National Research Council.[58]

Next, this article reviews the most important qualitative, semi-quantitative, and quantitative approaches in the context of risk-based safety assessment of dams. Harrald et al.[5] discuss several tools and categorized them as

- Dam safety risk assessment, for example, risk-based profile system (RBPS);
- Dam safety priority indexing, for example, technical priority rating (TPR) and condition indexing (CI);
- Dam safety risk assessment and priority indexing, for example, PRA and CI;
- Dam security risk (and vulnerability) assessment, for example, RAM-D and the Electric Power Research Institute (EPRI) tool.

USBR qualitative risk analysis

The US Department of the Interior Bureau of Reclamation (USBR) RBPS was developed in 1997, which could be used to characterize the risk associated with individual loading conditions or sums the total risk imposed by a given structure.[59] The “Failure Index” (FI) is the foundation of RBPS, in which the dam is assessed by assigning a maximum of 1000 points based on four categories: static (300 points); hydrologic (300 points); seismic (300 points); and operation, maintenance, and safety (100 points). The higher the point total, the greater the potential risk. To determine the FI, a series of worksheets need to be completed which address the full range of loading and physical conditions of the dam.

The FI is further multiplied by a loss of life factor (LoLF) to characterize the consequences associated with a failure and is called the “Risk Index” (RI). The LoLF is determined based on several factors including the total population at risk, the location of this population below the dam, the severity of the flooding, and the severity of the failure mode. The RI is calculated separately for each category of FI and then summed to represent the total RI.[59]

The final scoring for any particular dam is calculated by comparing its score to the highest score found for all the dams in Reclamation’s inventory, expressed as a percentage. This is a deterministic method based on qualitative assessment and heavily depends on the failure modes analysis. It falls under index prioritization approach category because the ranking is based on the calculated indices from a combination of weights, which are assigned to capture various attributes of dam safety deficiencies.[5] This technique is more suitable for initial screening of a portfolio of dams or a comparison to other forms of risk analysis.

USACE-USBR semi-QRA

The semi-quantitative risk analysis (SQRA) is a joint effort by USACE and USBR to establish a methodology for some projects at the beginning of an Issue Evaluation Study (IES) to re-evaluate the incremental risk and urgency of action.[4] This approach is mainly built on four concepts: (1) failure likelihood, (2) consequences, (3) confidence level, and (4) risk matrix. First each of those three is briefly described, then the step-by-step procedure for SQRA is discussed.

Failure likelihood categories

The following failure likelihood categories and descriptors were proposed for SQRA in dam safety:[4]

Remote: the annual failure likelihood is more remote than 10^{-6}. Several events (with negligible likelihood) must occur in series or parallel to cause failure.

Low: the annual failure likelihood is between 10^{-5} and 10^{-6}. The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred.

Moderate: the annual failure likelihood is between 10^{-4} and 10^{-5}. The fundamental condition or defect exists; indirect evidence suggests it is probable; and key evidence is weighted more heavily toward “less likely.”

High: the annual failure likelihood is between 10^{-3} and 10^{-4}. The fundamental condition or defect exists; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward “more likely.”

Very high: the annual failure likelihood is greater than 10^{-3}. There is direct evidence to suggest that it has initiated or is likely to occur in near future.

Consequences categories

In the USACE-USBR SQRA, the failure consequences is typically evaluated using potential life loss, with the idea that the broader socio-economic, environmental, and property damages would be generally commensurate. The following broad consequence categories are used for SQRA:[4]

Level 0: no significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river.
Level 1: downstream discharge results in limited property and/or environmental damage. Direct loss of life is unlikely due to severity or location of the flooding.
Level 2: downstream discharge results in moderate property and/or environmental damage. Incremental life loss in the range of 1–10.
Level 3: downstream discharge results in significant property and/or environmental damage. Incremental life loss in the range of 10–100.
Level 4: downstream discharge results in extensive property and/or environmental damage. Incremental life loss in the range of 100–1000.
Level 5: downstream discharge results in extremely high property and/or environmental damage. Extremely high direct loss of life can be expected. Incremental life loss greater than 1000.

Confidence level

The confidence level that the evaluating team has in the previous categories, should be determined using the following qualitative descriptors:[4]

High: the team is confident in the order of magnitude for the assigned category.

Moderate: the team is relatively confident in the order of magnitude for the assigned category.

Low: the team is not confident in the order of magnitude for the assigned category, and it is entirely possible that additional information would change the estimate.

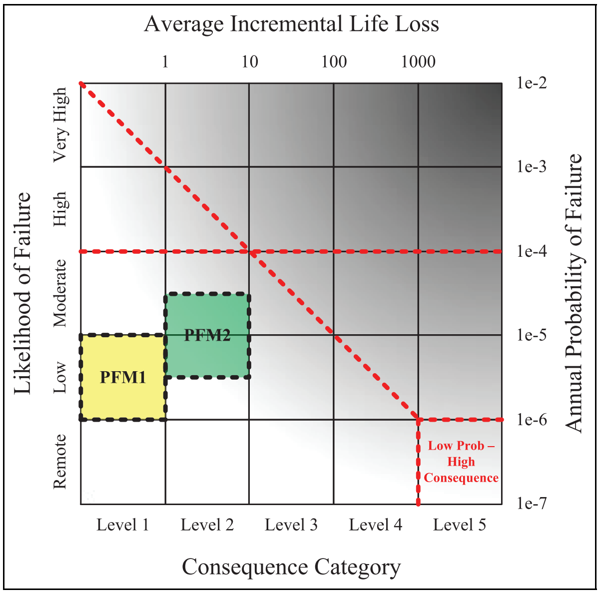

Figure 3. USACE-USBR incremental risk matrix; adopted from USACE-USBR[4]

Risk matrix

The risk matrix simply represents the relationship between the failure likelihood and incremental consequences (Figure 3). The "Annualized Life Loss" (i.e. social risk) is represented by the diagonal dashed line, while the "Annual Probability of Failure" (i.e. individual risk) is represented by the horizontal dashed line. The identified potential failure modes (PFMs) are supposed to fill a particular cell (e.g. PFM1 with yellow box) or even cross several cells (e.g. PFM2 with green box), refer Figure 3.

SQRA procedure

The following steps summarize SQRA:[4]

1. Review basic statistics and key features of the dam.
2. Review normal operating condition loadings.
3. Review available seismic hazard curves, more specifically the ground motions associated with 10^{-4} per year earthquake, the approximate return period of the maximum credible earthquake.
4. Review inundation studies including probable impacts to downstream dams, roads, bridges, and so on.
5. Develop the PFM.
6. Develop the factors making the PFM more likely and less likely to occur.
7. Elicit failure likelihood categories from each team member, along with the reasoning behind their estimate.
8. The facilitator or designated recorder captures the information, including the likelihood category and the rationale for its assignment (including the confidences).
9. A similar elicitation process is repeated to arrive at a consequence category for each PFM.

Semi-quantitative seismic ranking of dam portfolio

As it is stated in "Introduction" section, a semi-quantitative method is introduced by Bureauand and Ballentine[8] on the basis of some initial risk analysis metric published in ICOLD.[7] In this empirical method, various risk factors and different weights are incorporated in total risk factor, RF_{total}, of a single dam. RF_{total} depends on (1) the dam type, (2) dam age, (3) dam size, (4) the downstream risk potential, and (5) the dam's vulnerability. It can be expressed as[60]

$$RF_{total} = \left(\left(RF_{capacity} + RF_{height} + RF_{age}\right) + RF_{downstream}\right) \times DF_{predicted} \tag{6}$$

where RF refers to the risk factor. The first three terms include the dam-dependent factors (i.e. capacity, height, and age), while $RF_{downstream}$ is the downstream risk as a function of (1) population and (2) property at risk (note that this term will be expanded later). $DF_{predicted}$ presents the predicted damage factor which is a function of (1) the site-dependent seismic hazard and (2) observed performance of similar dams.

Three factors quantify the risk of a dam and the reservoir and are shown in Figure 4(a)–(c). Each of the plots include the original proposed threshold, as well as the updated and smoothed versions. $RF_{capacity}$ has a linear form in the logarithmic scale, while RF_{height} has sigmoid nature. Risk factor increases for higher dam with larger reservoir. Furthermore, RF_{age} is controlled by possible deterioration, lack of maintenance, obsolete construction methods and materials, reservoir siltation, or insufficient foundation treatment. For the construction age factor, two upper and lower bounds are proposed (Figure 4(c)), corresponding to the severely deteriorated (and not repaired, for example, alkali aggregate reaction[61,62]) and well-maintained conditions.

On the other hand, the overall downstream risk factor $RF_{downstream}$ can be divided into the following factors

$$RF_{downstream} = RF_{population} + RF_{property} + RF_{downtime} \tag{7}$$

where $RF_{population}$ is the downstream human population at risk, $RF_{property}$ is the property risk factor and depends on the value of private, commercial, industrial, or governmental property in the potential flood path.[60] Those information can be obtained from detailed breach

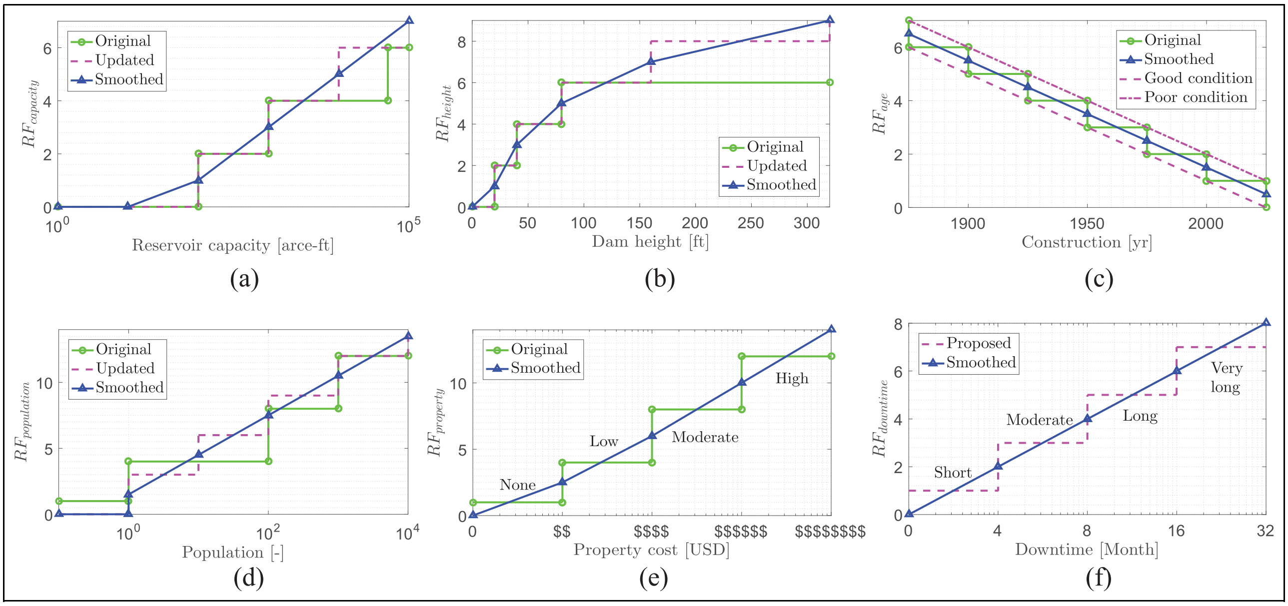

Figure 4. Quantification of dam-dependent and downstream risk factors: (a) reservoir capacity factor, (b) dam height factor, (c) age and construction factor, (d) evacuating population factor, (e) property cost factor, and (f) downtime factor.

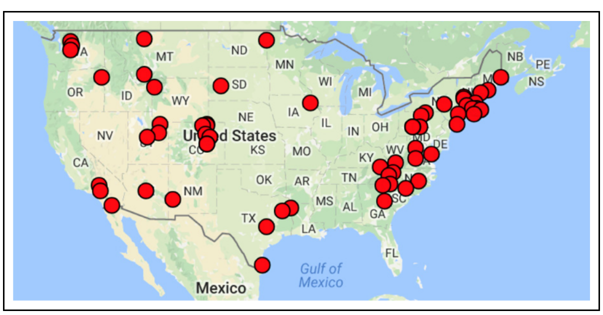

Figure 5. Location of dam failures including fatalities in the US (1850–2016), adopted from the National Performance of Dams Program.[63]

analysis, inundation mapping, and economic studies. These two factors can be quantified through Figure 4(d) and (e).

Since 1850, there have been 63 known dam failure in the United States (exclusive of tailings dams) that have involved fatalities (Figure 5).[63] It corresponds to the frequency of occurrence of 0.38 per year of dam failure. Range on the number of fatalities is 1–2209, and the average number of fatalities per year over the period of recording (i.e. 167) is about 20.6–22.4.

The USBR developed a procedure to estimate the loss of life using data from every dam failure in the United States that resulted in more than 50 fatalities and every post-1960 US dam failure that resulted in one or more fatalities. The information such as warning time, population at risk, flood severity, and fatality rates were used for this purpose. The procedure is comprised of seven steps:[64]

- Determine dam failure scenarios to evaluate.
- Determine time categories for which loss of life estimates are needed.
- Determine flooded area for each dam failure scenario.
- Estimate the number of people at risk for each dam failure scenario and time category.
- Determine when dam failure warnings would be initiated.
- Select appropriate fatality rate for estimating life loss. The fatality rate is based on the flood severity, the warning time, and the flood severity understanding.
- Evaluate uncertainty in various parameters which lead to uncertainties in the life loss estimates.

Although both $RF_{population}$ and $RF_{property}$ account for the downstream risk, they do not consider the indirect long-term loss factors due to repair or reconstruction of the damaged properties. This is an important factor that is already implemented in PEER PBEE methodology for framed structures.[37] To account for the downtime, Figure 4(f) proposes a metric for $RF_{downtime}$.

Note that when it is not cost-effective to obtain $RF_{downstream}$ from detailed studies (e.g. field investigations or numerical simulations), one can use Table 1, which provides a rough estimation of $RF_{downstream}$. This table is originally proposed by the NID and only accounts for the loss of life and monetary loss (and not the downtime).

Table 1. Downstream risk factor based on NID.

Classification	Loss of life	Economic, environmental or lifeline losses	$RF_{downstream}$
Low	None expected	Low, generally limited to owner's property	2
Significant	None expected	Yes	12
High	Likely, one or more expected	Yes or probable but not strictly required	24

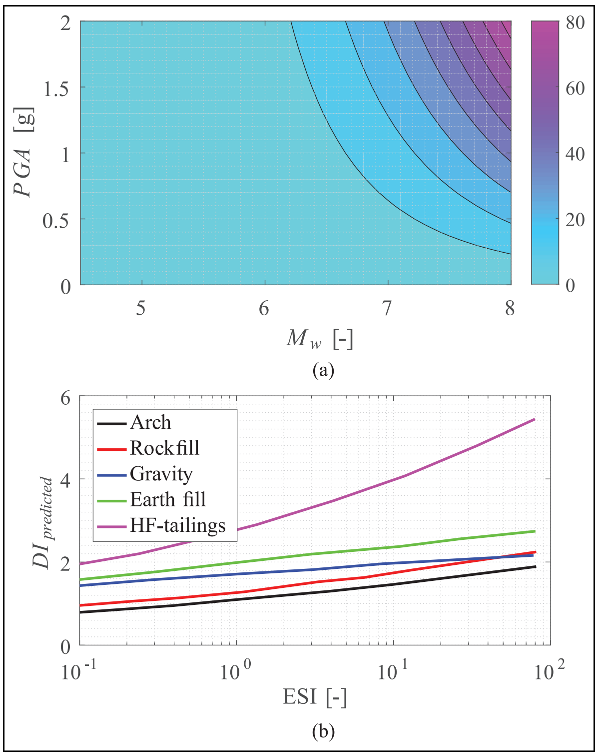

Figure 6. Quantification of elements in $DF_{predicted}$:.(a) graphical representation of ESI, (b) empirical DIpredicted; adopted from work of Bureauand and Ballentine.[8]

The only remaining term in equation (6) is $DF_{predicted}$. First, an intermediary term is defined as predicted damage index, $DI_{predicted}$. This is an empirical index developed by Bureauand and Ballentine[8] from observed seismic performance of dams during past earthquakes. Note that it is completely different from analytical damage indices which is used in the numerical simulations.[65,66] $DI_{predicted}$ depends on (1) the dam type and (2) site tectonic environment and seismic hazard parameters. The latter one is expressed by earthquake severity index (ESI),[67] Figure 6(a)

$$ESI = PGA \times (M_w - 4.5)^3 \tag{8}$$

where PGA is peak ground acceleration in g, and M_w is the moment magnitude (or Richter). PGA for the United States (and with more detailed information for California) is shown in Figure 7. The seismic hazard maps are provided in different probability of exceedance based on the required return period.

Next, $DI_{predicted}$ can be obtained from the following relations, Figure 6(b)

$$DI_{predicted} = \begin{cases} 1.08\exp(0.297\log(\mathrm{ESI})) & \text{Arch} \\ 1.28\exp(0.296\log(\mathrm{ESI})) & \text{Rockfill} \\ 1.69\exp(0.139\log(\mathrm{ESI})) & \text{Gravity} \\ 1.96\exp(0.185\log(\mathrm{ESI})) & \text{Earthfill} \\ 2.77\exp(0.356\log(\mathrm{ESI})) & \text{HF}-\text{tailings} \end{cases} \tag{9}$$

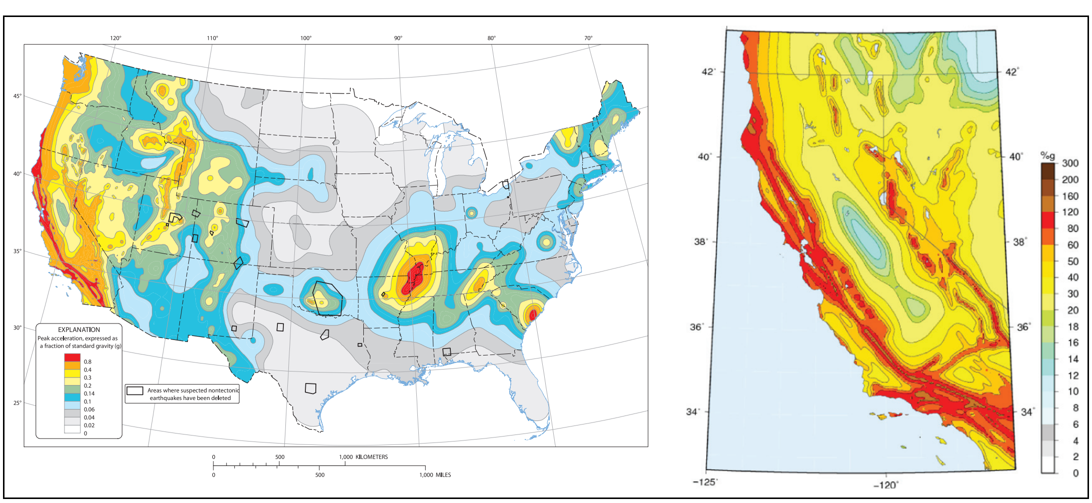

Figure 7. Two-percent probability of exceedance in 50 years map of PGA for USA (left) and California (right).

Earthquake hazard dependents on the location of dam site with respect to the seismic sources and, regional and site-specific geologic characteristics. It is characterized by identification of all the potential earthquake sources (e.g. faults or areal seismic source zones). Local topographic conditions (e.g. hills, valleys, and canyons) can also modify the character of earthquakes. Next, attenuation relationships (also known as ground motion prediction equations—GMPE) are used to derive earthquake intensities to be used in performance assessment. This step is usually refereed to as PSHA. GMPEs provide estimated values of ground shaking intensity parameters (e.g. PGA) for user-specified combinations of earthquake magnitude, M, and site-to-source distance, R.[68] The most famous functional form for GMPEs is[69]

$$\log(\mathrm{IM}) = \log(b_1) + \log[f_1(M)] + \log[f_2(R)] + \log[f_3(M,R)] + \log[f_4(E_i)] + \log(\varepsilon) \tag{10}$$

where IM is intensity measure, E_i is the possible source, site and geologic and geotechtical structures effects; ε is a parameter that represents the uncertainty and errors. Samples of GMPEs are[70]

Atkinson and Boore[71]

$$\log PGA = b_1 + b_2(M-6) + b_3(M-6)^2 + b_4 r + b_5 \log r + b_6 G_B + b_7 G_C \tag{11}$$

where PGA is in g, and $r = \sqrt{d^2 + h^2}$,

- For randomly oriented horizontal component: $b_1 = -0.105$, $b_2 = 0.229$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.778$, $b_6 = 0.162$, $b_7 = 0.251$, $h = 5.57$;
- For larger horizontal component $b_1 = -0.038$, $b_2 = 0.216$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.777$, $b_6 = 0.158$, $b_7 = 0.254$, $h = 5.48$.

Moreover

- For $V_{S30} > 750$ m/s, $G_B = 0$, $G_C = 0$;
- For $360 < V_{S30} < 750$ m/s, $G_B = 1$, $G_C = 0$;
- For $180 < V_{S30} < 360$ m/s, $G_B = 0$, $G_C = 1$.

Pezeshk et al.[72]

$$\log PGA = \theta_1 + \theta_2 M_w + \theta_3 M_w^2 + \theta_4 R + \theta_5 \log\left(R + \theta_6 10^{\theta_7 M}\right) \tag{12}$$

where PGA is in cm/s^2, $\theta_1 = -3.4712$, $\theta_2 = 2.2639$, $\theta_3 = -0.1546$, $\theta_4 = 0.0021$, $\theta_5 = -1.8011$, $\theta_6 = 0.0490$, $\theta_7 = 0.2295$. All records from rock sites.

Having $DI_{predicted}$ from equation (9) or equivalently Figure 6(b), $DF_{predicted}$ in equation (6) is defined as

Table 2. Indicator of historic damage to dams.

Dam type	DR_{factor}
Arch, arch-gravity	1
Multiple-arch, arch-buttress	3
Concrete gravity	2
Concrete gravity buttress	3
Masonry	4
Earthfill, composite	3
Concrete-face rockfill	1
Earth-core rockfill	1
Hydraulic fill, tailings	6
Unclassified	5

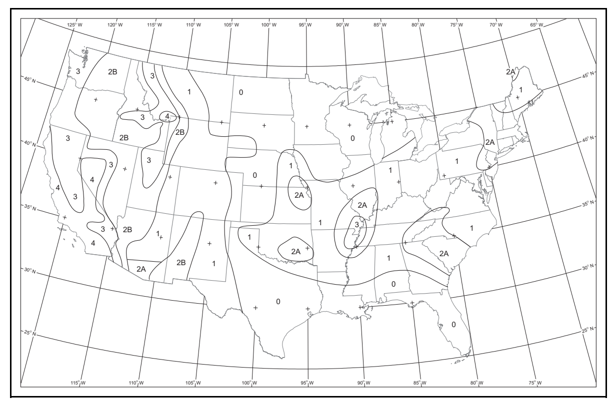

Figure 8. 1994 Uniform Building Code zone map, zones are identified from 0 to 4.

$$DF_{predicted} = 2.5 \times DI_{predicted} \tag{13}$$

where the coefficient 2.5 was empirically selected by Bureauand and Ballentine.[8]

Note that in equation (6), the term $DF_{predicted}$ can be substituted by $DF_{assumed}$ as

$$DF_{assumed} = DR_{factor} + SZ_{factor} \tag{14}$$

where DR_{factor} is a dam-dependent damage rating factor and is obtained from Table 2, and SZ_{factor} is the seismic zoning factor which depends on the code-based seismic zone factor of the site. For the United States, the 1997 Uniform Building Code (UBC) has six seismic risk zones as 0, 1, 2A, 2B, 3, and 4 (Figure 8). They can be correlated with SZ_{factor} as shown in Table 3.

Finally, the risk class of different dams can be obtained based on the total risk factor and Table 4. Moreover, it is possible to compare RF_{total} from a portfolio of dams in order to prioritize the most vulnerable dams and perform the subsequent rehabilitation.

Application on severely shaken dams

The revised methodology in the previous section is applied to a group of concrete dams shaken by

Table 3. UBC-based site classification.

UBC seismic zone	0	1	2A	2B	3	4
SZ_{factor}	1	2	3	4	5	6

Table 4. Definition of dam risk class.

Dam risk class	I (low)	II (moderate)	III (high)	IV (extreme)
RF_{total}	2–25	25–125	125–250	> 250

relatively strong motions as reported by Nuss et al.[73] The list of these dams including their structural properties are summarized in Table 5. Furthermore, the earthquake event (including the PGA and magnitude) which is occurred at the dam site and the observed damage (if any) are reported in Table 5 as well.

The semi-quantitative method is implemented on the selected dams and all the intermediary terms are summarize in Table 4. Note that the information on the population and property at risk are collected from available information on the web and also pictures taken by Google map, Figure 9. In majority of terms, the smoothed proposed curves are used. Downstream risk factor is computed based on the detailed method, $RF_{downstream}$ in Figure 4, and the NID proposed method, $RF^{NID}_{downstream}$ in Table 1. Moreover, $DF_{predicted}$ is computed for all the dams, while $DF_{estimated}$ is only provided for those dams in the United States. Subsequently, four total risk factors are computed (using two $RF_{downstream}$ and two DF) and reported as RF^{i}_{total} (Figure 10(a))

- RF^{1}_{total} = function of $(RF_{downstream}, DF_{predicted})$
- RF^{2}_{total} = function of $(RF^{NID}_{downstream}, DF_{predicted})$
- RF^{3}_{total} = function of $(RF_{downstream}, DF_{estimated})$
- RF^{4}_{total} = function of $(RF^{NID}_{downstream}, DF_{estimated})$

Dashed lines in this figure correspond to the dam risk class in Table 4. The major observation is that the risk factors computed by the $DF_{estimated}$ are larger than those based on $DF_{predicted}$. Finally, Figure 10(b) quantifies the uncertainty in RF^{1}_{total} and RF^{2}_{total}. Overall, the variation of these two assumptions is acceptable. Variation is zero in some cases, and it is as high as 40 in some others. Of 18 dams, 10 in this group exceed the RF_{total} of 125, meaning that based on Table 4, they are classified as high-hazard dams. Total risk factor in other five dams (i.e. ID 4, 8, 14, 15, and 16) is very close to 125 which makes them a critical candidate for future re-evaluation. Dams with ID 3, 11, and 13 have moderate risk factor.

Google map photos of dams

Detailed finite element simulation of high-hazard dams

After the initial screening and classification of a dam portfolio, those with highest RF_{total} are candidate for detailed finite element simulation. There have been many papers, reports, and guidelines on different approaches for numerical simulation of dams subjected to seismic excitation. One can emphasize on the national codes such as those published by USACE,[74–76] Federal Energy Regulatory Commission (FERC),[3,38] CDA,[49] Italian dam guideline,[77] and many bulletins published by ICOLD.[78,79] One of the most recent guidelines in finite element analysis of concrete dams can be found in.[80] Finite element discretization and detailed time integration procedure can be found in works of Chopra[81] and Zienkiewicz and Taylor.[82] Following is a summary of main factors that should be considered in numerical analysis of dams (depending on the level of complexity and the associated risk):

- Staged construction process[83]
- Fluid-structure interaction.[84,85]
- Soil-structure interaction.[86,87]
- Fluid-fracture interaction.[88,89]
- Thermal loads and thermal analysis?[90]
- Ice load[91]
- Aging of concrete[92]
- Alkali-aggregate (-silica) reaction[93]
- Creep[94]
- Concrete fracture and joint modeling[95]
- Concrete cracking and crushing[96]
- Concrete heterogeneity[97]

Developing a reliable FEM for linear or nonlinear analysis of dams is a challenging task and should be calibrated using the existing condition of the dam. Calibration is usually utilized on the static and thermal properties of the material. The dynamic properties

Table 5. Characteristics of the concrete dams shaken by significant earthquake, adapted from Nuss et al.[73]

ID	Dam	Year completed	Country	Type	Height (m)	Crest (m)	Concrete volume (m^3)	Reservoir storage (m^3)	Earthquake (date)	*R* (km)	*M*	PGA (g)	Notes
1	Lower Crystal Springs	1890	USA	Gravity	47	183	4450	71,430,934	San Francisco (18 April 1906)	0.4	8.3	0.6	Not the slightest crack
2	Koyna	1963	India	Gravity	103	807	1,555,000	2,797,400,000	Koynanagar (11 December 1967)	3	6.5	0.5	Cracks in both faces
3	Williams	1895	USA	Gravity	21	27	65	197,357	Loma Prieta (17 October 1989)	9.7	7.1	0.6	No damage
4	Bear Valley	1988	USA	Gravity	28	110	130	91,277,657	Big Bear (29 June 1992)	14.5	6.6	0.57	No structural damage
5	Gohonmatsu	1900	Japan	Gravity	33	110	22,000	772,000	Kobe (17 January 1995)	1	7.2	0.83	No damage of this masonry dam
6	Shih Kang	1977	Taiwan	Gravity	21.4	357	141,300	3,380,000	Chi-Chi (21 September 1999)	0	7.6	0.51	Vertical displacement of 9-m, concrete rapture
7	Mingtan	1990	Taiwan	Gravity	82	–	–	14,000,000	Chi-Chi (21 September 1999)	12	7.6	0.45	No damage
8	Kasho	1989	Japan	Gravity	46.4	174	87,000	7,450,000	Western Tottori (6 October 2000)	3–8	7.3	0.54	Cracks in control building
9	Takou	2007	Japan Â	Gravity	77	322	328,000	9,680,000	Tohoku (11 March 2011)	109	9	0.38	Cracking of gatehouse
10	Miyatoko	1993	Japan Â	Gravity	48	256	329,000	5,400,000	Tohoku (11 March 2011)	135	9	0.32	No damage
11	Gibraltar	1920	USA	Arch	52	183	2120	12,332,351	Santa Barbara (29 January 1925)	–	6.3	0.35	No damage
12	Pacoima	1929	USA	Arch	113	180	6400	4,658,861	San Fernando (9 February 1971) + Northridge (17 January 1994)	5–18	6.7	0.6	Joint opening near thrust block 2" Joint opening between arch and thrust block
13	Ambiesta	1956	Italy Â	Arch	59	145	29,000	3,520,000	Gemona-Friuli (6 May 1976)	20	6.5	0.36	No damage
14	Rapel	1968	Chile Â	Arch	111	270	695,000	680,000,000	Santiago (3 March 1985) + Maule (27 February 2010)	45–232	8.3	0.31	Damage to spillway and intake tower, cracked pavement
15	Techi	1974	Taiwan	Arch	185	290	–	218,150,000	Chi-Chi (21 September 1999)	85	7.6	0.5	Local cracking of curb at crest
16	Shapai RCC	2003	China Â	Arch	132	250	356,000	18,000,000	Wenchuan (12 May 2008)	32	8	0.35	No damage
17	Hsinfengkiang	1959	China Â	Buttress	105	440	–	11,500,000,000	Reservoir (19 May 1962)	1.1	6.1	0.54	Horizontal cracks in top of dam
18	Sefidrud	1962	Iran	Buttress	106	414	820,000	1,765,000,000	Manjil (21 June 1990)	–	7.7	0.71	Horizontal cracks near crest, minor displacement of blocks

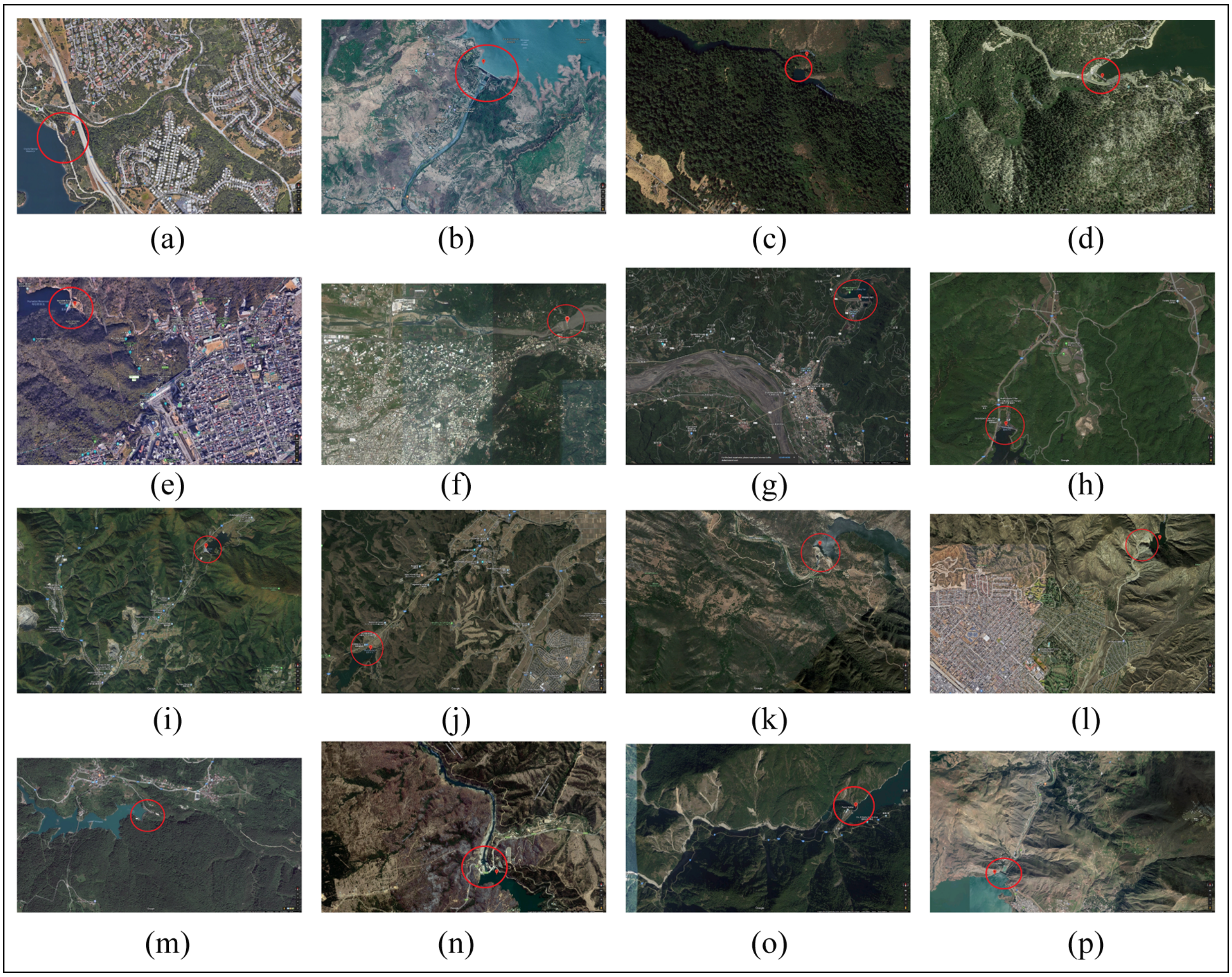

Figure 9. Google map of the selected dams and the downstream development: (a) ID 1, (b) ID 2, (c) ID 3, (d) ID 4, (e) ID 5, (f) ID 6, (g) ID 7, (h) ID 8, (i) ID 9, (j) ID 10, (k) ID 11, (l) ID 12, (m) ID 13, (n) ID 14, (o) ID 15, and (p) ID 18.

estimated either using the laboratory tests or statistics of the existing literature. Results of the finite element simulations should be compared with those recorded during the operational period of the structure. Figure 11 proposes a general methodology for system identification and calibration of the dam structure. Finally, Figure 12 is proposed for detailed seismic performance evaluation and risk assessment of dams in the context of fragility analysis. The procedure starts by evaluating the current condition of the dam by including details as much as possible/economic. Next, the outputs from finite element simulations are compared with predefined criteria. It is quite difficult and challenging. For instance, what constitutes failure? Many dam guidelines specific that the dam cannot have an uncontrolled release of the reservoir. Is an uncontrolled release of the reservoir a trickle of water, a spurt, a steady flow that drains the reservoir, a flow that is above downstream capacity, or a large total sudden release of water? If the potential damage exceeds the threshold one, extra studies are required on repair cost, downtime, and so on.

It is important to take into account the uncertainties associated with different different finite element inputs (e.g. material parameters, loading, and damping), modeling assumptions (e.g. pressure-based and displacement water simulation), software, and solution techniques. Accounting for these uncertainties is a daunting task and is not typically taking into account. Different researchers might use different approaches and get various answers for a same problem. Example, of this variation is shown in Figure 13 for the natural frequencies and crown cantilever displacement of a benchmark arch dam during the ICOLD12 workshop.[99] Even for a linear elastic analysis of an arch dam, there is a considerable variation in the reported outputs by 12 participants.

In order to support the field observations (Table 5) and semi-quantitative method (Table 6) and to integrate the numerical simulations in this context, 1 of the 18 case study dams is numerically analyzed. Koyna gravity dam is selected as a vehicle for this comparison. It is the most famous case study among the dam

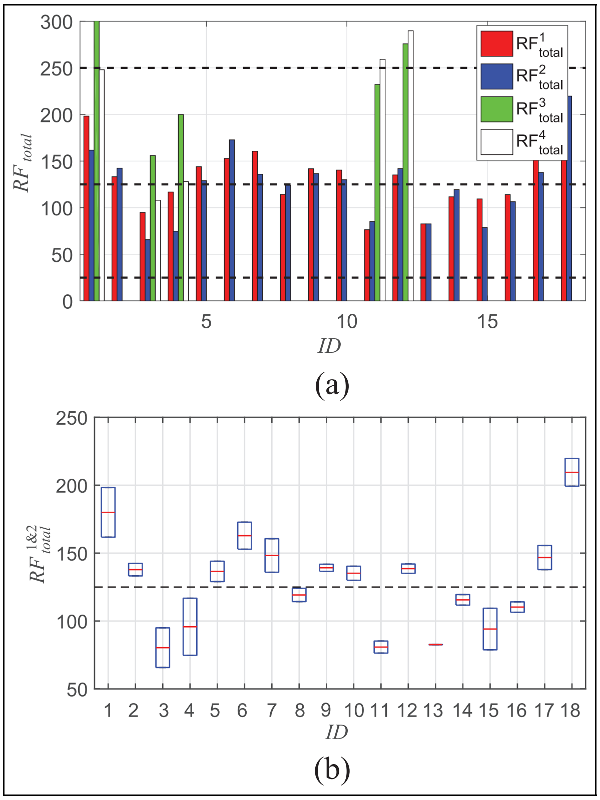

Figure 10. Total risk factor of the studied dams: (a) comparison of four models and (b) uncertainty of RF total.

researchers. Nearly all the existing papers follow the 2D model of the dam. Detailed nonlinear analysis of this dam by the authors can be found in works of Hariri-Ardebili and colleagues.[66,100] However, in order to add the uncertainty quantification on top, the results of the damage analysis by more than 15 researchers are illustrated in Figure 14. In all these studies, the damage is localized to the neck area and the concrete–rock interface. Except some minor differences in material properties, the major features in each simulation can be summarized as follows:

- Ghrib and Tinawi[101] used damage mechanics approach for concrete, along with rigid foundation and added mass water.
- Cervera et al.[102] compared the rate-dependent and rate-independent isotropic concrete damage models. Water and foundation effects were taken into account.
- Lee and Fenves[96] used a new plastic-damage model with plane stress formulation. Dam-water interaction was included by an added mass for incompressible water, while the foundation was assumed to be rigid.
- Guanglun et al.[103] developed a fracture mechanics model for concrete cracking with the re-mashing ability. Foundation was assumed to be rigid, and apparently, the fluid-structure interaction was ignored.
- Mirzabozorg and Ghaemian[104] analyzed the three-dimensional (3D) unit-thickness finite element mesh with a proposed smeared crack model. Hydrostatic load was considered; however, the water and foundation interactions were neglected.

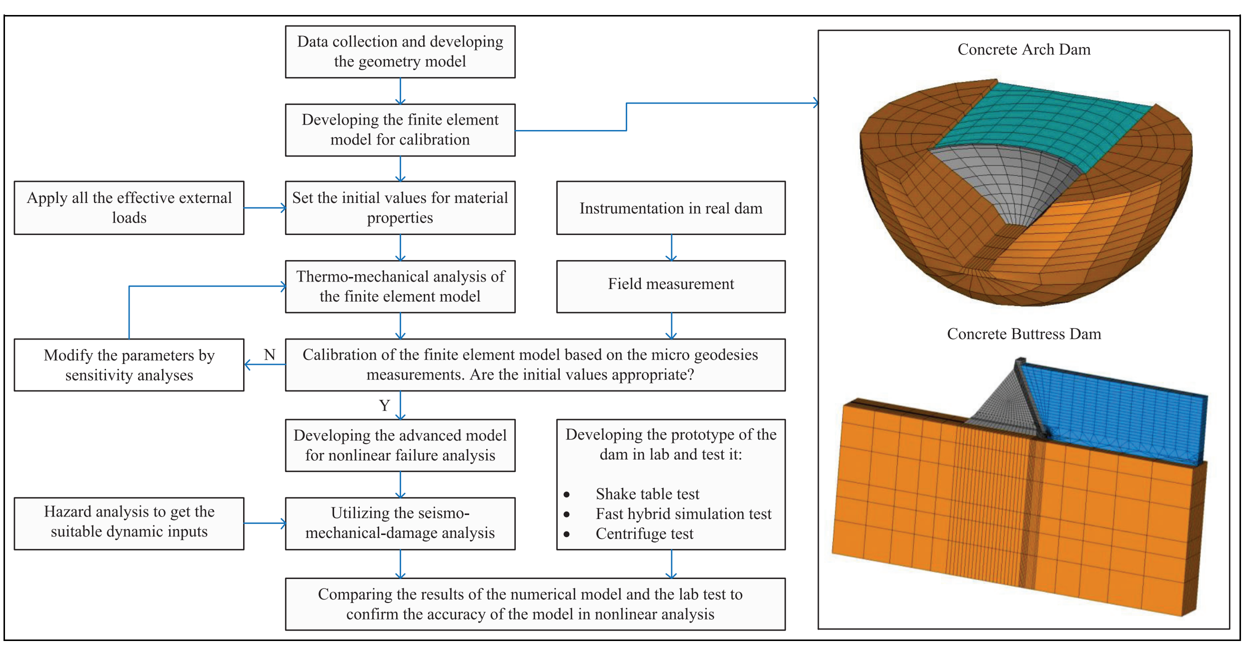

Figure 11. System identification and model calibration of dams.[98]

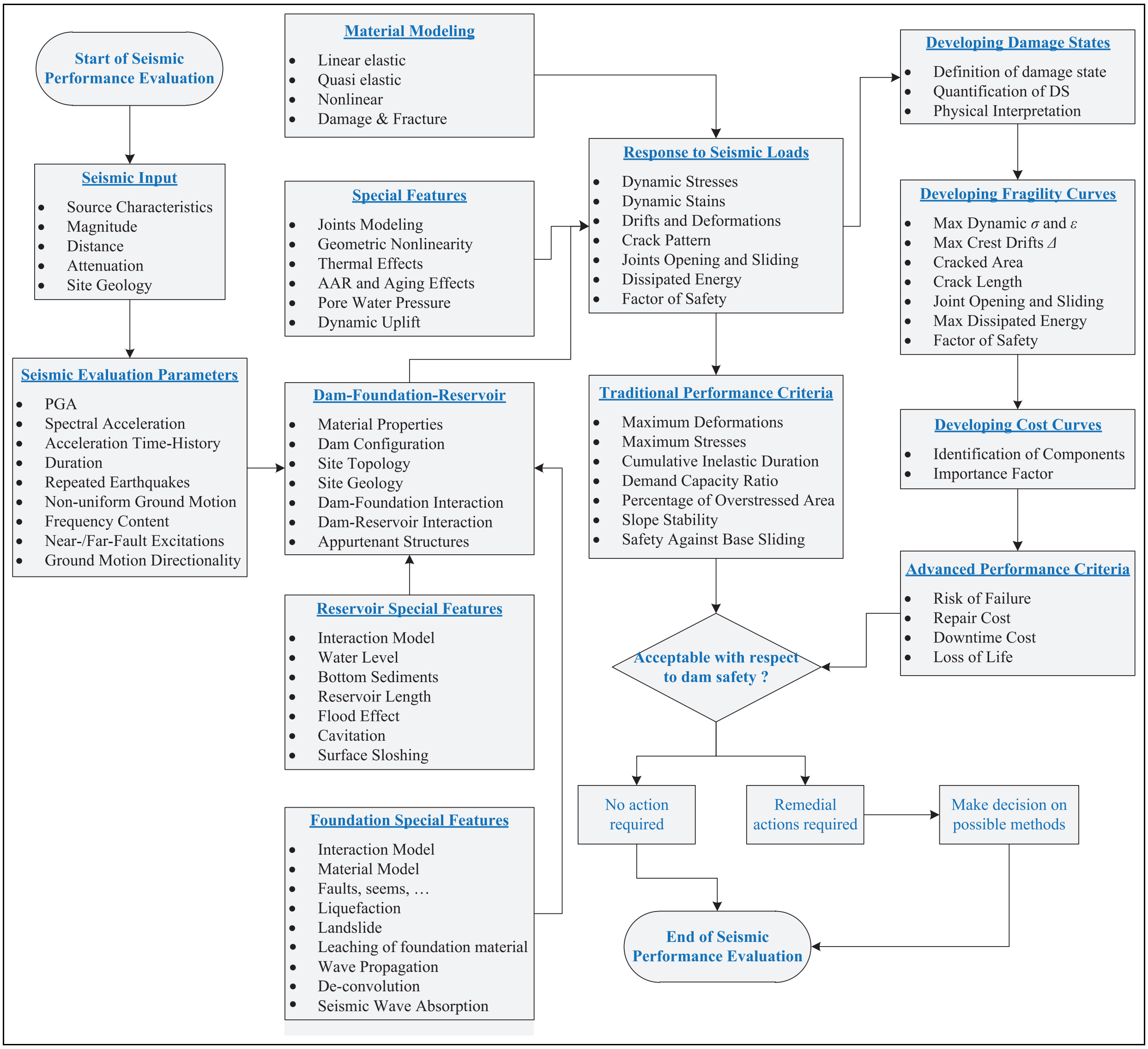

Figure 12. Big picture for seismic performance evaluation of dams and risk assessment.

- Calayir and Karaton[105,106] applied two different models of coaxial rotating crack model with biaxial failure envelope, and an orthotropic damage model. Lagrangian approach was used for fluid-structure interaction, while the foundation was rigid.
- Pan et al.[107] used three models of plastic damage, Drucker–Prager elasto-plastic, and extended finite element for damage analysis. Reservoir was modeled by Westergaard added mass, along with rigid foundation.
- Omidi et al.[108] developed a 3D plastic-damage model with constant and damage-dependent damping mechanism. Eulerian approach was used for reservoir, along with rigid foundation.
- Hariri-Ardebili et al.[100] compared the rotating smeared crack model with and without fracture energy effects. Pressure-based fluid elements were used with massless foundation.
- Zhang et al.[109] used concrete damage plasticity including the strain hardening or softening. Model had a rigid foundation with Westergaard added mass.
- Hariri-Ardebili and Saouma[66] used damage plasticity for concrete and Drucker–Prager elasto-plastic for rock including water–rock–dam interaction.
- Huang[110] used damage plasticity model to evaluate mesh size dependency.
- Chen et al.[111]used 3D polyhedron scaled boundary finite element method for damage simulation. Added mass approach was used with rigid foundation. Quadrilateral and triangular elements were compared.

Table 6. Seismic risk ranking of concrete dams shaken by significant earthquake.

ID	$RF_{capacity}$	RF_{height}	RF_{age}	$RF_{population}$	$RF_{property}$	$RF_{downtime}$	$RF_{downstream}$	$RF^{NID}_{downstream}$	ESI	$DI_{predicted}$	$DF_{predicted}$	DR_{factor}	SZ_{factor}	$DF_{assumed}$	RF^{1}_{total}	RF^{2}_{total}	RF^{3}_{total}	RF^{4}_{total}
1	6.5	6.9	5.6	7	8	4	19	12	32.9	2.1	5.2	2	6	8	198	162	304	248
2	7	9	3	2	6	2	10	12	4.0	1.8	4.6	2	–	–	133	142	–	–
3	1.5	4.5	5.5	1	5	2	8	2	10.5	1.9	4.9	2	6	8	95	66	156	108
4	6.7	5.2	2.1	3	6	2	11	2	5.3	1.9	4.7	2	6	8	117	75	200	128
5	2.5	5.8	5.5	4	7	4	15	12	16.3	2.0	5.0	2	–	–	144	129	–	–
6	3.8	4.5	2.4	7	9	4	20	24	15.2	2.0	5.0	2	–	–	153	173	–	–
7	5.1	8.4	2	6	7	4	17	12	13.4	2.0	4.9	2	–	–	161	136	–	–
8	4.5	6.8	2	2	6	2	10	12	11.9	2.0	4.9	2	–	–	114	124	–	–
9	4.8	8.1	1.2	3	6	4	13	12	34.6	2.1	5.2	2	–	–	142	137	–	–
10	4.2	7	1.9	3	7	4	14	12	29.2	2.1	5.2	2	–	–	140	130	–	–
11	5	7.2	4.6	2	5	2	9	12	2.0	1.2	3.0	3	6	9	76	85	232	259
12	4.1	9	4.3	7	11	4	22	24	6.4	1.4	3.4	1	6	7	135	142	276	290
13	3.9	7.5	3.3	4	6	2	12	12	2.9	1.2	3.1	1	–	–	83	83	–	–
14	7	9	2.7	2	6	2	10	12	17.0	1.6	3.9	1	–	–	112	119	–	–
15	7	9	2.6	2	6	2	10	2	14.9	1.5	3.8	1	–	–	109	79	–	–
16	5.3	9	1.5	4	8	2	14	12	15.0	1.5	3.8	1	–	–	114	106	–	–
17	7	9	3.1	4	8	4	16	12	2.2	1.8	4.4	3	–	–	156	138	–	–
18	7	9	3	7	9	4	20	24	23.3	2.0	5.1	3	–	–	199	220	–	

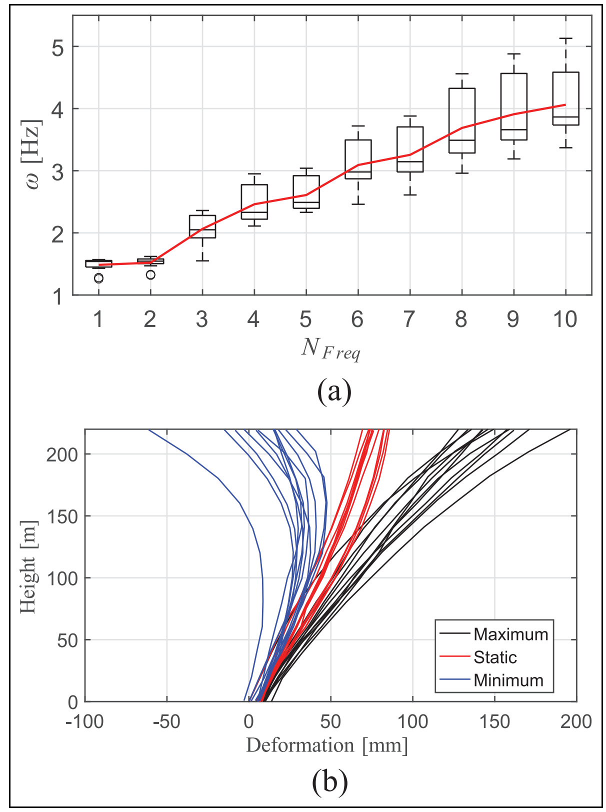

Figure 13. Summary of ICOLD12 Benchmark Workshops: (a) natural frequency and (b) displacement.

- Huang[112] used an extended finite element method including the effects of branching and intersecting cracks for damage analysis. Foundation and reservoir interactions were also taken into account.
- Poul and Zerva[113] used the concrete damage plasticity with two foundation types: standard massless and massed foundation.

Summary

As can be seen, there are numerous methods to prioritize a portfolio of dams subjected to potential seismic loadings. This article is intended to compile the current state of practice. It is not known at this time the effectiveness of these various methods. However, the authors believe PFMA, risk analyses, and portfolio prioritizations have greatly improved the dam safety process and has helped portray the condition of dams to dam safety officials and decision-makers. A lot still has to be accomplished, but the dams industry seems to be headed in the right direction by using risk-based approaches to prioritize portfolios of dams. Without these methods, the industry would probably be wastefully spending limited funds on unnecessary rehabilitations. It is apparent that there is uncertainty in the risk

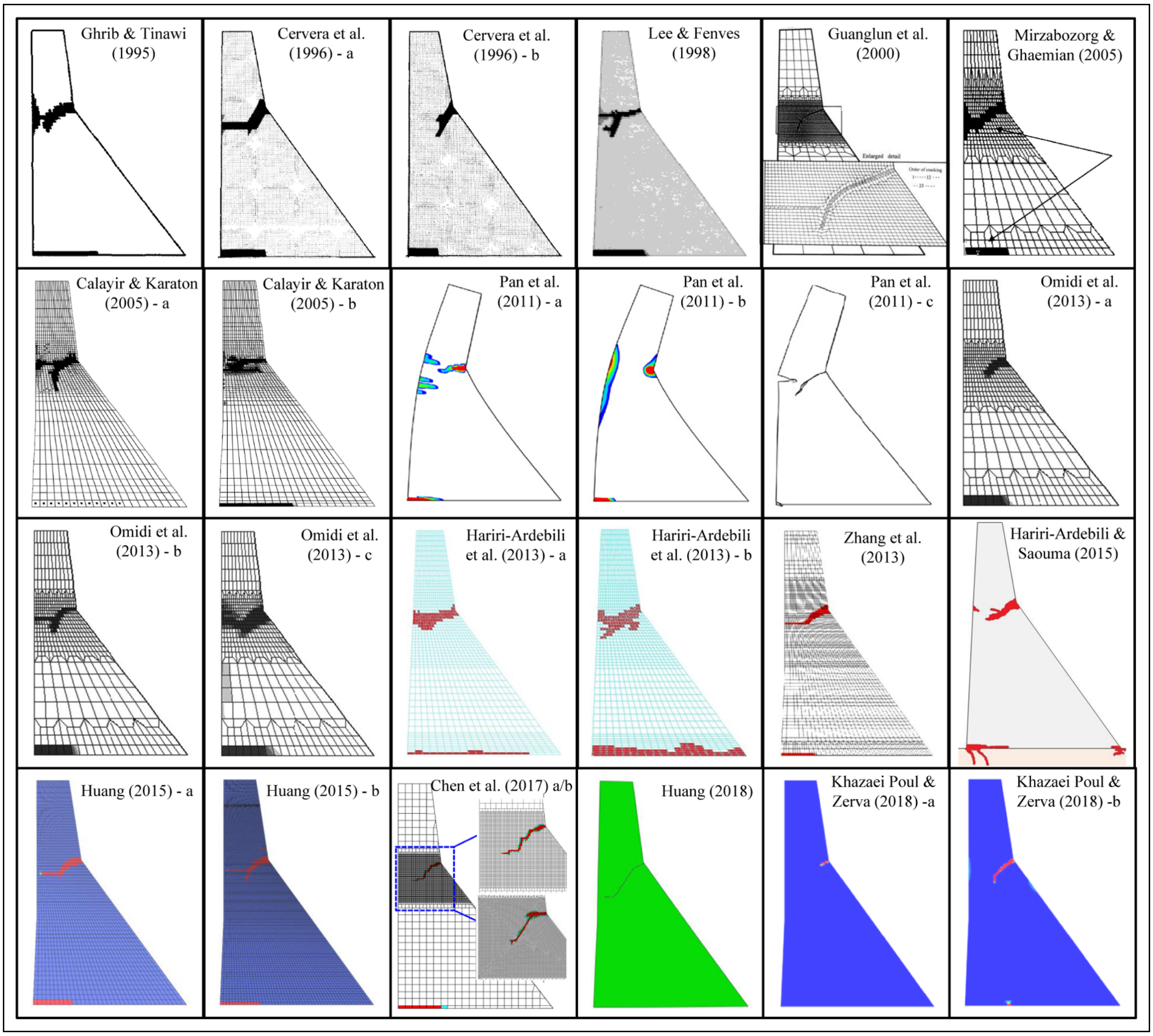

Figure 14. Crack profile of the Koyna Dam computed by different researchers under various assumptions.

methods, in the analytic methods that feed information into the risk process, and in the decision criteria. Addressing the uncertainties seems like an important next step and area of study.

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