Risk-based seismic safety assessment of concrete gravity dams with uncertainty quantification

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ABSTRACT

Risk-based seismic safety assessment of concrete gravity dams with uncertainty quantification

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Concordia University,2024

Dams are vital national assets that play a crucial role in water storage, hydroelectric power generation, and flood control. Globally, over 61,000 large dams have surpassed 50 years of service, and many show signs of deterioration. With over 300 dam failures recorded worldwide, the potential for catastrophic damage remains alarmingly high if these aging structures are not properly maintained and upgraded. Further, many of the existing dams were built upon outdated standards, and there is an increase in seismic hazards making it imperative to reevaluate their seismic performance to align with current safety standards. The need for improved dam safety measures is urgent, as dam owners, regulators, and policymakers grapple with the challenges of ensuring the structural integrity of aging dams in the face of growing risks. A key solution is shifting from traditional safety approaches to a modern, risk-based methodology, which addresses safety concerns more efficiently and economically. Various, global agencies have developed risk-based safety assessment guidelines; however, these often lack systematic implementation frameworks and sufficient reference studies, making them difficult for dam owners to adopt effectively. Furthermore, various uncertainties can impact the risk assessment and can complicate efforts to ensure dam safety. In this context, this research investigates uncertainties impacting seismic risk assessments for dams, including modeling choices, ground motion selection, aging, and material variability. Case studies of the Koyna Dam and Pine Flat Dam were used to evaluate these factors at each stage of performance evaluation: system response, fragility, and risk assessment. Key findings indicate that dam-foundation-reservoir (DFR) models incorporating acoustic elements exhibit less variability in system response, regardless of model complexity and solution procedure. Ground motion derived from the conditional mean spectrum (CMS) method yields better fragility estimates than the ASCE 7-16 standard, particularly for moderate to severe damage states. Additionally, aging and material variability significantly affect the dynamic characteristics of dams, with increased failure probabilities correlating with both age and return period. Based on these findings, the research proposes a comprehensive, systematic framework for risk-based seismic safety evaluation. This framework aligns with safety assessment objectives and ensures optimal use of computational resources.

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To my late father,

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List of Abbreviations

ALARP	As low as reasonably practicable
BMRA	Bayesian method for risk analysis
CDA	Canadian Dam Association
CDPM2	Modified concrete damage plasticity model
CGD	Concrete gravity dam
CMS	Conditional mean spectrum
CWC	Central Water Commission
D	Dam only
DAG	Directed acyclic graph
DAR	Damage area ratio
DBE	Design basis earthquakes
DF	Dam-foundation
DFR	Dam-foundation-reservoir
DI	Damage indices
DR	Dam-reservoir
DI_L	Local damage index
DI_s	Damage indices
DI_G	Global Damage Index
FEMA	Federal Emergency Management Agency
FSI	Fluid-structure interaction
FTA	Fault tree analysis
ETA	Event tree analysis
GCIM	Generalized conditional intensity measure
IM	Intensity measures
LEM	Limit equilibrium method
LOL	Loss of life
MCE	Maximum credible earthquake
NCD	Normalized crest displacement
OBE	Operational basis earthquakes
PBEE	Performance-Based Earthquake Engineering
PE	Probability of exceedance
PEER	Pacific Earthquake Engineering Research
PFMA	Potential failure mode analysis
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PGD	Peak Ground Displacement
PMCD	Probabilistic model code for concrete dams
PSHA	Probabilistic Seismic Hazard Analysis
RBA	Risk-Based Approach
SBA	Standard-Based Approach
SPANCOLD	Spanish National Committee on Large Dams

SRA	Structural reliability analysis
SSI	Soil structure interaction
UHS	Uniform hazard spectrum
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
USSD	United States Society on Dams
VI	Vulnerability Index

Chapter 1

Introduction

Dams are vital national assets, providing substantial benefits such as water storage, power generation, and flood control. However, they can become liabilities if not adequately maintained and operated, posing significant risks to communities and critical infrastructure downstream. Proper management, routine inspections, and adherence to contemporary safety standards are essential to ensure the continued safe utilization of these structures and uphold public safety [1]. With over 61000 large dams worldwide [2], concerns about the safety of aging dams have emerged on a global scale. Many large dams have exceeded the 50-year threshold, with others approaching the century mark [3], [4]. Structural, operational, and budgetary deficiencies, coupled with inconsistent safety assessment practices, raise significant concerns about dam safety [4], [5]. Moreover, seismic design approaches employed during the construction of most existing dams are outdated compared to current knowledge [6], [7]. The implications of dam failures have become even more catastrophic due to changes in downstream population settlement and infrastructure development [8]. Although dam failures are infrequent, they have high-risk potential, as evidenced by the 300 major dam failures worldwide [9], [10], [11]. To maximize sustainable benefits while avoiding catastrophic failure, it is critical to assess the seismic safety of existing dams [12]. Re-evaluating the safety of aging dams against modern standards is crucial for improving operational efficiency and withstanding extreme seismic events [13].

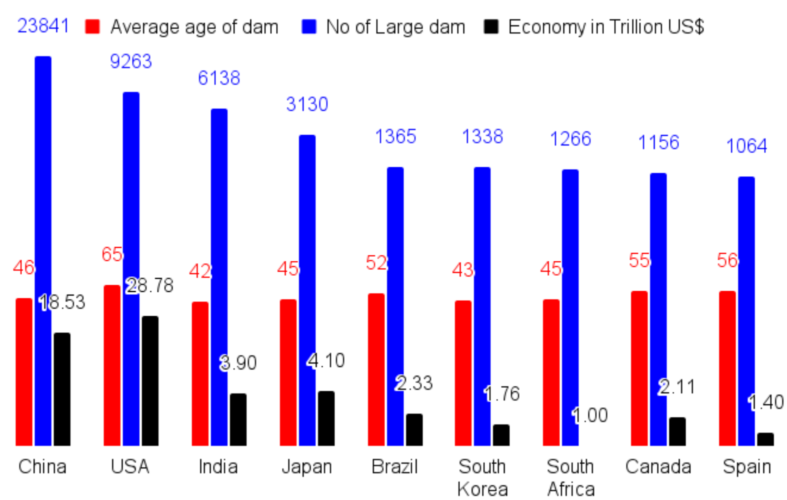


Figure 1. Countries with an inventory of large dams [4]

In this line, Figure 1 shows the top ten countries in terms of their inventory of large dams, the average age of these dams, and the size of their respective economies. A clear correlation emerges between a nation's economic scale and the number of large dams within its borders. Notably, China and the United States, boasting the largest economies, also claim leadership in dam infrastructure development. However, the average age of dams displays considerable diversity across countries. The United States distinguishes itself with the highest average age of dams, while India possesses a substantial number of dams with a relatively youthful average age. Canada's approach to dam infrastructure emerges as a striking example of a balanced strategy. With 1156 large dams and an average dam age of 55 years, Canada neither leads in dam quantity nor boasts the oldest dams [14]. This implies a judicious approach to dam construction, potentially emphasizing the maintenance of existing infrastructure and meticulous planning for new projects.

The concrete gravity dams have generally demonstrated resilience during earthquakes, exemplified by cases like the Koyna dam in India, the Pacoima dam in the USA, the Sefid-rud dam in Iran, and the Hsinfengkiang dam in China [15], [16], [17], [18], [19]. However, even if there have been instances of significant damage necessitating repairs and reinforcement, it's essential to note that no dam has yet faced a maximum credible earthquake (MCE) with a full reservoir, underscoring the continuous need for assessment and maintenance throughout their operational lifespans [8], [20].

The adoption of advanced safety assessment frameworks such as risk-based approach (RBA) and Bayesian model risk analysis (BMRA), in addition to the conventional standard-based approach (SBA), can significantly enhance the safety evaluation process [21], [22]. Considering these factors, ongoing scientific and professional research plays a pivotal role in this field. Quantifying seismic safety is paramount, encompassing considerations like structural robustness, operational safety, monitoring systems, and emergency readiness, all of which contribute to decision-making and the resilience of communities [21], [22]. While the construction of new dams is anticipated to decline, the rehabilitation of existing dams will become more prominent to maintain aging infrastructure [4], [5].

1.1. Review of safety assessment practices

This section scrutinizes various safety assessment practices employed in evaluating the safety of existing dams. It delves into three fundamental approaches: the SBA, the RBA, and the BMRA. Each approach is critically examined regarding its advantages and limitations, offering a comprehensive understanding of their applicability.

1.1.1. RBA as an improvement to SBA

SBA assesses structural safety by calculating safety factors FS = R/S, where R represents structural capacity, S denotes the demand, and defensive design measures are implemented [23]. Concrete dams are traditionally evaluated using the well-established limit equilibrium method (LEM), treating the dam as a rigid body [24], [25]. The FS in LEM is expressed as a function of load and material parameters as shown in Equation 1 [26], [27].

$$FS = \mathrm{f}(\mathrm{W}, \mathrm{U}, \mathrm{T}, \mathrm{c}, \varphi, \mathrm{A}, \alpha, \mathrm{FS}\varphi, \mathrm{FSc}) \qquad 1$$

Where W denotes weight; U is uplift force; T is shearing force; c and φ denotes cohesion and angle of friction at the considered plane, respectively; A is the area of rupture; α is the inclination of the sliding with respect to horizon; and lastly, $\mathrm{FS}\varphi \geq 1$ and $FSc \geq 1$ are the safety factors with respect to friction and cohesion, respectively. The SBA appears straightforward but carries inherent limitations. It treats all loads uniformly, relies on statics input parameters, confines analysis to service loads, lacks a comparison across different structure and performance modes, and showcases non-uniform practices in defining relevant design criteria. SBA also involves "blind" risk trade-offs, lacking a clear picture of existing safety concerns and hindering informed decision-making. Moreover, when determining the safety factor in limit state scenarios, the SBA approach provides limited insights into failure probability [28]. Due to these significant uncertainties, a higher FS in SBA does not necessarily imply a lower risk [29], [30].

Further, given the significant uncertainties associated with SBA, a shift to RBA is essential for efficient safety assessment [31], [32]. There is an increasing demand for informed decision-making to prioritize rehabilitation measures across a portfolio of dams or within a dam to make the best use of limited resources

[33]. Reliability assessment is at RBA's core and has been utilized in high-hazard industries for over 40 years. It was, however, first applied to dams in 1980 to supplement the well-established SBA [21], [34]. Existing dam safety practices that meet the goal of informed decision-making include (i) what-if/checklist analysis, (ii) preliminary hazard analysis, (iii) preliminary risk analysis, (iv) coarse risk analysis, and (v) Pareto analysis, (vi) root cause analysis, (vi) change analysis, (vii) common cause failure analysis, (ix) failure modes and effects analyses, (x) hazard and operability analysis, (xi) fault tree analysis, (xii) event tree analysis, (xiii) relative ranking/risk indexing, and (xiv) human error analysis [35], [36], [37].

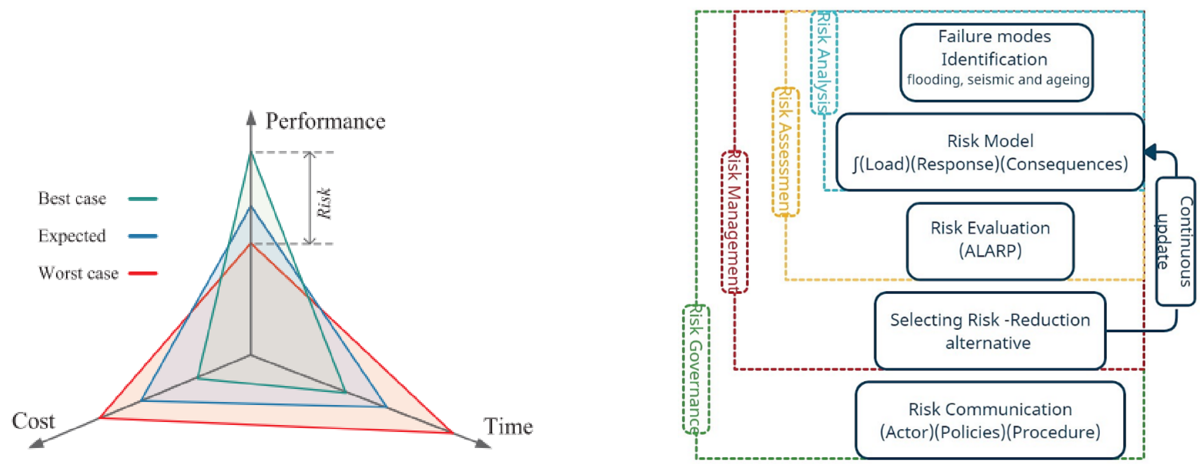
Furthermore, the risk assessment scope extends across any project's entire lifecycle, providing a framework for identifying, characterizing, and quantifying potential hazards and their impact on a target structure. It involves the development of strategies to minimize undesirable consequences related to life, health, the economy, and the environment. This systematic approach involves detecting hazards and failure modes, analyzing risks, determining risk tolerance, comparing various risk reduction strategies, and ultimately implementing the most effective strategy [38], [39]. In the context of RBA, the systematic processes of failure mode analysis and the as low as reasonably practicable (ALARP) review often lead to the recognition and resolution of dam safety hazards that might go unnoticed or unaddressed when using SBA in isolation [38]. Risk is a two-fold concept: firstly, the probability of structural failure resulting from all possible causes that violate a predefined limit state needs to be determined, and secondly, the consequences resulting from such failures need to be estimated [40]. Equation 2 illustrates the mathematical representation of risk in this context.

$$\text{Risk (Probability of an adverse event)} = \int \text{P(load)} * \text{P(failure)}|\text{ load} * \text{consequences }|\text{failure} \qquad 2$$

Dams, despite their classification as high-risk infrastructures, have a complex history of failures that still need to be fully comprehended [41]. The evolution of potential failure mode analysis (PFMA) and risk analysis methodologies has notably enhanced safety evaluation protocols [42]. The risk management triangle, as shown in Figure 2 (a), visually encapsulates the balance required between cost, time, and performance, three critical components of project management. The model underscores that any alteration in one element invariably impacts the other two. For instance, reducing the timeline may inflate costs or compromise performance. The triangle also delineates three scenarios: the best case, with optimal performance and minimal cost and time; the expected case, which aligns with the initial project plans; and the worst case, characterized by high costs, extended timelines, and diminished performance. At the core of the triangle is the concept of risk, which fluctuates with changes in the project's scope, budget, and schedule. Effective management of these three constraints is crucial to mitigate risk.

Figure 2(b) presents a comprehensive framework for RBA that facilitates the identification, evaluation, and management of risks. The process begins with identifying all possible failure modes, given hazards such as flooding, seismic activity, and structural aging, to determine the primary threats to the system's integrity. Afterward, a risk model is constructed, which captures the interplay between load, response, and consequences, thus outlining potential failure pathways. The risks are then assessed using the ‘as low as reasonably practicable’ (ALARP) principle to strike a balance between risk reduction and resource allocation. Finally, appropriate risk-reduction alternatives are chosen based on this assessment, with an emphasis on practical implementation and their effectiveness in mitigating risks. The final step in the RBA process entails risk communication, ensuring that all stakeholders are informed about the risks, mitigation strategies, and associated policies and procedures. This aspect is crucial for the practical enactment of risk management strategies. Embedded in a cyclical process with a feedback mechanism, RBA is characterized by its iterative nature, requiring continuous refinement as new data emerges, thereby upholding the principles of the risk triangle and managing and mitigating risks in an informed manner. As shown in

Figure 2 (b), adopting the RBA process aligns with the objectives represented in the risk management triangle, facilitating rational and informed decision-making to optimize performance, cost, and time, crucial components for project success and resilience.



(a) (b)

Figure 2. RBA framework, (a) risk dimensions (b) structure of the RBA adapted from [43], [44]

Contemporary dam safety protocols have advanced significantly, transitioning from traditional standard-based approach techniques to more nuanced RBA methods [44], [45]. RBA has emerged as a robust tool, guiding dam owners and operators worldwide toward comprehensive dam safety management and governance. Its implementation occurs progressively, involving stages such as screening and preliminary, detailed, and very detailed assessments [42], [46]. Depending on specific objectives and available data, RBA can be deployed through qualitative, semi-quantitative, quantitative, or hybrid approaches [44], [47]. The RBA method combines a range of information sources, including failure statistics, site inspection information, numerical simulations, and engineering expertise, to determine the probability of dam failure. This approach establishes a consistent metric that enables the assessment of estimated risks across a portfolio of dams or within a single dam while accounting for various potential failure modes [48]. Fundamentally, RBA relies on probabilistic analysis, adeptly addressing uncertainties in both hazards and modeling parameters during reliability assessments [38].

Through the lens of risk analysis, RBA provides a robust framework for prioritizing safety measures and devising strategies for implementing safety enhancements [49], [33]. The outcomes derived from the risk assessment process can be utilized in three key ways: optimizing the allocation of a finite safety budget, minimizing the overall cost to achieve a specific safety level, and furnishing decision-makers with evidence indicating that the facility is either adequately safe or has improved in safety compared to previous states [50].

In recent decades, there has been a significant increase in the application of risk-based techniques for concrete dams, as noted by [50], [51]. This trend has led to an ongoing effort to use such methods in gravity dams, resulting in the development of the probabilistic model code for concrete dams (PMCD) [4], [52]. PMCD offers a risk-based design framework, with defined limit states for concrete dams and design scenarios, as well as target reliability for load and resistance factors. Additionally, statistical distributions for critical parameters are provided, as outlined by (B. R. Ellingwood, 2001; Westberg Wilde

& Johansson, 2016). The US Army Corps of Engineers (USACE) has released an extensive set of guidelines for probabilistic limit state analysis of various types of dams [28], [56].

In addition, several computer programs have been developed to facilitate risk-based assessments of dam safety. These include RAM-DSM, a risk assessment methodology for dams [57]; LIFESim, a modular, spatially-distributed, dynamic simulation system for estimating potential loss of life from natural and dam failure floods [58]; DAMRAE-U, a tool for incorporating uncertainty into dam safety risk assessments [59]; iPresas Calc and iPresas Manager are powerful tools for developing influence diagrams and selecting appropriate measures for risk mitigation. These tools adhere to the guidelines set forth by USACE and SPANCOLD for accurate and reliable risk assessment, and they offer efficient resource utilization for optimal results [60]; BayesiaLab, a tool for risk analysis and prioritization of dams in Italy [61]; and other similar tools listed in Chapter 7 of "Software Tools for Dam Safety Risk Analysis" [62]. The USACE Risk Management Centre (RMC) has also developed a suite of software programs, including Quantitative Risk Assessment, Risk Calculations Suite, and Seismic Hazard Suite, which are available [63].

In summary, SBA and RBA are the primary methodologies used to evaluate the safety of dams. While the SBA is easy to apply, it has limitations as it does not adequately consider uncertainties or balance risks. On the other hand, RBA is a more comprehensive approach that assesses a range of potential scenarios, their likelihoods, and outcomes, thus providing a more thorough framework for safety evaluation and enriching the decision-making process. RBA has been effectively implemented in high-risk industries, resulting in standard guidelines and specialized software resources. Integrating RBA into dam safety protocols is crucial for making informed decisions, optimizing resources, and improving safety measures.

1.1.2. BMRA as an improvement to RBA

The existing risk analysis procedures have limitations in dealing with complex systems, dynamic risks, information updates, and accurately quantifying cause-effect relationships while considering uncertainties [64]. Risk assessment is an ongoing and evolving process that requires regular updates as new information becomes available [65]. On the other hand, BMRA provides a solution within the Bayesian theory's logical framework to address uncertainty in risk analysis. It offers a sophisticated and updatable approach to assessing dam risk [66]. Bayesian networks are valuable in this context as they provide probabilities about the state of nature instead of observations [67]. Both static and dynamic Bayesian networks allow the integration of information from various sources, resulting in a comprehensive knowledge base that can be updated with new information [66]. Furthermore, when prior knowledge is lacking, a Bayesian network can begin with expert opinions and then be updated as new information becomes available [66], [68], [69]. The Bayesian inference process starts by estimating the prior probability of an event based on the available information. Bayes' theorem is then used to assess the significance of additional information or evidence and obtain an updated or posterior estimate of the occurrence probability [33]. By implementing Bayesian model risk analysis, dam safety evaluations can benefit from increased flexibility, adaptability, and integration of new information, resulting in more informed and precise risk assessments.

A directed acyclic graph (DAG) structure is utilized by a Bayesian network (BN) to represent system risk, according to research by Torres-Toledano et al. [70]. In addition, BN integrates a range of information sources, including expert opinion, experimental data, numerical simulation data, and their uncertainties, while also combining past and new information and performing both forward and backward reasoning [71]. The incorporation of a time factor allows for the transition from a static Bayesian network (SBN) to a dynamic Bayesian network (DBN). A BMRA application is reported to assess dam overtopping risk under flood and seismic risks for a sequence of cascade dams subjected to flood and earthquake [69]. The risk factor associated with earth and rockfill dam breaches is complex and changes over time and during operation periods. Li et al. [66] studied the dynamic aspects of dam-breach probability using a DBN network. Numerous studies have shown that the Bayesian method is more effective and superior to traditional risk analysis methodologies, as demonstrated by Y. Chen et al. [69]. Smith et al. [72] established a dam risk analysis technique based on Bayesian networks that considers the interdependence of failure modes, uncertainties, and expert judgments. Su et al. [73] employed risk analysis in conjunction with fuzzy mathematics to assess the stability of concrete dams. Cloete et al. [74] provided a rational quantitative optimal strategy, which was a rigorous risk evaluation model that produced a decisive outcome for risk mitigation at the dam site.

To summarize, both RBA and BMRA play crucial roles in evaluating dam safety, but they take different approaches. RBA is known for its meticulous methodology, which considers potential scenarios and their likelihoods and impacts, thereby enhancing the decision-making process. However, it has limitations when it comes to capturing the complexities and nuanced uncertainties of a complex system. BMRA, on the other hand, is based on Bayesian theory, which allows it to address these challenges by providing an adaptable framework that quantifies uncertainties and integrates diverse information sources, including expert opinions. This makes it particularly useful when prior knowledge is limited. BMRA's adaptability and rigorous inferential capabilities improve the precision of risk assessments. While RBA provides a foundation for systematic safety assessments, BMRA takes a more iterative and evidence-responsive approach, making it effective in dam safety and other high-stakes industries that require evolving risk management strategies.

Maintaining the safety and reliability of dams is crucial for minimizing negative impacts and preserving their overall health, which is key to optimizing resource allocation. The preceding sections provide a comprehensive examination of three distinct methods for assessing dam safety: the traditional SBA, the currently in practice RBA, and the emerging approach of BMRA. Each method is thoroughly analyzed for its strengths and limitations, with a particular focus on how RBA enhances the effectiveness of SBA, and how BMRA further improves upon the RBA process. Additionally, a range of guidelines and tools currently employed for risk-based safety assessments are discussed. To facilitate comparison and ease of reference, Table 1 presents a side-by-side comparative analysis of these safety assessment practices, outlining their respective features and applications in the field of dam safety management.

Table 1. Comparison of safety assessment practices

Aspect	SBA	RBA	BMRA
Solution	Deterministic	Probabilistic	Probabilistic
Input	Best estimate	All plausible	All plausible
Output	Factor of safety	Probability of exceedance	Probability of exceedance
Information integration	Limited	Various sources*	Various sources+
Event correlation	No consideration	No consideration	Considered
Process	No Consideration	FTA, ETA unidirectional, FN curves	Directed acyclic graph Bi-directional
Effort	Easy to adopt	Exhaustive	Exhaustive
Load	Service load	No such limit	No such limit
PFMC	No risk-based	Risk-based	Risk-based
Risk scenario	Blind risk trade-off	Complete picture	Complete picture
Acceptance	Well established	In process of adoption	Research in progress
Guidelines	Guidelines exist	Guidelines exist	No guidelines exist
Output	Binary risk (S|F)	Static risk	Static and dynamic risk
Rehabilitation	Defensive	Optimized	Optimized

* More Information, + Minimum Information, FTA-Fault tree analysis, ETA-Event tree analysis, FN Frequency-Number curves, S-Safe, F-Fail

1.3. Problem statement

The primary focus of this thesis is the growing concerns about the seismic safety and resilience of aging concrete gravity dams. These dams are a crucial element of global infrastructure, but they are becoming increasingly vulnerable to failure due to various factors, including outdated design methodologies, inconsistent safety assessments, material degradation, changing seismic hazards, and prolonged exposure to environmental conditions. To address the gaps in current safety assessment practices, this thesis aims to integrate probabilistic analysis, reliability-based frameworks, and advanced numerical simulations to effectively reassess dam safety. The goal of the research is to create a comprehensive seismic risk assessment framework by utilizing available online tools, numerical simulation software, and theoretical frameworks.

1.4. Gap analysis

Although there have been advancements in seismic risk assessment methodologies for concrete gravity dams, there remain significant deficiencies in the existing frameworks. The current approaches concentrate solely on immediate structural responses and fail to consider the long-term effects of material aging and structural stability. This inadequacy is amplified by the variability and uncertainty inherent in ground motion selection techniques, which must still be fully researched to understand their long-term impact on aging dams. Additionally, the level of detail in numerical simulations in line with the safety assessment objective introduces uncertainty. There is no comprehensive, integrated benchmark research addressing these concerns. As a result, risk assessments are limited in their accuracy and dependability, as they do not account for the gradual deterioration of dam materials and the subsequent escalation of seismic vulnerability over time. A more holistic and temporally sensitive approach to seismic fragility assessment is needed to address these shortcomings. By adopting such an approach, we may develop a unified, probabilistic framework that can dynamically incorporate the evolving nature of seismic hazards, the degradation of structural materials, and progressive numerical simulation into the safety assessment of aging dams. This would significantly enhance our ability to anticipate and mitigate the hazards associated with aging concrete gravity dams, ensuring their safety and operational integrity over their lifecycle.

1.5. General Objective

This research aims to explore various aspects related to the risk-based seismic safety assessment of aging dam infrastructure. The objectives of the research are as follows.

1. This involves critically evaluating existing safety assessment practices, including standard and risk-based approaches, to identify their advantages and limitations.
2. To investigate the variability and constraints associated with structural modeling decisions in seismic analysis of dams, aiming to enhance the comprehension and effectiveness of dam safety assessments.
3. To explore the impact of uncertainties, both aleatory and epistemic, associated with ground motions on the risk assessment of concrete gravity dams, use of various ground motion selection methods such as ASCE 7-16 and the conditional mean spectrum method.
4. To conduct a detailed seismic fragility assessment of aging concrete gravity dams, considering material degradation due to aging and environmental factors, to develop robust fragility models that accurately reflect the vulnerability of these structures under seismic events.
5. Finally, based on the above study, develop a framework to carry out seismic risk assessment progressively and systematically, matching the problem topology.

1.6. Outlines of the Thesis

The thesis documents the author's endeavor to advance seismic fragility assessments of aging concrete gravity dams by incorporating comprehensive aging models and addressing the uncertainties in ground motion selection methods. A novel integrated approach, blending probabilistic analysis with progressive numerical simulations, is proposed to evaluate the seismic vulnerability of these critical infrastructures throughout their lifecycle. This work aims to enhance the current understanding and methodologies for assessing and managing the seismic risks associated with aging dams, focusing on integrating advanced modeling techniques, uncertainty quantification, and the impact of material degradation over time.

This introduction chapter lays the groundwork for the research topic by delving into risk-based seismic safety assessment and management of aging dams in the face of uncertainties. Then emphasizes the need to overcome the current limitations in safety assessment practices and highlights the key challenges that must be addressed. Additionally, it outlines the unique contributions that this research will bring to the field. Finally, research objectives are precisely articulated, providing a clear roadmap for the subsequent investigations.

Chapter 2: Literature Review

This comprehensive review covers various aspects critical to the thesis, including modeling techniques, model variability, fragility analysis, reliability frameworks, uncertainty quantification, risk management, ground motion selection, and material degradation effects due to aging. This background highlights existing research gaps and justifies the need for the proposed approach.

Chapter 3: Methodology

This chapter details the methodology adopted, focusing on selecting consistent numerical models and ground motion selection techniques, accounting for material variability and degradation, and conducting fragility assessments considering the impacts of aging and ground motion selection. It also discusses how the methodology addresses the challenges identified in the literature review and aims to demonstrate the impact of ground motion selection on risk assessment. Finally, this chapter details the proposed framework for carrying out seismic risk assessment.

Chapter 4: Model variability

Through the development of numerical simulations for two selected dams, Koyna and Pine Flat, this chapter aims to highlight the impact of model class uncertainty. It provides insights into selecting consistent models and demonstrates the methodology's applicability and effectiveness in addressing such uncertainties.

Chapter 5: Ground motion selection

Focusing on the Pine Flat Dam, this case study examines the influence of ground motion selection methods on fragility and risk assessment. It presents a comparative analysis of different selection methods and their implications for seismic safety evaluations.

Chapter 6: Material degradation

This chapter explores the impact of material variability due to aging and construction heterogeneity on the dynamic characteristics of dams. Using the Pine Flat Dam as a case study, it assesses the effects of aging at different stages (1, 50, and 100 years) on fragility assessments, highlighting the importance of considering material degradation over time.

Chapter 7: Conclusions and future work

The final chapter summarizes the research's key findings, contributions, and implications. It provides concluding remarks on the significance of the proposed approach for improving seismic risk assessments of aging dams. Additionally, this chapter outlines potential avenues for future research, suggesting ways to build upon the groundwork laid by this thesis.

This organization ensures a logical flow from identifying the problem and reviewing existing knowledge through developing and applying a novel methodology to presenting case studies that illustrate the methodology's effectiveness and concluding with reflections on the research's implications and future directions.

Chapter 2

Literature Review

This chapter of the thesis delves into a comprehensive review of the practices for the seismic performance assessment of concrete dams, aligning with the thesis objective. The discussion covers various topics, such as the framework for evaluating seismic performance, using numerical simulations with increasing complexity, assessing seismic hazards, selecting ground motions, material degradation, fragility evaluation, and risk assessment. The chapter also compares deterministic and probabilistic approaches to analysis, followed by an in-depth exploration of the reliability analysis framework. Furthermore, the chapter thoroughly outlines and categorizes various uncertainties, providing a comprehensive understanding of the factors that impact seismic performance evaluations.

2.1. Seismic performance evaluation of concrete dams

Concrete gravity dams, many of which have been in service for over half a century, are designed to withstand significant load effects from gravity, hydrostatic pressure, hydrodynamic, uplift, seismic, and ambient temperature without structurally significant cracking. However, due to the inherent low tensile strength of concrete, these structures are susceptible to cracking during extreme seismic events [75]. Over the years, there have been substantial advances in the methodologies for evaluating natural phenomena hazards, leading to upward revisions of the design-basis events for these dams. Simple stress evaluations, assuming a linear elastic response with Operational Basis Earthquakes (OBE), are typically used to assess a concrete dam's seismic performance. The resulting stresses are expected to remain within permissible limits [76].In the case of a Maximum Credible Earthquake (MCE), the design strategy anticipates considerable structural damage but ensures the dam's ability to sustain the reservoir [24]. The seismic performance is evaluated on three levels: serviceability, damage control, and collapse prevention [77]. A detailed, nonlinear, dynamic assessment of the Dam-Foundation-Reservoir (DFR) model is employed to evaluate the safety of dams subjected to severe intensity earthquakes (MCE). These events can generate internal stresses that surpass the structure's elastic strength capability [78], [79]. Given the potentially devastating impact of seismic events, it is crucial to develop a comprehensive framework for modeling and conducting nonlinear seismic response simulations. These are timely and significant research topics that can provide a more realistic evaluation of behavior under seismic loads [8], [80].The seismic analysis process commences with determining the dynamic characteristics of the dam. This is followed by a dynamic analysis using at least three different spectrum-compatible acceleration time histories [81]. The International Commission on Large Dams (ICOLD) seismic committee has been developing numerous guidelines on seismic aspects of dam design since 1975 [78], [82]. These guidelines, along with those from the United States Army Corps of Engineers (USACE), the United States Bureau of Reclamation (USBR), the Federal Emergency Management Agency (FEMA), and the Canadian Dam Association (CDA), provide a robust framework for the seismic performance evaluation of concrete gravity dams. These global guidelines ensure that the evaluation and design processes are in line with the latest advancements in the field, thereby enhancing the safety and resilience of these critical structures.

2.2. Seismic performance evaluation framework

The presented framework in Figure 3 offers a comprehensive approach to evaluating the seismic performance of dams. It involves a multi-faceted approach that integrates various analytical aspects and considerations. The process begins with seismic input, which takes into account source characteristics, magnitude, distance, site geology, and attenuation equations. This leads to ground motion (GM) selection, which involves methods like uniform hazard spectrum (UHS), conditional mean spectrum (CMS), and generalized conditional intensity measure (GCIM). Material modeling is then addressed, ranging from linear elastic and classical damping to nonlinear approaches and damage and fracture mechanics. This informs the response to seismic loads, analyzing dynamic stress and strain, safety factors, drifts and deformation, joint behavior, and energy dissipation. Concurrently, the framework considers the dam-foundation-reservoir system, including special features like interaction models, reservoir and foundation special features such as sediment, length, cavitation, and surface sloshing, as well as foundation features like liquefaction and wave propagation. Seismic evaluation parameters like peak ground acceleration (PGA), velocity (PGV), displacement (PGD), and aspects of repeated earthquakes and non-uniform ground motions are also evaluated. The evaluation then shifts to examine the dam's response, developing damage states through definitions and quantifications that transition into developing fragility curves based on maximum dynamic crest drift and other criteria. Cost curves are also developed for components, considering their importance. The process concludes by assessing both conventional and advanced performance criteria to determine if seismic safety is acceptable and deciding on potential interventions. This approach ensures that all aspects of seismic performance evaluation are considered, leading to informed decisions on whether any intervention is required and the possible methods to be employed.

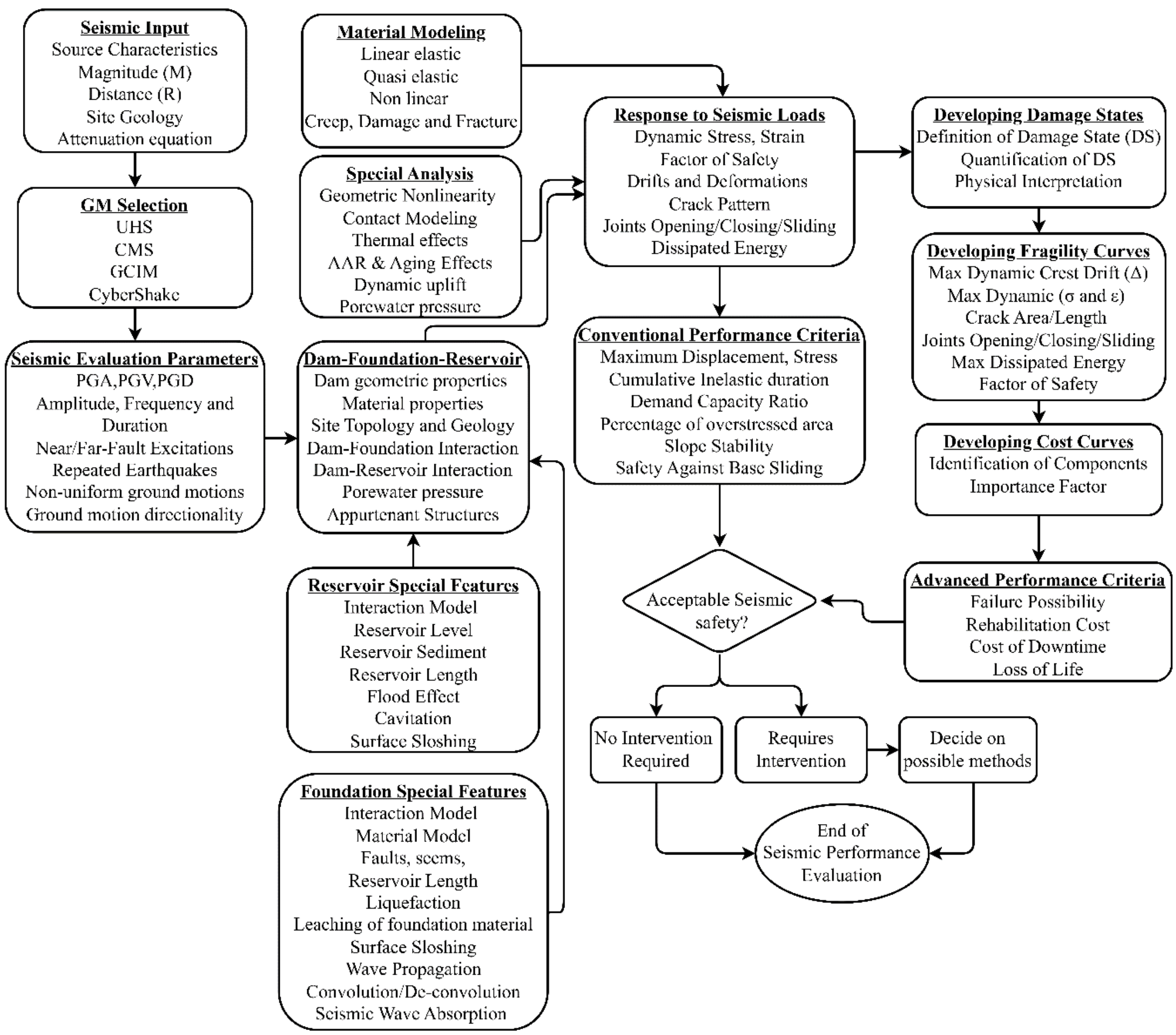


Figure 3. The broad picture of seismic performance evaluation adapted from [21]

2.3. Progressive seismic performance assessment

The seismic safety assessment of concrete dams heavily relies on numerical simulations, employing specialized analysis techniques to accurately predict the system's response [83]. Dynamic analysis can be either linear or nonlinear and conducted in either the time or frequency domain, depending on the analysis objectives, computational stability, and required precision. The frequency-domain approach is generally employed for linear analyses. In contrast, direct time integration methods like the Newmark methodology, Hilber-Hughes method, or generalized α technique are utilized for linear and nonlinear transient seismic analyses. Throughout the seismic safety evaluation process, careful attention is needed at all stages, including defining material properties, selecting appropriate ground motion data, ground motion scaling considerations, choice of numerical modeling (2D or 3D), imposition of boundary conditions, and selection of the analysis method [84], [85]. The seismic performance of a concrete gravity dam must be evaluated progressively, i.e., from linear to nonlinear, considering the complexity, computing effort, analysis time, and expense [86], [23], [87], [88].

Linear analysis can offer insights into areas experiencing excessive stress but falls short of comprehensively understanding the actual dynamic behavior of the structure [89], [90]. Stress and deflection patterns can be approximated through linear analysis, suggesting potential areas of concern. For dams subjected to an Operating or Design Basis Earthquake (OBE or DBE), linear-elastic analysis with added safety margins is usually sufficient. However, it is essential to note that linear analyses can predict damage but not failure, as they do not account for stress redistributions caused by cracks or openings and disregard the closing of contraction joints [86], [91]. Moreover, simplifications are inherent in linear analysis, such as assuming treating dams and foundations as monolithic entities (ignoring joints and discontinuities), considering added mass for hydrodynamic interactions, and employing linear elastic material models [79], [92]. These simplifications introduce uncertainties and may not fully capture the actual behavior of the structure.

In contrast, nonlinear analysis removes these simplifications and can provide more accurate estimates of the likelihood of a structure's failure [93]. Furthermore, nonlinear analysis plays a critical role in seismic risk assessment in estimating failure probabilities and defining risk levels. Various research-based and commercial software packages are available for conducting 2D and 3D seismic safety assessments, each with capabilities, limitations, and solution methodologies [28]. In summary, numerical simulation has become increasingly practical, incorporating the latest advancements in the field, and serving as the cornerstone for enhanced dam design and safety assessments. Figure 4 (a) and (b) show the evolution from static to dynamic analysis and progressive seismic analysis procedure with increasing complexity and efficacy for seismic safety evaluation. Finally, progressive simulations are invaluable for optimizing resource utilization and increasing efficiency in seismic risk assessments. Resources are efficiently allocated by tailoring the analysis depth based on the complexity of the dam and the specific seismic challenges it faces. This approach ensures a thorough assessment while preventing unnecessary expenditure on overly complex analyses for simpler structures. Thus, progressive simulations enhance the accuracy of risk assessments and ensure prudent utilization of resources, making them a cornerstone in efficient and effective seismic safety evaluations for critical infrastructures like dams.

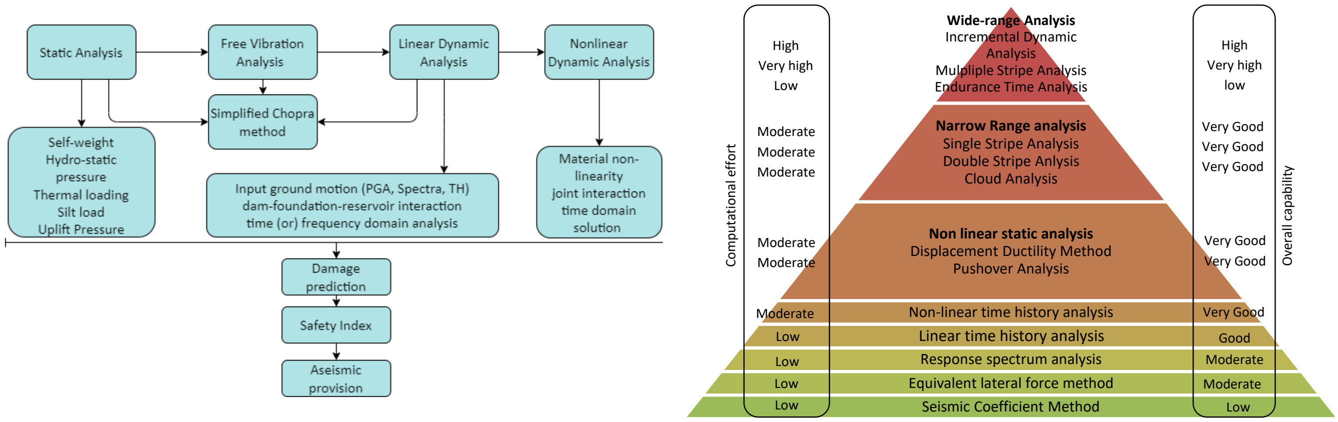


Figure 4. Numerical simulation (a) evolution from static to dynamic analysis (b) progressive seismic safety assessment [94], [87]

2.4. Ground motion selection

The careful selection of ground motions emerges as a cornerstone in both dynamic structural analysis and the fragility assessment of structures, significantly influencing the accuracy of structural response estimations and the reliability of seismic performance evaluations. The traditional approach to ground motion selection often neglects the variance of the target response spectrum or addresses it in an ad hoc manner, which can introduce potential biases in structural response estimates and fragility curves critical for predicting damage states of structures during seismic events. To mitigate these issues, researchers have proposed computationally efficient and theoretically consistent algorithms that ensure a match between the target response spectrum's mean and variance and the selected ground motions' response spectra. These algorithms employ probabilistic methods to generate multiple response spectra from a target distribution and select recorded ground motions that individually match the simulated spectra, with a greedy optimization technique further enhancing this match [95]. Moreover, the generalized conditional intensity measure (GCIM) approach has been highlighted for its holistic selection capabilities, allowing for the construction of a multivariate distribution of ground-motion intensity measures and facilitating a more comprehensive assessment of seismic risks [96]. Ground motion models, crucial for describing the probability distribution of spectral acceleration, have been complemented by studies measuring the correlations between spectral acceleration values at multiple periods, providing essential data for seismic hazard analysis and ground motion selection [97]. The Conditional Mean Spectrum (CMS) and multiple stripe analysis have been specifically lauded for their ability to enhance the representativeness of seismic inputs in fragility analyses, reflecting a spectrum of ground motion records that mirror varied seismic hazards [95], [98]. This comprehensive approach to ground motion selection, including both as-recorded amplitude-scaled and synthetic/simulated motions, aligns closely with seismic hazard analysis, ensuring hazard consistency and enhancing the predictive accuracy of fragility assessments [99], [100]. Collectively, these methodological advancements underscore the critical role of judicious ground motion selection in improving the seismic risk management of structures, by capturing a broader range of potential seismic inputs and their probabilities of occurrence, thereby bolstering the predictive capabilities of fragility assessments.

2.5. Impact of aging on seismic performance

The resilience of concrete gravity dams in seismic events depends on various factors such as the materials used, structural integrity, and natural wear over time. Researchers have extensively studied the complex interplay between these factors to better understand their collective impact on dam behavior during earthquakes. Early studies by Bhattacharjee et al. [101] focused on seismic-induced cracking and energy dissipation, using finite element methods to analyze seismic fractures and highlighting the importance of material degradation. Ghrib et al. [102] and Cervera et al. [103] expanded on this research by exploring damage mechanics and advanced continuum damage models to deepen the understanding of concrete's mechanical properties under seismic stress. Gogoi et al. (Gogoi & Maity, 2005) emphasized the role of aging, which is exacerbated by environmental exposure and mechanical stress, and pointed to the progressive decline in concrete durability over time. The performance of an aged dam with a known percentage of isotropic or orthotropic damage due to seismic excitation is studied. Advancements in research methodology, such as those by Pan et al. [104] and Zhong et al. [105], refined finite element methodologies to more accurately depict failure mechanisms in dams under significant seismic forces, stressing the need to consider concrete's inherent non-uniformity. The trajectory of research evolved to address the aging effects on seismic behavior, with studies by [106], Nahar et al. [107], and Li et al. [108] leveraging fragility analysis and examining spatial variability of material parameters to assess risks. This collective research underscores the critical influence of aging on dam seismic robustness, advocating for ongoing vigilance through regular assessments, maintenance, and strategic retrofitting. Additionally, Wang et al. proposed an approach to assess and predict the seismic risk of existing dams considering the aging effect of the Ertan arch dam, which suggests that the aging of concrete gravity dams impacts their seismic risk [109]. it is crucial to consider both material degradation caused by aging and material heterogeneity when assessing the seismic performance of concrete gravity dams. These factors have a collective impact that calls for a comprehensive approach to research and methodology development. Decades of research have shown that incorporating aging effects and material variability into seismic evaluation models is essential for accurate performance assessments. This integration is vital in developing effective maintenance and retrofitting strategies, ultimately ensuring the safety and longevity of dam infrastructures in the event of seismic hazards.

2.6. Risk-based framework

In the field of civil engineering, the importance of implementing a risk-based framework for the design and upkeep of dam infrastructure cannot be overstated. This approach prioritizes the establishment of a methodical process for assessing and mitigating the inherent risks associated with dam operations, particularly in the event of natural disasters like earthquakes. As such, the advancement and utilization of Performance-Based Earthquake Engineering (PBEE) and potential failure mode analysis are critical in bolstering the safety and durability of dams. This section outlines the essential terms connected with a risk-based framework, such as PBEE created by Pacific earthquake engineering research (PEER) [110] and potential failure mode analysis [111]. The concise definitions below along with reported inline works, provide a quick overview of the probabilistic risk-based paradigm. The ICOLD benchmark workshops in the years 2011,2013,2015 and 2019 covered some of these critical concepts on risk, reliability, and fragility. It concluded that a risk-based probabilistic framework remains useful in assessing dam risk and consequences and prioritizing key activities such as rehabilitation, implementation of an emergency action plan (EAP), and modification of operation and maintenance (O&M) modification [112]. The risk-based paradigm is an integral component of many risk-based dam safety guidelines [113], [38], [114], [115], [44] and is a focus of current dam engineering research [116], [117], [118], [119], [120]. The risk assessment approach calculates the probability of failure using structural reliability analysis (SRA), widely used in limit state design guidelines to calibrate partial safety factors. A mathematical description of the failure mode and a limit state function are required for the reliability analysis. The safety index (likelihood of failure) is determined and compared with the target safety index to determine structural safety. There are challenges in adopting SRA for dams due to the scarcity of such calculations and the specification of failure scenarios [50].

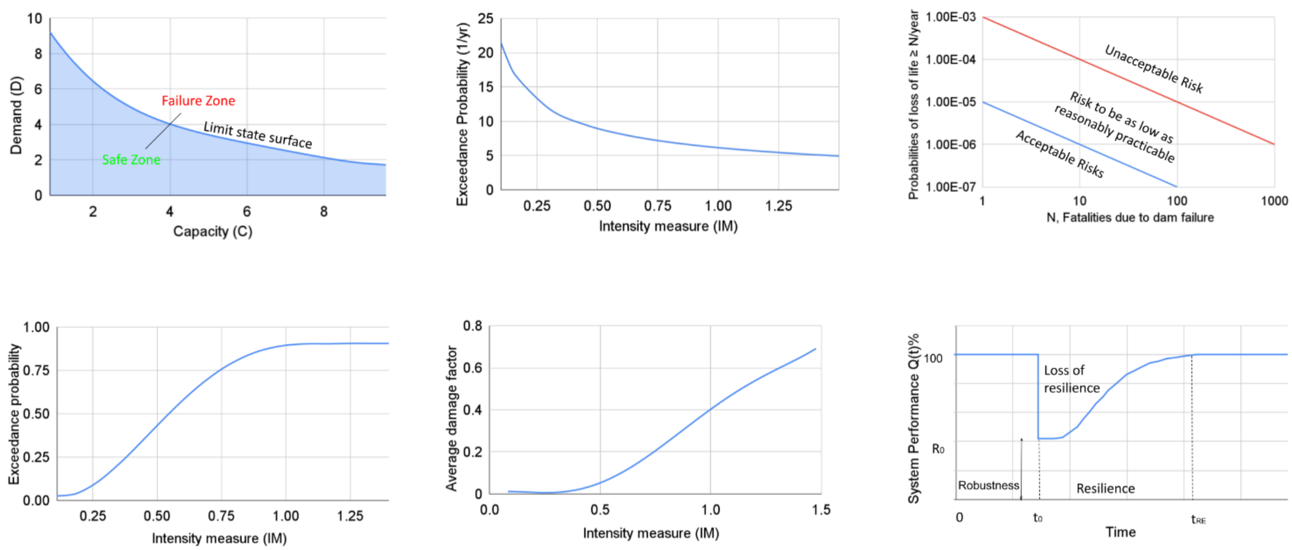


Figure 5. Terminologies in a Risk-based framework (a) reliability, (b) hazard, (c) risk, (d) fragility, (e) vulnerability, and (f) resilience

a) Reliability

The probability of no failure or violation of a specific limit state function for a given time is known as structural reliability. Furthermore, reliability can be viewed as the inverse of the probability of failure. The probability failure function (P_f) can be represented as the exceedance of a limit state (LS) function shown in Equation 3, i.e., G(X) = R(X) - S(X). The G(X) ≤ 0 signifies that the system has failed [40]. Figure 5 (a) shows the limit state surface as a function of capacity and demand with a safe or fail zone.

$$P_f = P[R(X) \le S(X)] = \int_{G(x<0)} f_R(R) f_s(S) dRdS \qquad 3$$

R and S are resistance and demand, respectively; X is a random vector of (N) basic variables $X = X_1, X_2 ..., X_N$; R and S are also written as probability density functions (PDF) as $f_R(x)$ and $f_s(x)$, respectively. A concrete dam can be viewed as a series system with numerous different failure modes; failure in either mode will collapse the structures [50]. As a result, the reliability of the system is defined by integrating various failure modes. Various methodologies are employed in the field of engineering to accurately calculate the probability of failure, each with its unique approach and level of precision. These include direct integration techniques, which solve the problem through numerical integration, and reliability methods such as the First-Order Reliability Methods (FORM) and Second-Order Reliability Methods (SORM). FORM approximates the failure surface linearly at the most probable point of failure, while SORM provides a more refined approximation by considering the curvature of the failure surface. Alongside these, sampling techniques like the Point Estimate Method (PEM) offer a simplified approach by estimating moments of the output function based on a limited number of deterministic analyses. More comprehensive sampling methods include Crude Monte Carlo Simulation (MCS), which relies on random sampling over the entire input space, and its variants such as Monte Carlo Simulation with Latin Hypercube Sampling (MCS-LHS), which improves sampling efficiency by ensuring that the entire input space is evenly explored. Monte Carlo Simulation with Importance Sampling (MCS-IS) further refines this approach by focusing the sampling effort on the most critical regions of the input space to efficiently estimate probabilities of rare events. Each of these methods plays a crucial role in the assessment of structural reliability, offering a spectrum of tools for engineers to determine the likelihood of failure under various conditions and scenarios [121], [122].

(b) Hazard Analysis

The process of estimating the exceedance rate of a specific level of ground motion within a designated reference period forms a critical component of seismic hazard analysis, as delineated by key studies in the field [123], [62]. This is achieved through Probabilistic Seismic Hazard Analysis (PSHA). This method yields a hazard curve illustrating the relationship between the intensity measure (IM) of ground motion at a given site and the corresponding annual exceedance rate (Cornell, 1968). Figure 5 (b) shows the hazard curve where the horizontal axis of this curve denotes the IM, such as Peak Ground Acceleration (PGA) or Spectral Acceleration (SA), while the vertical axis quantifies the annual rate of exceedance, expressed in 1/year. Utilizing the Poisson probability model, as shown in Equation 4, PSHA facilitates the calculation of these IM values, offering a systematic approach to quantifying seismic risks [124]. Ground motion attenuation relationships play a pivotal role in this analysis, establishing a connection between the PGA or SA and the variables of distance from the seismic source to the site, as well as the magnitude of the potential earthquake [125]. These relationships are instrumental in generating seismic hazard curves, which are a fundamental screening tool for identifying and assessing seismic hazards and risks.

$$\lambda_{\mathrm{IM}} = -\frac{\ln(1 - P_E)}{t} \quad 4$$

In practical terms, the Probability of Exceedance (P_E) is defined as the likelihood of a specific level of ground motion being exceeded at least once over the lifespan of a structure, often considered to be 100 years for dams. This concept is vital for understanding the seismic risk associated with rare seismic events, which are typically characterized by P_E values ranging from 2% to 5%. To accommodate varying conditions and requirements, seismic hazard maps are produced, delineating different damping values and PGA levels, each associated with its annual recurrence interval. Such detailed mapping and analysis enable engineers and policymakers to make informed decisions regarding the design and reinforcement of critical infrastructure, ensuring resilience against seismic events.

(c) Risk

Risk management is an integral process that permeates the entire life cycle of any project, particularly in ensuring the safety and sustainability of structures during normal operation, flood, and seismic events. This process initiates with the meticulous identification of potential hazards and their impacts on the targeted entities, whether they are structures or populations. Following identification, a series of strategic actions are implemented to minimize, mitigate, or transfer the risks associated with these hazards, aiming to reduce the possibility of undesirable outcomes to the lowest feasible level [126]. Risk characterization emerges in two distinct forms: firstly, through the evaluation of the likelihood of structural failure triggered by any conceivable cause, such as exceeding predefined limit states or encountering unforeseen events; and secondly, by assessing the consequent losses stemming from such failures [40]. In the area of quantitative risk assessment (QRA), methodologies like Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are employed to manage input uncertainties effectively. These approaches facilitate the calculation of both individual and cumulative probabilities of failure for specified modes of failure, thereby providing a comprehensive understanding of risk [127], [128]. The foundational Equation 2, Chapter 1 encapsulates the three principal components of risk, offering a basis for its quantitative analysis. A validation process against the As Low as Reasonably Practicable (ALARP) principle is conducted after the risk estimation. A representative ALARP diagram with regions of acceptable and unacceptable risk is shown in Figure 5 (c). This validation serves not only to assess the adequacy of the system's safety and reliability but also to determine the necessity for the implementation of additional safety measures [129]. The articulation of risk through the f-N or F-N curves underscores the variability in acceptable risk levels, which are influenced by a multitude of factors including economic, environmental, social, and technological considerations [75]. This multi-faceted approach to risk management underscores the complexity and necessity of addressing risk comprehensively across various stages of a project's lifecycle.

(d) Fragility Analysis

Fragility analysis is used to analyze the seismic safety of existing facilities and make decisions by incorporating sources of uncertainty that may affect dam performance using a probabilistic framework [130], [131]. Fragility analysis is a crucial tool in seismic analysis for evaluating the probabilities of various damage states as a function of structural seismic response [22]. Fragility curves as shown in Figure 5 (d), represent the likelihood of a specific level of damage for a given intensity of an earthquake. It establishes the relationship between earthquake hazards and vulnerability [123], [132]. It was initially devised to quantify the seismic risk of nuclear facilities [133]. However, they have since been used in large systems such as buildings, bridges and individual components [134]. The development of fragilities for progressively more severe limit states or performance goals depicts the robustness of dam performance under increasing hazard intensity [135]. Fragility analysis is a time-variant reliability problem with no closed-form solution; hence numerical simulation is unavoidable [136]. Although crude Monte Carlo Simulation (MCS) produces the most accurate results, it has a considerable computing cost. Latin Hyper Cube Sampling (LHS) comes to the rescue to reduce the effort [137].

$$\text{Fragility} = \text{P}[\text{D} \geq \text{C}_{LS} | \text{IM} = \text{im}] \quad (5)$$

Equation *5* shows the fragility equation, where D is the demand parameter, C_{LS} is the capacity associated with the specified limit state, and IM is the intensity measure of ground motion.

(e) Vulnerability

Within a risk-based framework for dam safety, vulnerability is a complex concern encompassing the susceptibility of the dam structure to various threats and the potential consequences of failure. Analytical frameworks commonly quantify vulnerability by evaluating the dam's response to specific hazards, considering the probability of occurrence and the magnitude of resulting damage [138]. Recent studies have broadened this concept by incorporating hazard interactions into assessments, resulting in a more comprehensive understanding of the dam's vulnerability to cascading events [139]. In the context of dam safety, vulnerability is closely tied to the structure's performance under specific load conditions, where the average damage factor correlates with the event's intensity measure (IM) [140]. Figure 5 (e) represents a vulnerability curve that illustrates the relationship between the Intensity Measure (IM) and the Average Damage Factor for a dam or similar infrastructure. An applicable formula that could be used in this context is the Vulnerability Index (VI) as shown in Equation 6.

$$VI = \frac{1}{N}\sum_{i=1}^{N} P(D_i \mid IM) \quad 6$$

where $P(D_i \mid IM)$ is the probability of damage state D_i, given the intensity measure IM, and N is the total number of considered damage states.

A notable contribution in the field is the Generic Multi-Risk framework, which emphasizes the interaction of various hazards and their cumulative impact on large dams [138]. Additionally, the bow-tie methodology has been employed for monitoring dam safety risks, which aids in both the prevention of collapse and the mitigation of consequences by assessing and reporting the performance status of safety barriers [141]. The digital twin technology has also been proposed as a transformative tool in vulnerability assessments, enabling a next-generation risk-based inspection and maintenance framework that integrates data from the construction phase and provides a dynamic platform for stakeholders [142]. Finally, the continual advancement in the assessment of dam vulnerability is crucial for risk-based dam safety frameworks, as it directly impacts the management strategies for these critical infrastructures. The development and integration of complex analytical models and innovative technological approaches reflect the evolving nature of vulnerability considerations in ensuring dam safety.

(f) Resilience

Resilience in a risk-based dam safety framework encapsulates the capacity of a dam to anticipate, prepare for, withstand, and recover from disruptive events, embodying a multifaceted approach to ensure operational continuity and structural integrity under adverse conditions [143], [144]. Resilience lacks a one-size-fits-all definition, with strategies for enhancing it often tailored to the specific needs of individual infrastructures [116], [145], [146]. Recognizing the intrinsic vulnerability of critical infrastructures like dams to a plethora of threats including natural disasters, terrorist acts, aging infrastructure, and maintenance lapses, emphasizes the imperative for a resilient design and operational framework [147]. This notion is echoed in global guidelines by the USBR, USACE, and FEMA, which advocate for a holistic resilience strategy encompassing robustness, redundancy, resourcefulness, and rapid recovery to mitigate risks and enhance safety protocols [148], [149], [150]. These principles are underpinned by the need for dams to possess inherent resistance to failure mechanisms, ensuring they can maintain critical functions and services in the face of unforeseen disruptions.

Scholarly contributions [116], [145], [146] have further refined our understanding of resilience by quantitatively assessing the resilience of civil infrastructures, including dams, through analytical studies. These works collectively highlight the importance of a systemic resilience assessment that integrates technical, organizational, social, and economic dimensions to achieve a comprehensive evaluation of dam safety and operational readiness [151], [152], [153]. Figure 5 (f) shows the concept of resilience can defined as a normalized function that indicates the ability to maintain a level of performance, $\mathrm{Q(t)}$, for a specific system over time,t_{LC} (life cycle time) [154]. The structural recovery time, t_{RE}, and the business interruption time, t_{BL}, are both included in t_{LC} (usually negligible). The time required to restore the functionality of a critical infrastructure system is denoted by t_{RE} (and usually an RV with high uncertainties). The formula for resilience as shown in Equation 7,

$$\mathrm{Resilience} = \int_{\mathrm{t_o}}^{\mathrm{t_{RE}}} \frac{\mathrm{Q(t)}}{\mathrm{t_{RE}}}\,\mathrm{dt} \quad 7$$

The emphasis on resilience, particularly resistance, within critical structures like dams is paramount due to the significant consequences associated with their failure. Resistance serves as a key parameter in ensuring that dams can endure and function during and after catastrophic events, thereby minimizing potential damages, preserving public safety, and ensuring the continuity of essential services. To summarize the seismic risk assessment of dams utilizing a risk-based framework assessment remains challenging due to the paucity of failure case histories and the uniqueness of each structure, which impedes the establishment of limit states [22]. Similarly, a performance-based earthquake engineering (PBEE) framework is already in place to assess buildings and bridges' seismic safety [155]. However, its application to dams is still being researched, and recently various publications discussed incorporating the PBEE framework in the dam sector [156], [157].

2.5. Deterministic and probabilistic analysis

Conventional seismic safety analyses rely on extreme loads that are statistically rare, which can overlook a variety of uncertainties. While safety is paramount, this approach can sometimes result in suboptimal or even hazardous outcomes due to oversimplifying complex situations [131]. Experts use judgment to determine load and resistance factors that provide a safety cushion, ensuring that the dam meets acceptable performance standards while accounting for uncertainties such as load intensity, resistance precision, and inaccuracies in structural analysis techniques [75], [158]. However, this binary approach of labeling structures as either 'safe' or 'failed' is becoming more widely recognized as insufficient, sometimes leading to costly and unnecessary modifications [159], [115].

In recent years, dam safety practices have shifted towards probabilistic methods that embrace inherent ambiguities. Through contemporary research, these methods have demonstrated numerous advantages [55], [160]. While not a new concept, probabilistic methods are rooted in construction safety practices [124] and nuclear facility safety protocols [133]. Their evolution has led to their current application in performance-based earthquake engineering (PBEE) for buildings [161] and potential failure mode analysis (PFMA) for dams [162]. Probabilistic assessments establish a more intricate risk profile, serving as a standalone evaluation and a corroborative layer for deterministic safety checks [163]. By conceptualizing load and material properties as stochastic variables, probabilistic models effectively translate uncertainties into a measurable likelihood of structural failure. Although probabilistic methods require a more comprehensive data set than deterministic methods, they provide profound insight into the model's robustness. Key performance indicators such as the probability of failure (P_f), design points, response statistics (mean and variance), and sensitivity indices [164] are offered to provide a comprehensive understanding of the model's reliability.

Figure 6 presents an illustrative comparison between deterministic and probabilistic analytical approaches. The schematic distinguishes the fundamental methodological differences, showcasing how deterministic analysis typically produces a definitive outcome based on fixed input parameters. In contrast, probabilistic analysis acknowledges the variability in these inputs and computes a spectrum of possible outcomes represented by a range of probabilities. This contrast underlines the shift from a binary perspective of safety, prevalent in deterministic methods, to a gradient of risk levels that probabilistic methods offer, providing a richer, more nuanced understanding of potential safety scenarios.

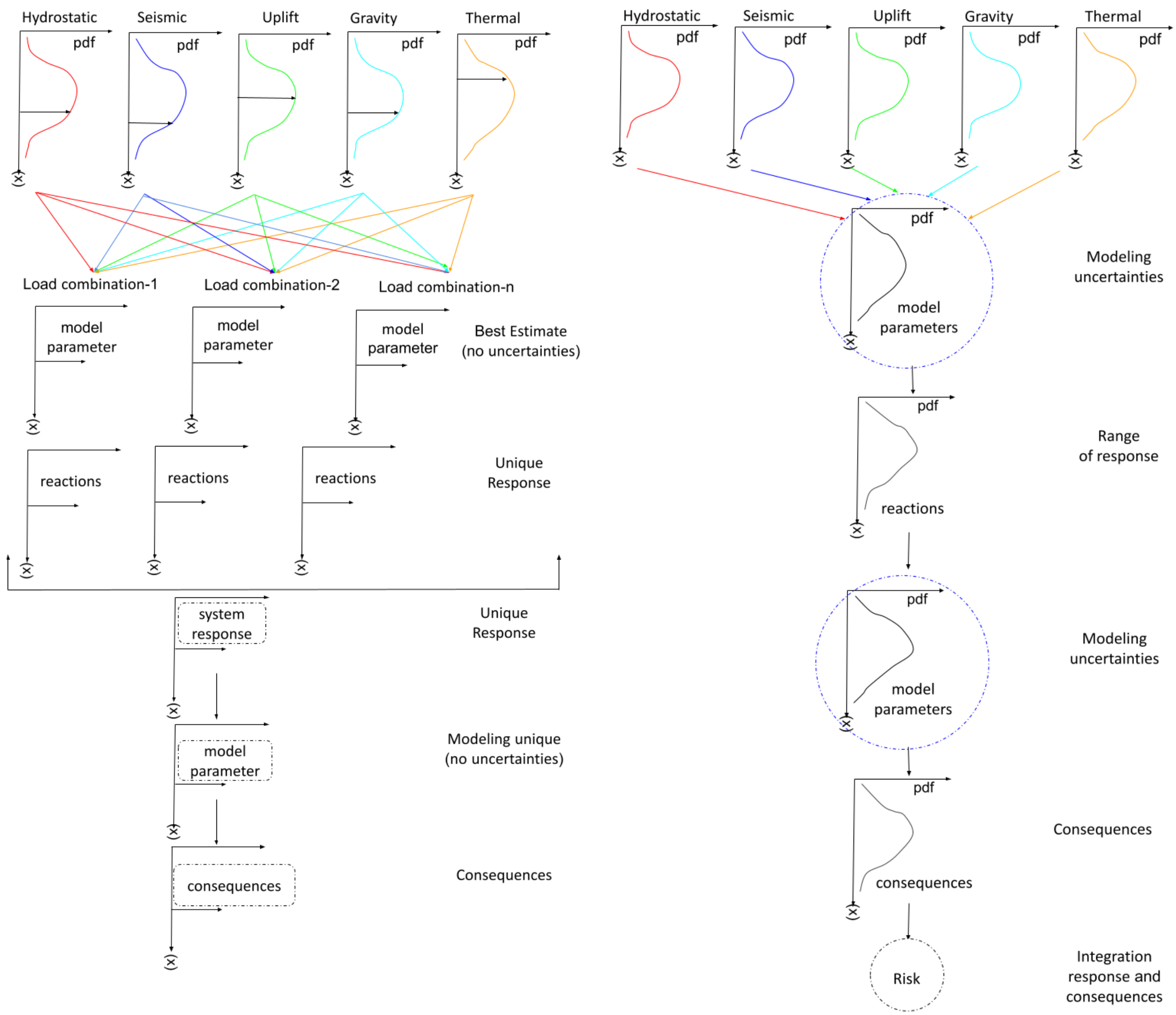


Figure 6. Analysis type a) deterministic; b) probabilistic [165]

2.6. Classification of uncertainties in RBA process

Risk is inherently tied to uncertainty; without uncertainty, the outcomes of events could be forecasted with absolute certainty, nullifying potential risks [50]. A myriad of uncertainties can impinge on the safety assessment process, including but not limited to uncertainties in phenomenology, decision-making, modeling, predictions, physical parameters, statistical data, and human factors [40], [50]. In risk analysis, uncertainties often arise from assumptions in modeling, inaccuracies, or parameter variability, such as loadings and material properties. Addressing these uncertainties necessitates conducting sensitivity analyses and employing stochastic or probabilistic methods [166].

Contrastingly, deterministic analysis overlooks uncertainties or relies on the most plausible estimates from expert judgments [167]. Integrating uncertainty analysis with risk assessment furnishes a more comprehensive understanding of the risk landscape, with the confidence levels in risk assessment being shaped by how uncertainties are processed through risk analysis protocols [168]. However, representing and managing uncertainties within risk assessments remains complex, especially concerning their influence on decision-making processes. The critical challenges are twofold: (i) effectively characterizing and presenting available knowledge to facilitate informed decision-making and (ii) ensuring decision-makers comprehensively comprehend the uncertainties involved [120]. Given their influence on outcomes, it is imperative to categorize and assess various uncertainties associated with loads, material characteristics, and numerical models [59], [22]. These uncertainties, which include epistemic and aleatory uncertainties, demand nuanced levels of analytical depth for systematic identification, classification, and reduction [169]. As shown in Figure 7 (a) and (b), these uncertainties permeate different stages of risk assessment and are broadly categorized accordingly. Handling uncertainty involves defining a range or distribution for each node within the event tree, subject to Monte Carlo analysis to delineate the "cloud" of uncertainty [170]. Tools like DAMRAE-U and iPresas Calc facilitate the structured analysis of epistemic and aleatory uncertainties within event tree variables [59], [60]. However, a thorough treatment of uncertainty is only sometimes practical due to feasibility and cost implications, necessitating a stepwise and systematic approach contingent upon the problem's complexity [171]. The process of uncertainty quantification encompasses the classification of random variables, sensitivity analysis, sampling strategies, design of experiments, machine learning techniques, and the application of various uncertainty treatment methods as discussed by various authors [114], [51], [172]. While uncertainties are typically expressed in probabilistic terms, there is an emerging discourse on the need to extend beyond conventional probability to account for vast, profound uncertainties and unpredictable events, such as "black swans," through alternative frameworks like imprecise probability, probability-bound analysis, and possibility theory [18], [173].

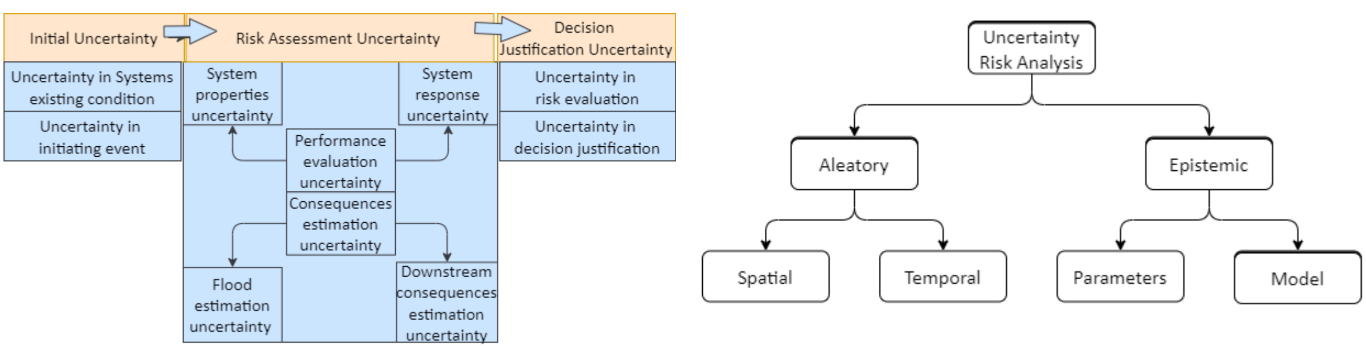


Figure 7. Classification of uncertainties (a) uncertainties at various levels [167], (b) taxonomy of uncertainty [33]

2.7. Methods of seismic safety assessment

Seismic safety assessments for concrete gravity dams are designed to evaluate the likelihood of failure or damage when subjected to various intensities of seismic activity. Multiple approaches exist to determine this seismic risk. Failure modes-based assessment involves identifying possible failure mechanisms such as sliding, cracking, and overturning. The likelihood of each failure mode is evaluated through either basic or advanced analytical methods, considering the specific conditions and characteristics of the dam. Critical stress state assessment, concentrating on the dam's most vulnerable points, like the base, heel, toe, and lift joints, this method calculates the odds of the stress at these points surpassing the strength or allowable stress limits of the concrete or its foundations. Energy Dissipation Assessment: by analyzing the energy dissipated by the dam under seismic load, including hysteretic, radiation damping, and fracture energies, this approach estimates the likelihood of damage using metrics like the energy dissipation ratio or a damage index. Performance-based assessment defines specific performance goals and limits states for the dam, such as functionality, safety, and prevention of collapse; this method utilizes nonlinear dynamic analysis and fragility curves to determine the probability that the dam will meet these established objectives. Damage coefficient assessment, utilizing a damage coefficient that depends on factors such as peak ground acceleration, velocity, displacement, and the dam's natural frequency, this method quantifies seismic damage to derive fragility curves. Each method has its strengths and weaknesses, including varying levels of precision, complexity, data requirements, and ease of interpreting results. The selection of the most appropriate method for seismic risk assessment hinges on the study's specific goals, scale, and available resources.

In conclusion, this chapter has laid down a foundation for understanding the seismic performance evaluation of concrete gravity dams, intricately weaving through the various threads of deterministic and probabilistic assessments, model selection, and the important role of ground motion selection. It has shed light on the impact of aging on these critical structures and factored into any risk assessment framework. Additionally, the chapter has underscored the multifaceted nature of uncertainties inherent in risk assessment, emphasizing the need for careful consideration. This groundwork will be instrumental in guiding the case studies that follow, serving as a cornerstone for the applied research and analysis that form the core of this thesis.

Chapter 3

Methodology

In this research, a structured approach is employed to investigate the seismic safety of concrete gravity dams. The approach is carefully designed to cover every aspect of the problem, from foundational background to advanced analysis and framework proposal. To begin, the stage is set by defining the problem and establishing the research context in an introductory chapter. A comprehensive review of relevant literature across key domains pertinent to dam safety assessment is then conducted in the second chapter. This critical analysis identifies gaps and opportunities for further investigation.

Subsequent chapters are dedicated to in-depth case studies that form the core of the seismic performance evaluation. Chapter four focuses on selecting a consistent numerical model and evaluating various modeling approaches to determine the most effective strategy for simulating the seismic behavior of dams in alignment with the study objective. In chapter five, the impact of ground motion selection techniques on dams' fragility and risk assessment is examined, using the Pine Flat Dam as a primary example. This case study showcases how different ground motion selection methods can influence the outcomes of seismic safety evaluations.

Chapter Six delves into the effects of material degradation due to aging and construction heterogeneity, further exploring how these factors affect the fragility assessment of dams. The Pine Flat Dam is again the main subject for analysis, providing a detailed examination of how material properties impact seismic risk assessments. In chapter seven, the findings from the case studies are synthesized to propose a comprehensive framework for the seismic risk-based safety assessment and management of concrete gravity dams. This chapter also outlines the future scope of work, suggesting directions for extending and enhancing the research. The important steps involved in this research, are listed below, to ensure a systematic investigation of the seismic safety of concrete gravity dams.

A) Comparative assessment of existing safety assessment practices;

B) Comprehensive literature review of the key inline domains;

C) Selection of a consistent numerical model;

D) Defining target spectrum and ground motion selection;

E) Variation of material properties due to aging and construction heterogeneity;

F) Identification of the failure mode of a gravity dam;

G) Defining the damage index or limit states;

H) Developing the fragility curves;

I) Impact of variation in material properties and ground motion selection on fragility assessment;

J) Formulation of risk assessment;

K) Development of proposed seismic risk assessment framework.

The research methodology encompasses a systematic exploration of seismic safety assessment for concrete gravity dams, articulated through a series of logically sequenced steps and thematic chapters.

Each chapter builds upon the previous, culminating in a cohesive framework that addresses the multifaceted aspects of dam safety under seismic threats. Below is a detailed outline of the concepts and analytical approaches as they unfold in the subsequent chapters of this thesis.

3.1. Consistent numerical model

Numerical simulation is pivotal in assessing the coupled dynamic behavior of Dam-Foundation-Reservoir (DFR) systems, underpinning the accurate estimation of their responses to seismic events. The development of numerical models for such complex systems encompasses a range of simulations, including two-dimensional DFR models that account for static and dynamic conditions, with analyses extending from linear to nonlinear realms. Material nonlinearity is particularly emphasized to capture the realistic behavior of structural components under stress. At the same time, dynamic analyses incorporate the critical interactions of Fluid Structure (FSI) and Soil Structure (SSI), further enriched with spectrum-matched seismic histories to simulate actual ground motion scenarios.

Given the intricate nature of finite element models required to elucidate the fundamental dynamics of the dam-foundation-reservoir interaction, coupled with the substantial computational demands of conducting fully probabilistic analyses, this study advocates for a progressive simulation strategy. This approach gradually increases in complexity, meticulously balancing computational efficiency and the accuracy of results. Model variability, which refers to the differences and uncertainties inherent in using various numerical models to simulate complex systems, emerges as a significant challenge. Such variability is rooted in divergences in model assumptions, boundary conditions, material properties, and computational techniques, where minor discrepancies can lead to markedly different predictions of system behavior.

To mitigate the impacts of model variability and enhance the reliability of simulation outcomes, it is critical to implement rigorous verification and validation protocols, undertake comprehensive sensitivity analyses, and employ advanced uncertainty quantification methods. These methodologies are crucial for assessing the reliability and precision of model predictions, thereby bolstering the trustworthiness of computational analysis, and supporting informed engineering decisions.

Within dam safety evaluations, the significance of model variability is magnified by the disparate results that can arise from different modeling approaches and levels of complexity. From fundamental linear analyses that approximate general structural behaviors to sophisticated nonlinear simulations that account for material and geometric nonlinearity, the choice of modeling strategy profoundly influences the fidelity of dam response predictions under seismic loading. Transitioning from simplified dam models to more complex coupled systems that integrate the dam, its foundation, and the reservoir introduces additional dimensions of complexity, necessitating fluid-structure and soil-structure interaction considerations for a holistic representation of the dam system dynamics. Selecting an appropriate modeling approach tailored to the unique characteristics of the dam and the specific objectives of the safety assessment is paramount. This careful selection process ensures the accurate management of model variability, safeguarding dam infrastructure's structural integrity and operational safety against seismic threats.

3.2. Target response spectra and ground motion selection

In the context of seismic safety assessments, defining a target spectrum and selecting appropriate ground motions are pivotal steps to ensure the accuracy and relevance of the analysis. This study employs the ASCE 7-16 guidelines and the Conditional Mean Spectrum (CMS) method for ground motion selection, which is instrumental in capturing the site-specific seismic hazards and the expected seismic performance of structures. A target spectrum is developed for various seismic hazard intervals derived from the site's seismic hazard curve, incorporating common target spectra such as the Uniform Hazard Spectrum (UHS), Conditional Spectrum (CS), and CMS. The UHS is constructed by aggregating seismic hazard curves across multiple vibration periods, determining the spectral acceleration Sa (T*) for a given exceedance probability or return period. The CS defines the distribution of spectral accelerations over a range of periods, conditioned on the acceleration at a particular period T* [174], considering the correlation between spectral accelerations at different periods [97].

While the UHS and CMS are often similar for frequent seismic events, the CMS provides a less conservative but more precise spectrum for singular earthquakes, reflecting lower amplitude at specific periods for less frequent events than the UHS. Unlike the CMS, the CS introduces variability in spectral values, enhancing the precision of response estimates for specific earthquake intensities. The CMS and CS methodologies offer more accurate response predictions than the UHS but require a more detailed development process. Moreover, the Generalized Conditional Intensity Measure (GCIM) method extends CMS's capabilities by including various ground motion parameters beyond response spectra [96]. The GCIM technique involves creating a multivariate distribution for a set of ground motion Intensity Measures (IMs) based on the occurrence of a specific ground motion IM, typically derived from Probabilistic Seismic Hazard Analysis (PSHA). This nuanced approach to target spectrum definition and ground motion selection, incorporating ASCE 7-16 and CMS alongside advanced methodologies like GCIM, ensures a thorough and site-specific assessment of seismic risks, crucial for the reliable evaluation of dam safety under seismic loading.

3.3. Variation in material and loading properties

In assessing seismic safety for concrete gravity dams, the uncertainty of material properties and loading parameters is crucial in shaping risk evaluations and mitigation strategies. Two primary sources contribute to the critical uncertainties: the inherent variability in material properties and loading conditions. Material properties, such as strength and elasticity, can vary significantly due to aging and construction heterogeneity, leading to deterioration in material strength over time and non-uniform material characteristics across the structure. These variations introduce epistemic uncertainties, making it challenging to accurately predict how materials will perform under stress.

Likewise, the loading on a dam encompasses a wide range of uncertainties, from hydrostatic pressures and thermal loads to the seismic forces themselves. Ground motion variation is a critical concern, as the intensity and characteristics of seismic events can significantly differ based on geographical location and local geological conditions. Site-specific response spectra further complicate this picture, requiring detailed knowledge of local seismic activity to model potential loads accurately. These uncertainties demand a comprehensive approach to seismic safety assessment, incorporating advanced modeling techniques and probabilistic analyses to account for the spectrum of variables affecting dam stability and performance. The process for quantifying uncertainty involves several key steps, including identifying and classifying random variables, conducting sensitivity analysis to determine their impact, performing uncertainty analysis to understand the potential range of outcomes, applying sampling techniques to explore the variable space, and evaluating the correlation between variables. Figure 8 illustrates various loads that act on a gravity dam, highlighting the complexity of the forces at play and the importance of considering these diverse factors in the dam's safety assessment.

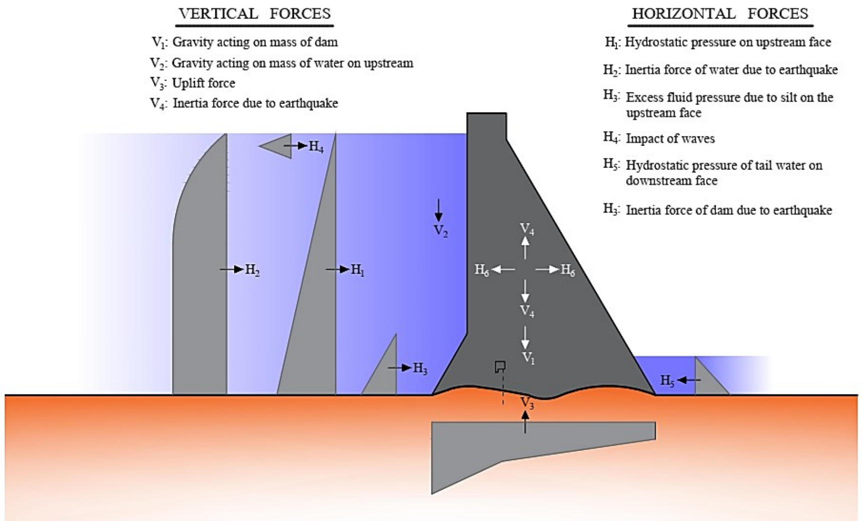


Figure 8. Various loadings on a gravity dam

3.4. Potential failure modes

Identifying potential failure modes is a critical step in assessing the seismic safety of gravity dams, as it informs the selection of appropriate damage indices for robust risk evaluations. Figure 9 highlights key areas within a gravity dam structure where cracking and subsequent failure are most likely to initiate, particularly under the stress of normal reservoir levels and seismic loading conditions. These critical areas include (A) the neck region at the change of slope on the downstream face, where tensile stresses can concentrate; (B) at lift joints across various elevations, which may weaken and allow for the propagation of cracks; (C) along the dam-foundation interface at both the toe and heel of the dam, where shear and tensile stresses can lead to separation and sliding; and (D) within the dam's foundation itself, where horizontal, vertical, or inclined cracking may occur due to the transmission of seismic forces through the dam structure into its base. Understanding these failure mechanisms is essential for developing effective monitoring and mitigation strategies to enhance the seismic resilience of gravity dams.

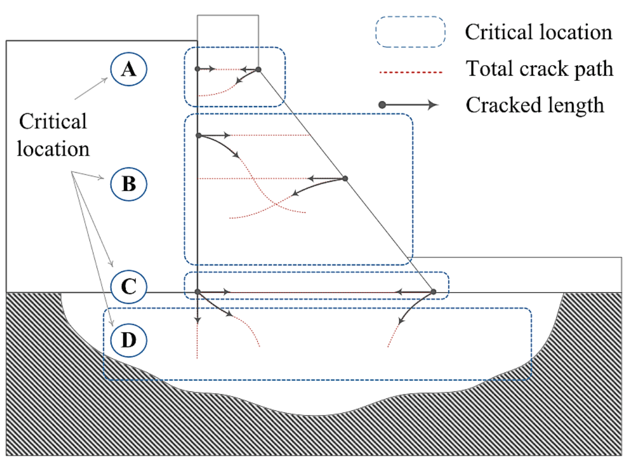


Figure 9. Potential failure modes of a gravity dam adapted from [162]

3.5. Damage Index

Damage indices (DI_s) play a pivotal role in assessing the seismic performance of dams by quantifying the extent of structural damage. These indices are derived from key structural response parameters, such as modal values, crest displacement, stress at critical locations, energy dissipation due to damage, drift ratio, and interface sliding. Guidelines from authoritative bodies like the US Army Corps of Engineers (USACE) and the United States Bureau of Reclamation (USBR) provide thresholds and limiting values for these parameters, which have become a standard practice among researchers and practitioners for evaluating seismic performance.

Building upon this established practice, various authors have proposed the concept of damage indices to assess damage at local, intermediate, and global levels of a structure. As detailed in Table 2, these indices are developed as either univariate or multivariate functions of response parameters, offering a nuanced view of structural integrity post-seismic events. (DI_s) are categorized based on several criteria: their applicability at local versus global levels, whether they analyze a single variable or multiple variables, their accumulation of damage over time (cumulative vs. non-cumulative), their basis on deterministic or probabilistic methods, their focus on physical damage or economic implications, and their evaluation of structural versus economic impacts.

A local damage index (DI_L) pinpoints failure along specific crack paths, highlighting areas of concentrated damage, while a global damage index (DI_G) encapsulates the overall failure state of the system. This distinction allows for a comprehensive understanding of a dam's seismic vulnerability, from pinpointing localized damage that may require immediate attention to assessing the overall structural integrity and safety. By employing damage indices, engineers and safety professionals can gauge the level of damage more accurately, informing repair, retrofit, and maintenance decisions to ensure the continued safety and functionality of dam structures.

Table 2. Damage indices proposed by various authors

Authors	Damage Indices (DI_s)	Summary
Banon and Veneziano [175]	$DI_{NCR} = \sum_{i=1}^{n} \frac{\lvert(\theta_{max})_i - \theta_y\rvert}{\theta_y}$	$(\theta_{max})_i$ is maximum rotation at i^{th} cycle; θ_y is yield value; and n = number of cycles; NCR is normalized cumulative rotations
Park and Ang [176]	$DI_{p-A} = \frac{\Delta_{max}}{\Delta_{mon}} + \beta \frac{E_H}{F_y \Delta_{mon}}$	Δ_{max} is maximum deformation; Δ_{mon} is ultimate deformation; F_y is yield strength; E_H is dissipated energy
Wang and Shah [177]	$DI_D = 1 - \frac{F_y}{F_{max}}$	F_y is failure force during a loading cycle; F_{max} is maximum force during the previous cycle
Dipasquale and Cakmak [178]	$DI_{max} = 1 - \frac{T_{UD}}{T_{max}}$ $DI = 1 - \frac{T_D^2}{T_{max}^2}$ $DI_F = 1 - \frac{T_{UD}^2}{T_D^2}$	T_{UD} is period corresponding to undamaged structure; T_{UD} is period corresponding to damaged structure; T_{max} is natural period related to maximum softening
Hariri-Ardebili and Saouma [179]	$f(L^c, E_F, \mu_{max})$	L^c is crack length; E_F is dissipation energy; and μ_{max} is maximum drift
Powell and Allahabadi [180]	$DI_\mu = \frac{\Delta_{max} - \Delta_y}{\Delta_{mon} - \Delta_y} = \frac{\mu - 1}{\mu_{mon} - 1}$	Δ_{max} is maximum deformation; Δ_y is yield deformation; Δ_{mon} is maximum deformation due to monotonically increasing lateral deformation
Cosenza and Manfredi [181]	$DI_{EH} = \frac{E_H}{E_{Hmon}}$	E_H is non-recoverable dissipated hysteretic energy; E_{Hmon} is hysteretic energy capacity of the structure obtained from pushover analysis

3.6. Development of fragility function

The development of fragility functions is a critical aspect of seismic risk assessment, providing a quantifiable measure of the likelihood of failure or exceeding a specified limit state in response to varying applied load levels. These functions are versatile and applicable across various stressors, including earthquakes, floods, and wind events. Fragility functions can be depicted in two formats: as two-dimensional fragility curves or three-dimensional fragility surfaces, as illustrated in Figure 10. A fragility curve represents a continuous function that maps the probability of exceeding a particular limit state (LS) against a specific level of ground motion intensity measure (IM), as detailed in Equation 5. Fragility curves are further categorized into empirical, heuristic, analytical, or experimental types depending on the nature of the data utilized for their development.

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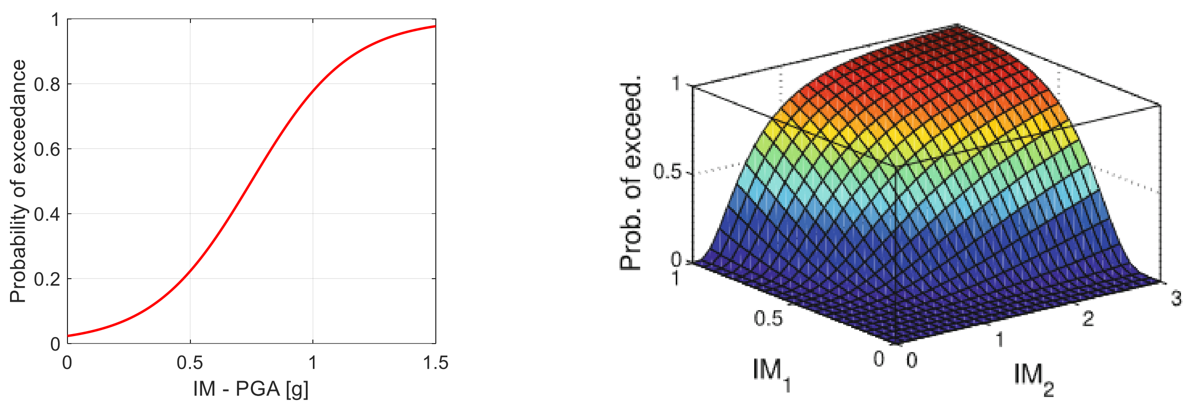
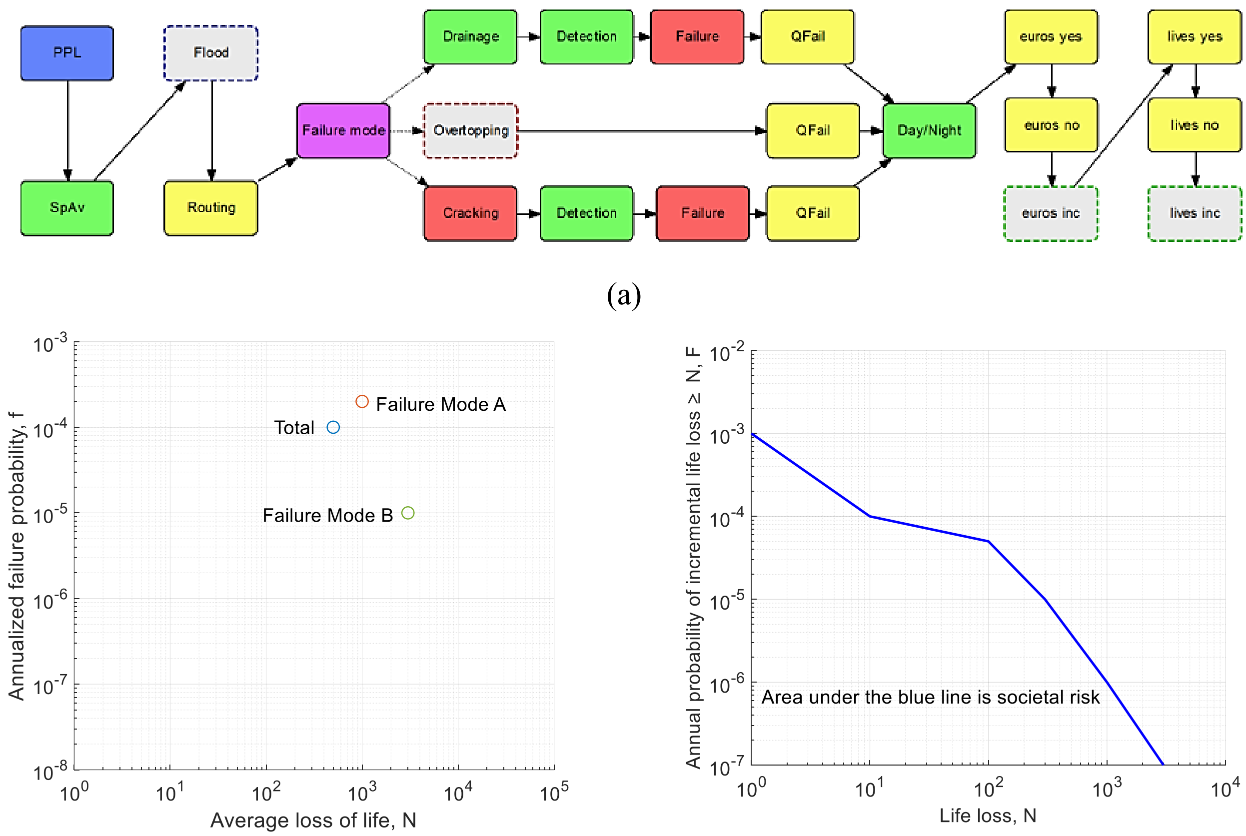


Figure 10. Fragility functions (a) fragility curve (b) fragility surfaces two IMs adapted from [182]

This study focuses on formulating analytical fragility curves, derived from the outcomes of numerical simulations tailored to assess predefined limit states. Such an approach allows for a refined understanding of the dam's behavior under seismic loading, accounting for the complexities and variabilities of seismic forces and material properties.

3.7. Formulation of risk assessment

The formulation of risk assessment in this study is intricately linked to the outputs derived from fragility analysis, offering a comprehensive understanding of the seismic vulnerability of dams to various failure modes. By examining the impact of ground motion variability, the risk assessment process specifically targets selected failure modes, providing a detailed evaluation of potential risks associated with seismic events. The iPresas software suite, particularly iPresas Calc [60], is crucial for assessing risks associated with dam infrastructure. It allows the creation of visual models such as influence diagrams or event trees, as seen in Figure 11 (a), to illustrate possible sequences of events that could lead to dam failure, incorporating probabilities based on fragility functions. iPresas Calc is user-friendly and capable of evaluating diverse load scenarios, failure modes, and consequences. iPresas Manager augments this by facilitating the management of safety-related investments, while iPresas HidSimp offers a streamlined option for hydrological risk assessments of dams. Additionally, the software's output functions, depicted in Figure 11 (b) and (c), provide a quantitative understanding of the likelihood and impact of each identified failure mode. This approach allows for a detailed risk analysis, where the likelihood of different failure scenarios and their impacts are systematically quantified and visualized. Integrating fragility analysis results with risk assessment through tools like iPresas Calc enables researchers and engineers to construct a detailed and actionable understanding of seismic risks, guiding decision-making processes for mitigation, preparedness, and response strategies to enhance the resilience and safety of dam infrastructures against seismic threats.



(b) (c)

Figure 11. (a) Event tree (b) fN plot for loss of life and (c) FN plot loss of life, developed using iPresas Calc [60]

In summary, the methodology employed in this thesis presents a unified framework for seismic risk assessment of concrete gravity dams, incorporating a thorough literature review, the use of sophisticated numerical models, and the development of criteria for ground motion and target spectra. It systematically addresses the impact of material aging and construction inconsistencies, the identification of failure modes, and the establishment of damage indices. By constructing fragility curves and integrating the influence of material properties and ground motion selection, the research meticulously formulates a comprehensive risk assessment protocol, along with quantifying the impacts of associated uncertainty. This approach enriches the current understanding of dam safety, providing innovative strategies for improved seismic resilience and advocating for the adoption of more systematic dam safety practices. This meticulous approach facilitates a holistic understanding of the current state of dam safety assessment and offers novel insights and a valuable framework for enhancing the seismic resilience of concrete gravity dams. By meticulously addressing crucial elements of seismic safety and presenting evidence-based solutions, this research aims to advance the field and promote the adoption of more robust and reliable dam safety methodologies.

3.8. Proposed Framework for seismic risk assessment

In evaluating the seismic performance of dams, it is crucial to first understand the strengths and limitations of current safety practices. This foundational knowledge sets the stage for subsequent analyses and improvements. Recognizing that model variability significantly impacts system response and fragility assessments, it becomes essential to carefully select and validate modeling approaches. To manage computational resources effectively while exploring seismic impacts in a nuanced manner, the adoption of progressive analysis techniques is recommended. This approach not only conserves resources but also provides a deeper understanding of potential structural responses. Ground motion selection is another critical factor influencing dam response. Methodical selection processes are necessary to ensure accurate seismic risk assessments. Additionally, the effects of material degradation and construction variability must be considered, as these factors can alter system responses and fragility outcomes. Understanding the uncertainties inherent in the assessment process is key to reliable risk estimation. This includes variability in solution procedures, model complexity, ground motion selection, and material properties. Addressing these uncertainties through strategic planning enhances the seismic resilience of dam structures. By integrating these elements evaluating safety practices, managing model variability, adopting progressive analysis, selecting ground motions methodically, considering material degradation, recognizing assessment uncertainties, and planning strategically for uncertainty control a comprehensive and resilient framework for seismic risk assessment of dams can be established. This holistic approach ensures robust safety evaluations and the long-term resilience of critical dam infrastructures.

Chapter 4

Model variability

This chapter presents a case study that addresses the critical issue of variability in the seismic analysis of dams caused by modeling choices. To enhance the accuracy and usefulness of dam safety evaluations, it is important to understand the limitations and assess the impact of different modeling techniques. In pursuit of this goal, a comprehensive parametric study was conducted to explore the seismic response variability of Koyna and Pine Flat dams, using a range of analytical approaches and levels of model complexity. The study involved 2D numerical simulations across three different software platforms, examining various dam system configurations. Additionally, it modeled reservoir dynamics using Westergaard-added mass or acoustic elements, adding to the complexity. The study conducted both linear and nonlinear analyses, incorporating the concrete damage plasticity model for material properties.

4.1. Introduction

Seismic performance evaluation plays a pivotal role in safeguarding the integrity and functionality of critical infrastructure, such as dams. It involves scrutinizing how these structures withstand severe events like earthquakes and ensuring compliance with regulatory standards. Nonetheless, this evaluation process encounters diverse uncertainties stemming from the intricate nature of the system, limited understanding of seismic hazards, and simplifications made during analysis. These uncertainties wield significant influence over dam behavior and decision-making processes, underscoring the imperative of comprehensively understanding their implications.

The uncertainties affecting seismic assessments can be classified into two main categories: aleatory and epistemic. Epistemic uncertainty arises from knowledge limitations, stemming from data gaps, incomplete understanding of phenomena, and simplifications in modeling. It encompasses variations in model parameters, structural attributes, and solution methodologies, all of which affect the computation of structural responses. In contrast, aleatory uncertainty, also referred to as inherent or irreducible uncertainty, originates from natural randomness and variability, encompassing ground motion characteristics and the complexity of systems. Unlike epistemic uncertainty, which arises from inadequate information, aleatory uncertainty is inherent and cannot be eliminated through enhanced data or understanding. To enhance the precision and robustness of seismic assessments, it is crucial to explore and quantify the uncertainties associated with various modeling decisions. This entails scrutinizing the selection of solution procedure, model complexities, and the incorporation of various loading and boundary conditions [33], [183]. Figure 7 (b), Chapter 2 shows the taxonomy of uncertainty in risk analysis.

These uncertainties stem from various factors, including the selection of solution procedures, model complexities, and consideration of loading and boundary conditions. By exploring and comprehending these uncertainties, engineers, and researchers can make informed decisions in rehabilitation and risk management processes for structures facing seismic hazards. The choice of solution procedures in seismic analysis involves selecting suitable numerical methods and algorithms to simulate the dynamic behavior of structures. Additionally, different solution procedures may produce different results due to the inherent assumptions and limitations of each method [184], [90]. Understanding the uncertainties linked with different solution procedures enables the identification of the most appropriate approach for various stages of seismic assessments.

Model complexities play a pivotal role in capturing the behavior of real-world structures. It is crucial to emphasize the significance of a progressive approach in dam safety assessment, which entails using increasingly complex models. This approach is particularly valuable in the dam industry, where conducting detailed analyses for every situation may not be feasible. The level of detail in modeling influences the accuracy of predictions and the capacity to consider important structural features [185]. The selection of the method for safety assessment is influenced by various factors: the structure's scale and potential damage consequences, its current state (well-maintained or deteriorated), and the required precision of the analysis [186]. Furthermore, the impact of modeling uncertainty on system response parameters can be mitigated by incorporating a robust verification and validation framework [187]. The study presented in [187], model variability arising from epistemic uncertainty was thoroughly investigated using data from the International Commission on Large Dams (ICOLD) and United States Society on Dams (USSD) benchmark studies [188], [80], and the quantification of modeling variability was carried out using dispersion or logarithmic standard deviation. A comprehensive understanding of modeling uncertainty is imperative for enhancing the reliability of seismic assessments in dam safety.

The chosen modeling approach must also consider the trade-off between the need for accuracy and detail with the practical constraints of time, resources, and available data, which will also influence risk management decisions. Traditionally, if simpler and more expedited analyses (such as 2D, linear, and pseudo-static approaches) do not meet the minimum seismic safety requirements, a more detailed analysis is necessary. Understanding the variability introduced by the different layers of model complexities is critical to help engineers determine the level of detail required for reliable assessments and assess the sensitivity of structural response to different modeling choices [189]. To this end, this chapter aims to evaluate the dam's response variability associated with different modeling configurations within a progressive seismic analysis framework. To achieve this, a detailed parametric study incorporating various solution approaches and model complexities will be used. The assessment was carried out using different software such as EAGD-84, ADRFS v1, and Abaqus 6.14 [190], [191], [192]. The response of the dam only, as well as the interaction with the foundation and reservoir, was considered. The modeling variability in the seismic response is evaluated through the comparison of modal parameters and crest displacement time-histories, across the different modeling configurations. The methodology was applied to two case study dams with well-documented geometric, material, and dynamic properties, Koyna, and Pine Flat. These findings are essential for the improvement of safety assessment, shedding light on the variations associated with different modeling decisions, advantages, and disadvantages and the adequacy of each approach for different dam safety analysis stages where varying complexity methods might be required.

4.2. Seismic analysis of dams

The seismic analysis of concrete dams primarily relies on numerical simulations, employing suitable analysis methodologies to accurately estimate system response [193], [194]. Throughout the seismic safety assessment process, thorough attention must be given at every stage. This involves ensuring the utilization of accurate material properties, the selection of appropriate ground motion, proper scaling, the choice of a suitable numerical model (either 2D or 3D), the application of appropriate boundary conditions, and the implementation of the correct analysis techniques [195], [196], [197]. As illustrated in Figure 4 (b), Chapter 2, the seismic performance evaluation of a concrete gravity dam should be conducted progressively, meaning that increasing complexity, computational effort, and alignment with the assessment objective should be taken into account [86], [87], [88], [198]. In this study, both linear and non-linear analyses were employed with varying system configurations. According to Figure 4 (b), Chapter 2, linear analysis offers good capability with low computational effort, whereas non-linear analysis provides very good capability with moderate computational effort. The subsequent sections further elaborate on the different analyses considered in this study.

4.2.1. Linear vs. non-linear analysis

Based on the solution objective, required computational stability, and accuracy considerations, dynamic analysis can be either linear or nonlinear and can operate in either the time or frequency domain. A linear analysis can offer insights into overstressed areas, but to truly grasp the actual dynamic behavior, a nonlinear analysis becomes necessary [89], [199]. While a linear analysis can estimate the response of a structure (stress and deflection) and suggest potential deterioration, it is limited in its ability to predict failure. Linear-elastic analysis, augmented with increased safety margins, is typically sufficient for dams subjected to an operating or design basis earthquake (OBE or DBE). Linear studies can predict damage but not failure, as they do not account for stress redistribution caused by fractures or the opening and closing of contraction joints [86]. Moreover, linear analysis often relies on simplifying assumptions, such as modeling monolithic dams (ignoring contraction joints and weak lift lines), monolithic foundations (ignoring joints and discontinuities), incorporating added mass for hydrodynamic interactions, and employing linear elastic material models [200], [92], [201]. Due to these simplifications, linear assessments are inherently limited and fail to fully capture the structure's true behavior. By alleviating the simplifying assumptions inherent in linear analysis, nonlinear analysis can provide more accurate estimates of a structure's dynamic behavior [202]. Consequently, nonlinear analysis can offer a more realistic estimation of the likelihood of failure and the extent of damage, which are crucial for seismic risk assessment.

4.2.2. Horizontal vs. combined earthquake components

In the realm of dam seismic assessment, analyzing solely the horizontal earthquake components, rather than considering both horizontal and vertical components together, introduces distinct considerations for stability analysis. Both horizontal and vertical ground motions play a role in influencing the seismic response of dams, with each contributing differently to the overall structural behavior. When focusing solely on horizontal earthquake components, the primary emphasis lies on the lateral forces and torsional effects that dams may encounter during seismic events. This approach is particularly pertinent for evaluating the stability of dam structures against sliding, overturning, and other failure modes induced by lateral ground motion. Horizontal ground motions are pivotal for comprehending the potential effect of seismic events on the dam's integrity, its foundation stability, and its interaction with the reservoir [203].

Conversely, incorporating both horizontal and vertical components offers a more comprehensive depiction of the dynamic forces acting on a dam. Vertical ground motions introduce additional effects, such as uplift and dam-water interaction, which can significantly influence the structural response and potential failure modes. Vertical motions also contribute to the potential for base sliding, foundation settlement, and alterations in the reservoir water level [204].

Two-dimensional (2D) analyses of dam geometries remain the predominant approach for designing or evaluating gravity dams. Many of the three-dimensional analysis methods developed in the past were tailored to arch dams [205]. In such analyses, either a single (horizontal) or two-component (horizontal and vertical) approach is utilized for seismic loading. However, when incorporating the second horizontal component, the analysis transitions into three-dimensional (3D), offering a more realistic depiction of the intricate interaction among the dam, foundation, and reservoir. The decision to analyze with only one horizontal component, with a single horizontal and vertical component, or with both horizontal components hinges on the specific characteristics of the dam, the seismic hazard scenario, and the engineering objectives. The presence of construction joints, a requisite for conventional concrete dam bodies, rationalizes to some extent the use of 2D analyses for concrete gravity dams, under the assumption that the monoliths behave independently during seismic events. The necessity for 3D modeling may arise when the accuracy of 2D models proves inadequate. Factors such as dam typology or the presence of dams in narrow canyons may influence this requirement [206]. For critical structures like dams, it is often advisable to conduct analyses using both approaches to comprehensively evaluate potential failure modes and ensure the structure's safety under varied seismic conditions [207].

4.2.3. System configuration

In the seismic assessment of dams, the selection of system configuration significantly influences the accurate prediction of structural response under seismic loads. Four primary model configurations are commonly employed: (i) dam only (D), (ii) dam-foundation (DF), (iii) dam-reservoir (DR), and (iv) dam-foundation-reservoir (DFR) system. The gradual integration of these complexities allows for a more realistic portrayal of the dynamic behavior and interaction of the entire dam system when subjected to seismic forces [186].

Commencing with the dam-only model, the structural response of the dam is scrutinized without considering interactions with its foundation or reservoir. This furnishes a fundamental understanding of the dam's inherent stiffness and response characteristics. As complexity escalates, the dam-foundation interaction is taken into account, introducing the effects of soil-structure interaction on the dam's seismic response. Subsequently, the dam-reservoir interaction incorporates hydrodynamic effects caused by the reservoir's water mass, including water-induced pressures and uplift forces. The pinnacle of complexity is reached in the coupled dam-foundation-reservoir model, which captures the combined effects of all three components. With increasing model complexity, damping and periods of vibration may alter, affecting the mechanisms of energy dissipation. The presence of foundation and reservoir components introduces additional vibration modes, influencing the system's natural frequencies and mode shapes.

Boundary conditions may vary depending on the model configuration. As complexity intensifies, boundary conditions encompass the interplay of structural, geological, and hydrodynamic factors incorporated into the model. Enhancing model complexity enriches seismic assessment by offering a comprehensive understanding of the entire dam system's behavior [208]. By progressively integrating dam-foundation-reservoir interaction, informed decisions can be made, optimizing design strategies, and fortifying the seismic resilience of dam structures.

4.3. Modeling variabilities in seismic analysis

The study highlights how the differing model complexities within the same solution procedure and variations across different solution approaches can impact the dam's response and subsequent safety assessments. Modeling variabilities are examined by considering various solution procedures, such as time or frequency domain, linear or nonlinear analysis, and model complexities encompassing D, DF, DR, and DFR systems. Further complexity is introduced by simulating the dynamic interaction of the reservoir using Westergaard-added mass and acoustic elements with non-reflecting boundary conditions. The foundation is modeled with uniform material properties and three sides fixed.

The numerical simulation is executed using three analysis tools: EAGD-84, ADRFS v1, and Abaqus, each employing a distinct solution procedure. The models are uniformly constructed across the software tools, maintaining identical material parameters, loads, mesh configurations, and boundary conditions.

Additionally, each software employs a unique approach to implement damping for both the dam and foundation. Specifically, EAGD-84 utilizes hysteretic damping, ADRFS v1 employs a damping ratio, and Abaqus adopts Rayleigh damping. The reservoir level is set to zero during the dynamic analysis for the D and DF models. Conversely, the full reservoir load is considered in the case of DR and DFR models. The study comprises two stages: firstly, conducting modal analysis on various model configurations (D, DF, DR, and DFR) to characterize the system's dynamic behavior; and secondly, estimating the maximum crest displacement while accounting for both linear and nonlinear material properties, along with either horizontal or horizontal and vertical seismic components. Table 3 presents a summary of the scenarios modeled in each software. Each simulation will be designated as shown in Equation 8 and Figure 12.

$$\mathrm{S}\overbrace{x}^{\text{Scenario}}.\underbrace{y}_{\substack{\text{Model}\\ \text{complexity}}}.\overbrace{z}^{\text{Software}} \qquad (8)$$

where x corresponds to the scenario and can take the following values:

- x=1, linear analysis considering only the horizontal seismic component;
- x=2, linear analysis considering the horizontal and vertical seismic components;
- x=3, non-linear analysis considering only the horizontal seismic component;
- x=4, non-linear analysis considering the horizontal and vertical seismic components;

y corresponds to different model complexities configurations corresponding to:

- y=1, dam only, D;
- y=2, dam-foundation, DF;
- y=3, dam-reservoir, DR;
- y=4, dam-foundation-reservoir, DFR;

and z corresponds to the software used for that simulation:

- z=1, EAGD-84;
- z=2, ADRFS v1;
- z=3, Abaqus M (added mass);
- z=4, Abaqus A (acoustic).

Table 3. Modeling capability of the software

	Software, z=			
Scenario, x=	1	2	3	4
1	✓	✓	✓	✓
2	✓	×	✓	✓
3	×	×	✓	✓
4	×	×	✓	✓

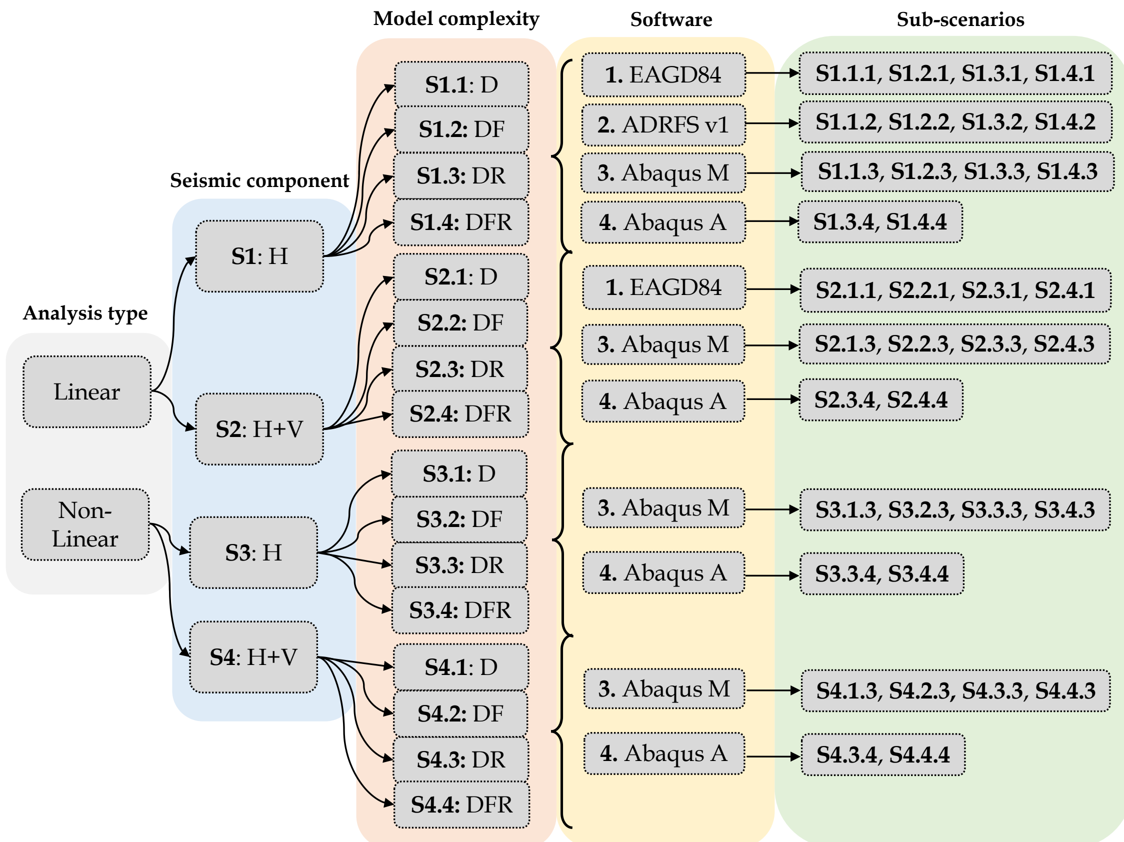


Figure 12. List of analysis scenarios considered for numerical simulation

The comparative analysis of various analysis scenarios using the three software tools offers insights into factors such as ease of use, flexibility, or scalability for parametric studies, the time required for each analysis, and modeling capabilities. The subsequent section delves into the selected software suite, namely EAGD-84, ADRFS v1, and Abaqus, focusing on their solution methodologies and modeling techniques employed in this study.

4.3.1. EAGD-84

The EAGD-84 software assesses the seismic response of concrete gravity dams utilizing a substructure formulation and a frequency domain analysis approach, incorporating dynamic dam-foundation-reservoir interactions, water compressibility, and reservoir bottom absorption [190]. The dam monolith is represented as a 2D arrangement of planar, non-conforming four-node finite elements. The typical dam-foundation-reservoir system, as implemented in the program, is depicted in Figure 13. Constant hysteretic damping is employed to represent energy dissipation in both the dam concrete and foundation. The reservoir is modeled as a fluid domain of constant depth and infinite length in the upstream direction, with the absorptiveness of the reservoir bottom materials defined by a wave reflection coefficient at the reservoir bottom. To incorporate the effects of dam-foundation interaction, the frequency-dependent dynamic stiffness matrix for the foundation region is established with regard to the degrees of freedom of the nodal points at the dam base. Horizontal and vertical seismic components can be applied simultaneously or individually using free-field ground acceleration.

Outputs from the program include hydrostatic loads, nodal point displacements, and element stresses due to static loads. Modal parameters can be estimated for the dam or dam-foundation with the selected interaction. Complete stress and displacement response histories for each finite element, as well as the peak maximum and minimum principal stress in each finite element, including the times of occurrence, are also provided. For both pre-processing input and post-processing output from EAGD-84, the source code can be run independently in a Windows environment or through a MATLAB [209] interface as developed by Løkke [210].

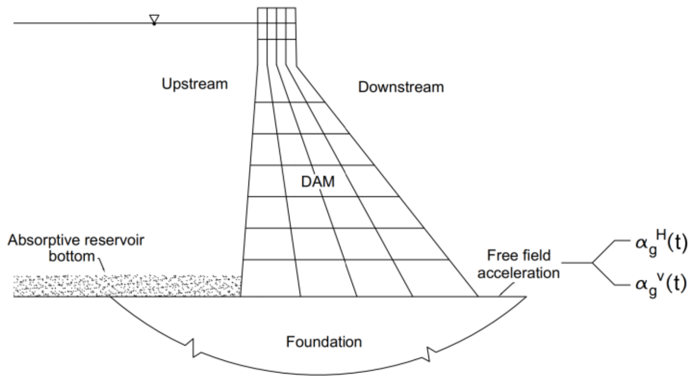


Figure 13 Dam- foundation-reservoir system [190]

In the context of this study, the dam and foundation are configured to plain stress, and linear dynamic analysis simulations incorporating various model complexities (D, DF, DR, and DFR) were conducted, considering both horizontal and combined horizontal and vertical components.

4.3.2. ADRFS v1

The ADRFS v1 is a MATLAB [209], based graphical user interface (GUI) software utilized for seismic analysis of concrete gravity dams, considering dam-foundation-reservoir interaction [192]. The software employs eight-noded isoparametric quadrilateral plain stress elements for both the dam and the foundation. It accommodates the foundation's flexibility and the compressibility of the reservoir. The dam and foundation domains utilize displacement-based plane stress/strain finite element formulation, while a pressure-based finite element formulation is employed for the reservoir domain [208], [211].

Damping for the dam and foundation is implemented through damping ratio considerations. The software also factors in concrete aging effects [212], reservoir bottom absorption effects [213], reservoir infiniteness using non-reflecting boundary conditions, and semi-infinite foundation using non-radiating boundary conditions. It offers solutions for individual components or a coupled system and can conduct modal analysis and linear time history analysis in the time domain for random vibration (as a single component of ground acceleration, either horizontal or vertical) and harmonic excitation. Output is provided as displacement and stress history envelope values for a coupled DFR system.

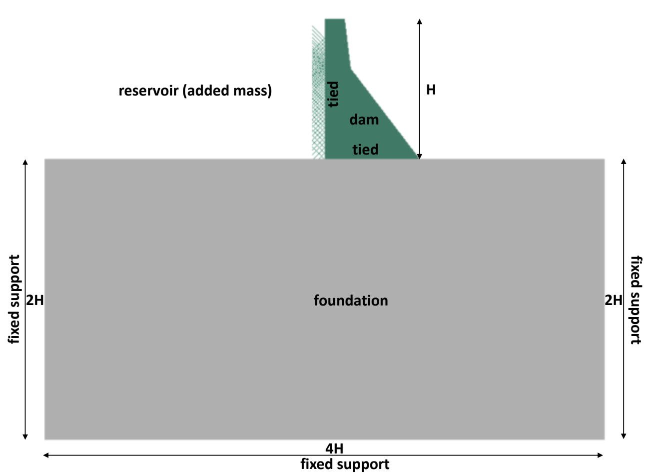
The infinite computing domain of the foundation is constrained to a bounded one with truncated borders, where three sides are fixed. Similarly, different truncation non-reflecting boundary conditions are applied to consider reservoir infiniteness. However, spurious wave reflections from these truncated boundaries may propagate back into the medium's interior. To counteract such reflections, non-reflecting boundary conditions are employed to efficiently absorb the incident stress waves.

In this study, the dam and foundation are modeled using eight-noded isoperimetric quadrilateral plain-stress elements, while the reservoir is represented with eight-noded pressure-based elements. The reservoir's infiniteness is simulated using the Maity-Bhattacharya boundary condition [214] at the truncation boundary. The surface wave at the reservoir's free surface and the absorptive boundary at the reservoir bottom were not considered. Gravity loadings applied to the dam body and hydrodynamic effects are taken into account for scenarios involving the reservoir. The linear analysis with model complexity (D, DF, DR, and DFR) only with the seismic horizontal component was conducted.

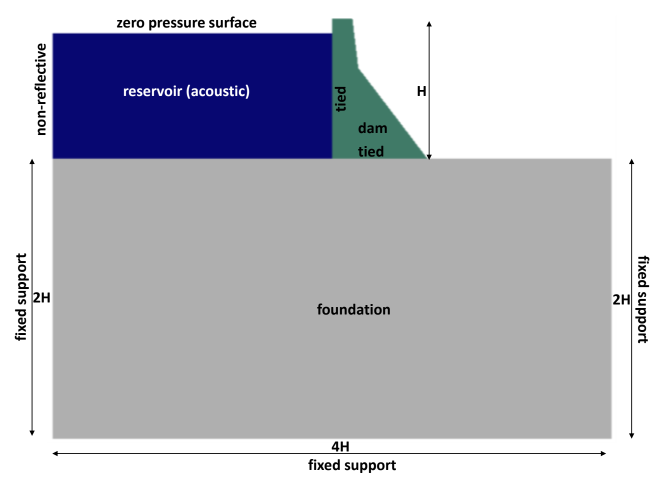
4.3.3. Abaqus

Abaqus is a versatile finite element-based software renowned for its extensive library of element types and materials, enabling the modeling of various geometries and material behaviors to simulate stress and deformation in both linear and nonlinear scenarios. Material nonlinearity can be introduced using damaged plasticity models. In this study, a comparative analysis was conducted to assess the degree of variation between the classical concrete damage plasticity (CDP) and modified concrete damage plasticity model, specifically for the dam-only case of Koyna Dam, denoted as scenario 4.1.3 as shown in Figure 12.

For the dam and foundation, a plain stress-type element (CPS4R) was selected. Two distinct approaches were employed to model the hydrodynamic loading of the reservoir: Westergaard's added mass [215] and acoustic elements (AC2D4), referred to as "Abaqus M" and "Abaqus A" respectively. Direct coupling was implemented using tie constraints, and Rayleigh damping was applied for the dam and foundation. Modal analysis for the first four modes was conducted using the Lanczos Eigen solver. The interfaces between the dam and foundation were tied, and the foundation bottom was fixed on three sides. When modeling a reservoir using an acoustic element, a non-reflective boundary condition was applied at the truncation point, and a zero-pressure boundary condition was implemented at the free water surface. The dynamic interaction of DR and DF was achieved through tied constraints. Seismic loading was applied horizontally and vertically at the dam-foundation interface. Figure 14 (a) and (b) illustrate the DFR model with the reservoir modeled as added mass and acoustic, along with other details such as boundary conditions and model size. Modal analysis was conducted for various model complexities: D, DF, DR, and DFR. Subsequently, dynamic analysis with increasing model complexity was carried out for scenarios as depicted in Figure 12.



(a)



(b)

Figure 14. Considered Abaqus DFR models: (a) Abaqus M and (b) Abaqus A

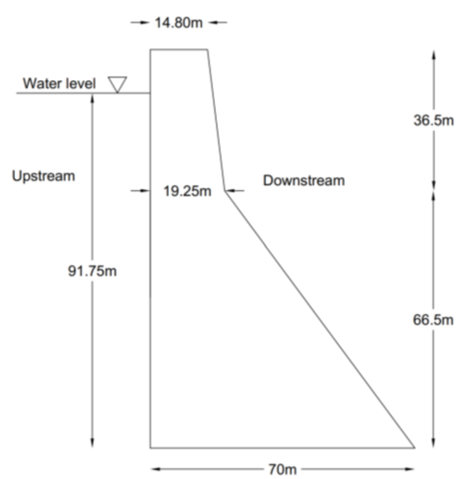
4.4. Case study: Koyna and Pine Flat dams

This section presents an overview of two concrete gravity dams selected for the case study: the Koyna and Pine Flat dams. These dams have been extensively studied, and their geometric, dynamic, and material properties are well-documented in existing literature [199], [216], making them suitable candidates for investigating the effects of various modeling approaches. Their selection is primarily based on shared attributes such as geometric similarity, diverse seismic conditions, and the availability of comprehensive data for model creation and validation.

In this study, aging effects were not considered. However, it is important to note that material properties can change over time due to aging, which can impact the seismic response of the dams. Although aging effects were neglected, the characteristics of the selected dams align with our research objectives, which aim to explore dynamic response variations under different solution methodologies rather than estimating the current seismic behavior of a specific dam. Through this comparative analysis of the two dams, valuable insights can be gained into the factors influencing their seismic responses.

4.4.1. Location and geometry description

The Koyna dam, situated in Maharashtra, India, and the Pine Flat dam, located in California, USA, serve critical roles in water storage, hydroelectric power generation, and flood control within their respective regions. The downstream view and cross-section of the Koyna dam considered in the numerical simulation are depicted in Figure 15 (a) and (b) respectively. The Koyna dam boasts a crest length of 853.5 m and a height of 85.34 m above the riverbed, descending to a depth of 103.02 m below the deepest foundation. It comprises a total of 27 monoliths, each measuring 15.24 m in width. Similarly, the Pine Flat dam stands at a height of 130 m with a crest length of 561 m, consisting of 36 monoliths, each spanning 15.25 m in width, along with an additional 12.2 m wide block. Figure 16 (a) and (b) provide illustrations of the downstream view and cross-section of the Pine Flat dam, respectively, as considered in the numerical simulation.



(a) (b)

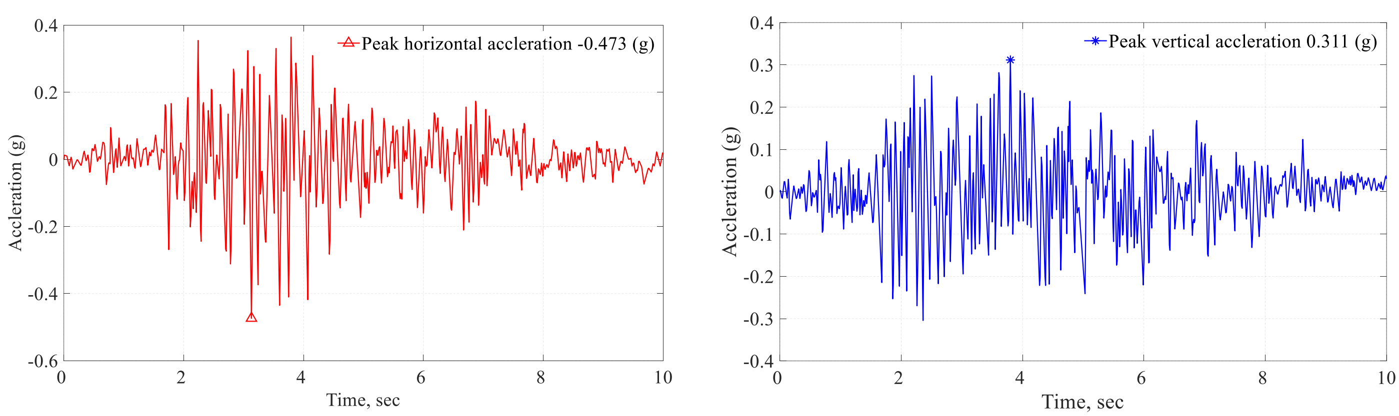
Figure 15. Koyna Dam (a) Downstream view [217], (b) Cross-section [218]

(a) (b)

Figure 16. Pine Flat Dam (a) Downstream view [219], (b) Cross-section [220]

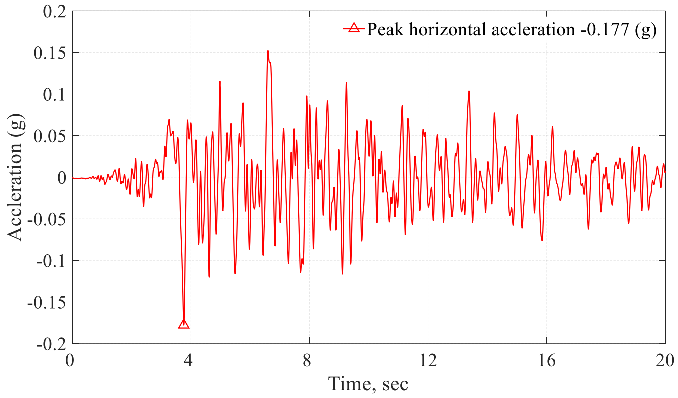
4.4.2. Static and dynamic loading

The analysis incorporates the combined influence of gravity, hydrostatic, and hydrodynamic loading on the system. The seismic response of the Koyna dam was assessed using ground motion data recorded from an accelerograph in one of the galleries of the dam during the earthquake on December 11, 1967, with a moment magnitude of M_w=6.5 [199]. The analysis considered ground motion characterized by peak horizontal accelerations of 0.473g (perpendicular to the dam axis) and peak vertical accelerations of 0.311 g, as illustrated in Figure 17 (a) and (b). Similarly, for the Pine Flat dam, the seismic analysis focused on the Taft Lincoln School Tunnel earthquake (referred to as Taft), which occurred on July 21, 1952, with a moment magnitude of M_w=7.3. Following a similar approach to the Koyna dam, the dynamic behavior of the Pine Flat dam's cross-section was evaluated. For this analysis, the ground motion characterized by peak horizontal accelerations of 0.177 g and peak vertical accelerations of 0.108 g were considered, as depicted in Figure 18 (a) and (b) [90].

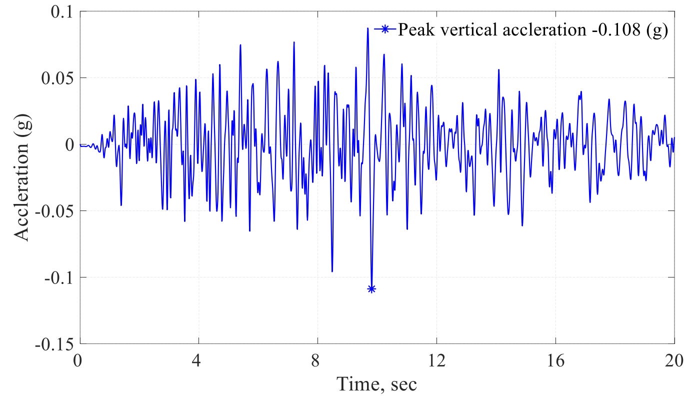


(a) (b)

Figure 17. Koyna ground motion (a) horizontal acceleration and (b) vertical acceleration component



(a)



(b)

Figure 18. Taft ground motion (a) horizontal acceleration and (b) vertical acceleration component

4.4.3. Material properties

Understanding the material properties of the dam, foundation, and reservoir is paramount for conducting a comprehensive seismic assessment to accurately predict their behavior and facilitate informed decision-making for the safety and integrity of dam structures. These properties encompass both general characteristics and specific values utilized in the analysis. While some values are typical, others possess specific characteristics relevant to each dam's behavior. A comparison of the material properties of the two dams reveals significant differences. For instance, the Koyna dam exhibits a higher modulus of elasticity (E) values compared to the Pine Flat dam, indicating a stiffer response. Such disparities can significantly impact structural behavior, influencing factors such as vibration damping and deformation. Foundation properties, which reflect the structural interaction with the underlying terrain, play a crucial role in dissipating energy during seismic events, thereby affecting the dam's response to ground motions. Similarly, reservoir properties, such as density and wave reflection coefficient, influence the hydrodynamic effects on dam behavior. A higher wave reflection coefficient, as observed in both dams, has the potential to amplify hydrodynamic forces. The material properties utilized in the numerical simulation are presented in Table 4 and Table 5.

Table 4. Elastic material properties of the dam, foundation, and reservoir for Koyna Dam [221]

Material properties General and Specific to Abaqus	Dam	Foundation	Reservoir
Density (ρ)	2643 kg/m^3	2643 kg/m^3	1000 kg/m^3
Modulus of elasticity (E)	31027 MPa	27580 MPa	-
Bulk modulus (K)	-	-	2070 MPa
Poisson's ratio (ν)	0.15	0.333	-
Rayleigh damping Alpha (α)	-	1.64	-
Rayleigh damping Beta (β)	0.00323	0.0012	-
Specific to EAGD-84			
Wave reflection coefficient (α)	-	-	0.75
Hysteric damping for dam	0.07	0.04	-
Specific to ADRFS v1			
Wave reflection coefficient	-	-	0.75
Wave speed	-	-	1440.00 m/s
Damping ratio (ζ)	0.03	0.02	-

Table 5. Elastic material properties of the dam, foundation, and reservoir for Pine Flat Dam [222]

Material properties General and Specific to Abaqus	Concrete	Foundation	Reservoir
Density (ρ)	2482 kg/m^3	2640 kg/m^3	1000 kg/m^3
Modulus of elasticity (E)	22407 MPa	22407 MPa	-
Bulk modulus (K)	-	-	2070 MPa
Poisson's ratio	0.2	0.333	-
Rayleigh damping Alpha (α)	-	1.64	
Rayleigh damping Beta (β)	0.004333	0.00668	
Specific to EAGD-84			
Wave reflection coefficient (α)	-	-	0.75
Hysteric damping for dam	0.1	0.1	-
Specific to ADRFS v1			
Wave reflection coefficient	-	-	0.75
Wave Speed	-	-	1440.00 m/s
Damping ratio (ζ)	0.04	0.07	-

4.4.4. Material models

Concrete damage plasticity (CDP) stands as a widely embraced material model in finite element analysis, offering a robust method to simulate concrete behavior across a spectrum of loading conditions. It adeptly captures inelastic deformation and the accumulation of damage in concrete structures, providing a comprehensive characterization of tensile, compressive, and tension damage responses, as illustrated in Figure 19. However, conventional CDP models falter in capturing the variations in material properties based on the stress and deformation states at different stages of the solution. In response, a modified CDP model based on a Lagrangian formulation was developed by Grassl et al. [223], [224]. The concept of modified concrete damage plasticity (CDPM2), as elucidated in [224] and implemented in the Abaqus explicit solver [225], incorporates the effects of solution-dependent parameters that influence material behavior under dynamic loading, high strain rates, cyclic loading, and multi-axial loading, among others.

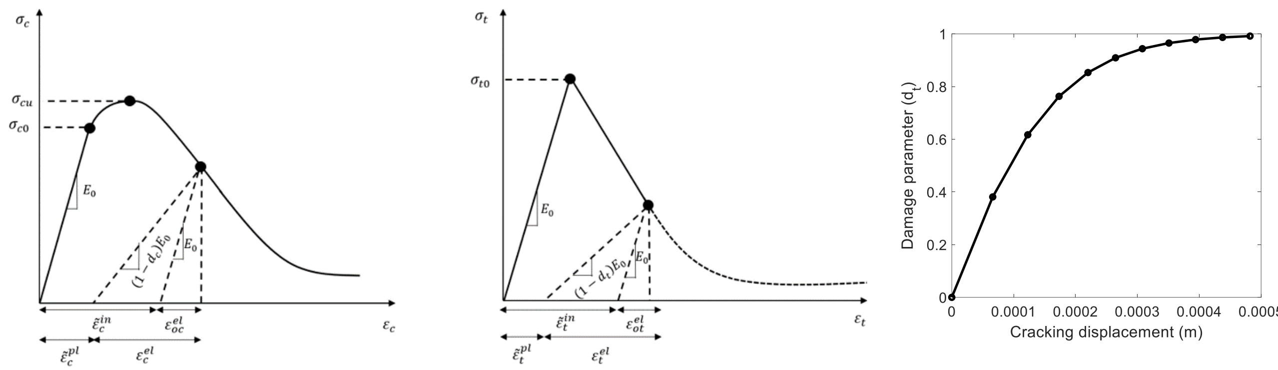


Figure 19. Concrete behavior under uniaxial (a) compressive (b) tension loading, and (c) Concrete tension damage [191]

To comprehend the impact of material modeling in the solution, six simulations were conducted for the dam-only case of the Koyna dam, scenario 4.1.3, utilizing both the CDP and CDPM2 models. These simulations comprised two scenarios with mean values of the compressive strength and related input parameters for the material models, while the remaining four scenarios incorporated mean values of the compressive strength ± σ (standard deviation) of these relevant material parameters. The explicit solver was employed for these simulations, as the CDPM2 model is available only for the explicit solver in Abaqus. The mean values of the material properties are detailed in Table 4 and Table 6. A standard deviation of 35% in σ_{cu} was considered based on the work of Rahman Raju et al. [226], aligning with the resistance factor for concrete utilized in design across various codes and standards. Other pertinent input parameters such as E, σ_{co}, and σ_{to} were estimated. A comparison of crest displacement histories for both the CDP and CDPM2 models is illustrated in Figure 20. It is evident that the original CDP model marginally overpredicts the crest displacement compared to the CDPM2 model. Such observed differences are anticipated, as the CDPM2 model is regarded as more adaptive. The traditional CDP model yields a slightly conservative response, approximately 5% to 6% higher compared to the CDPM2 model. As a result, the original CDP model was adopted for all cases of nonlinear analysis and implemented using the implicit solver in Abaqus.

Table 6. CDP properties for Koyna and Pine Flat Dam

	ψc*	σ_{co} (MPa)	σ_{cu} (MPa)	σ_{to} (MPa)	e	R
Koyna	36.31°	13.0	24.1	2.90	0.1	1.16
Pine Flat	36.31°	12.08	22.41	2.24	0.1	1.16

* ψc: dilatation angle; σ_{co}: compressive initial yield stress; σ_{cu}: compressive ultimate yield stress; σ_{to}: tensile failure stress; e: flow potential eccentricity and R: ratio of the initial equibiaxial to the uniaxial compressive yield stress.

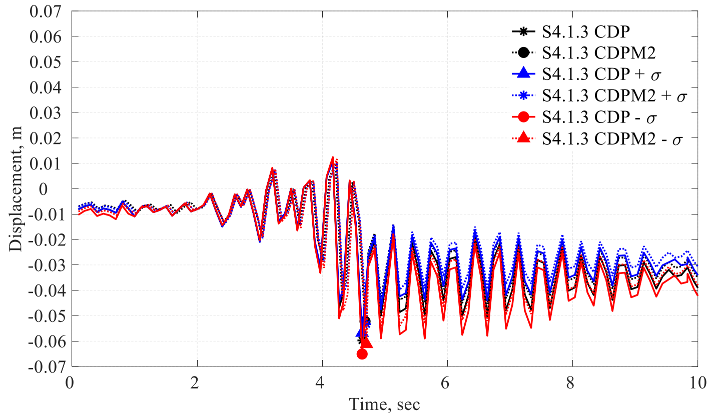


Figure 20. Comparison of Koyna dam horizontal time displacement with CDP and CDPM2

4.5. Results and discussion

The following section explores the differences in modal parameters and crest displacement histories between the Koyna and Pine Flat dams. Despite sharing geometric similarities, these dams differ significantly in terms of material properties and loading conditions. This analysis seeks to compare and contrast these dams, illustrating how these differences influence their responses. Our focus is on highlighting variations in both magnitude and trends within the context of our study's defined scope. We employ various solution approaches and model complexities to achieve this comparison. It's important to note that our aim is not to directly compare the structures but rather to present them as distinct case studies of similar yet individually unique dams.

4.5.1. Modal analysis

This section delves into the modal analysis of the Koyna and Pine Flat dams, providing insights into their dynamic behavior under varying model complexities and solution procedures. Figure 21 presents a comparative examination of modal periods, offering valuable insights into their distinct dynamic responses. The analysis investigates the impact of model complexity, ranging from simple D models to more intricate DFR models, on modal periods, as well as how solution procedures influence these periods. Additionally, the study scrutinizes the variation in modal periods between fundamental and higher modes, elucidating the factors contributing to these distinctions. The analysis focuses on the first four modes of vibration, as these modes hold significance in seismic analysis, representing primary vibration modes with potential implications for the dams' seismic response. Moreover, considering higher mode periods is crucial for a comprehensive understanding of the dams' dynamic behavior and assessing potential resonance conditions. Key observations regarding the variation in modal periods across different solution procedures and levels of model complexity are highlighted below.

4.5.2. Comparison of the modal period

The fundamental periods for both dams fall within a similar range, suggesting comparable primary vibration modes. However, the fundamental period of vibration is relatively shorter for the Koyna Dam compared to the Pine Flat Dam, indicating that Koyna tends to vibrate at a higher frequency. There is significant variation in higher-mode periods between the two dams, likely due to differences in their structural characteristics, such as size, geometry, and material properties.

4.5.3. Impact of model complexity

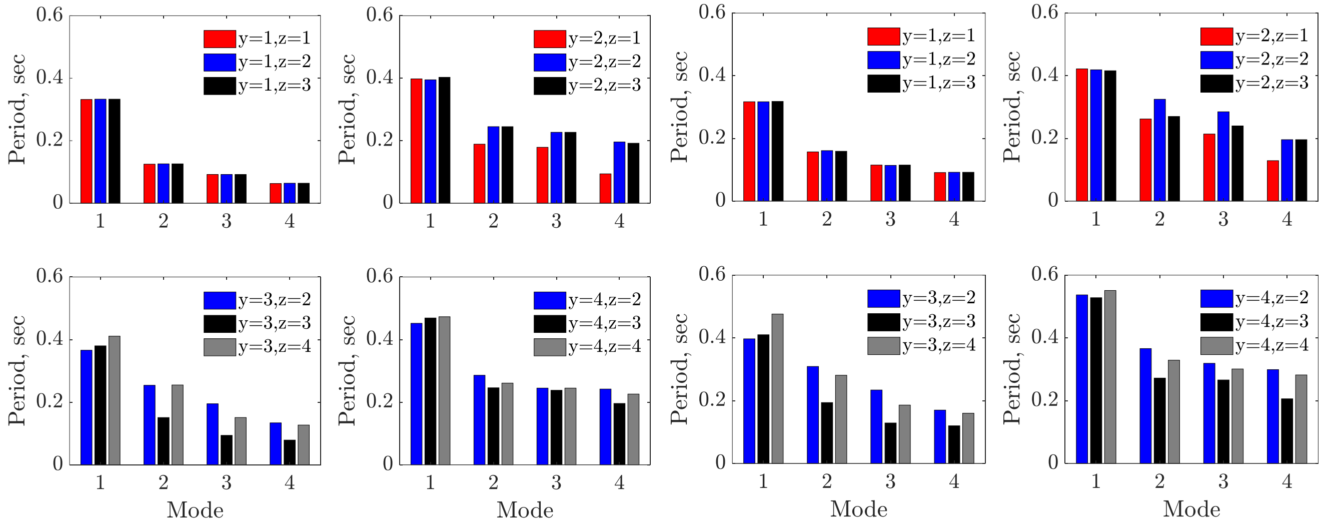
The variation in modal periods with increasing model complexity stems from the additional complexities introduced by considering the effects of the reservoir and foundation. These effects have the potential to alter the natural vibration characteristics of the dam. As the model complexity increases from D to DFR, the fundamental period tends to increase for both dams, as expected, since the system incorporates additional elements and complexities. More complex models can account for additional structural details and interaction effects, resulting in slower vibrations. The variation in modal periods is particularly pronounced in higher modes, indicating that the effect of model complexity is more significant in these modes.

4.5.4. Impact of the solution procedure

The selection of solution procedures significantly influences the modal periods, resulting in variations observed among the different procedures. In the D models, as anticipated, the modal periods remain relatively consistent for both dams, regardless of the solution procedure employed. However, across both dams, Abaqus A tends to yield longer fundamental periods compared to other procedures, indicating a less stiff system response. ADRFS v1 also exhibits variations in the modal periods, albeit generally shorter than those produced by Abaqus A. Meanwhile, EAGD-84 and Abaqus M tend to generate similar modal periods, with some differences depending on the dam and model complexity. Notably, solution procedures with distinct damping characteristics impact the modal periods, with Abaqus Acoustic introducing higher damping and consequently longer periods.

4.5.5. Variation in the higher modes

The fundamental period in DF, DR, and DFR models remains relatively consistent across different solution procedures, indicating that the primary influence on the fundamental period is solely due to the increase in model complexity. Conversely, higher modes exhibit greater variation in modal periods compared to the fundamental mode. This discrepancy arises because higher modes entail more intricate and localized deformations within the structure. Even small alterations in model parameters or solution methods can have a more significant impact on these modes. Furthermore, the variation in modal periods can be attributed to the inherent disparities in how each software package formulates and resolves the dynamic equations of motion. Additionally, factors such as the choice of elements, integration schemes, and convergence criteria can contribute to differences in results.



(a) (b)

Figure 21. Comparison of modal parameters: (a) Koyna and (b) Pine Flat Dam

4.5.6. Crest displacement

When scrutinizing variations in the system response, it's crucial to consider several key factors. Firstly, evaluating model complexity, which includes D, DF, DR, and DFR configurations, is essential to understanding its impact on crest displacement. Secondly, comparing the effects of different solution procedures is necessary to identify any discrepancies or inconsistencies in the outcomes. Thirdly, examining various reservoir modeling techniques, and seismic load application scenarios, comparing linear and nonlinear analyses, and assessing computational efficiency are vital aspects. By comprehensively considering these factors, we conducted an evaluation to gain insights into the variations in the system response and the underlying factors contributing to them.

4.5.7. Mean and standard deviation for S1 and S2

The mean (μ) and standard deviation (σ) values for the maximum crest displacement obtained from the three software systems corresponding to each model complexity for S1 and S2 are illustrated in Figure 22. These values are analyzed across various model complexities and seismic scenarios, providing the following insights into the seismic response of the Koyna and Pine Flat dams:

- As the models incorporate more complexities, such as DR and DFR interactions, the mean displacement values generally increase. This trend is observed in both dams, indicating that the inclusion of additional complexities results in larger average displacements. Additionally, the standard deviation tends to rise with higher model complexity, suggesting that more intricate models introduce greater variability in the dam's seismic response, possibly due to the consideration of intricate features.
- Comparing the two dams, Koyna consistently demonstrates higher mean displacement values than Pine Flat. This difference stems from inherent structural and material disparities between the dams. However, the standard deviation for Koyna is typically smaller than that of Pine Flat, suggesting that Koyna's responses are more consistent and less variable, except in the most complex scenarios.

- The variation across model complexities is most notable in the most complex model, DFR, which accounts for a wide range of intricate factors. This model introduces the greatest variability in the results, underscoring the importance of carefully selecting the appropriate level of complexity for seismic analysis.

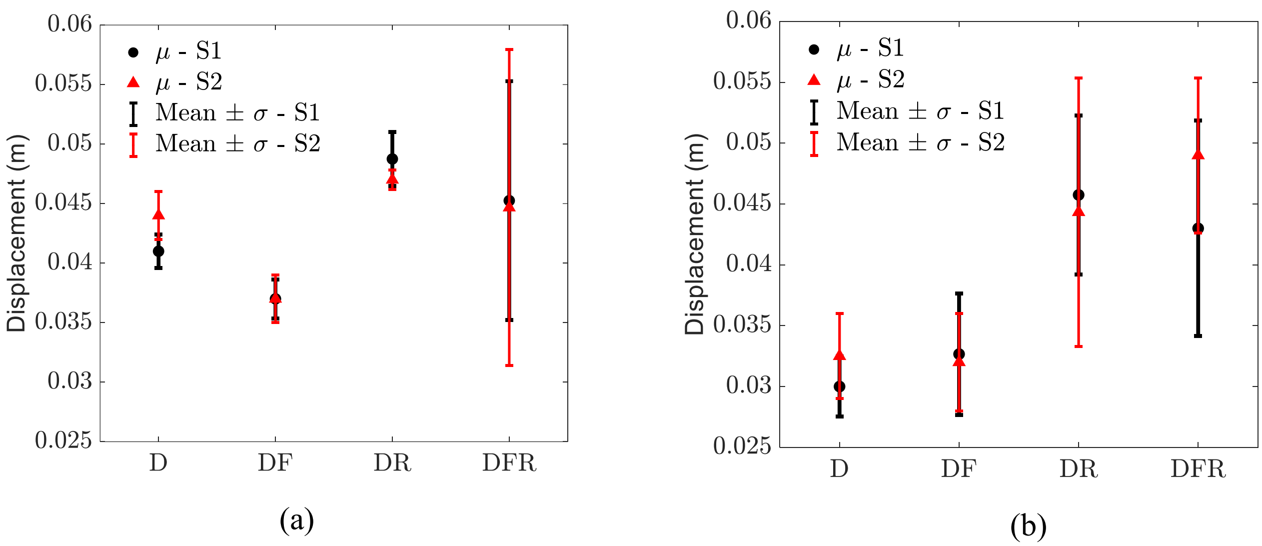


Figure 22. Displacement variation among software for different model complexities: (a) Koyna Dam and (b) Pine Flat Dam

4.5.8. Displacement histories S1 and S2

Table 7 displays the maximum crest displacement across different solution procedures and model complexities. Figure 23 and Figure 24 illustrate the displacement time histories for S1, elucidating the variations in trends and magnitudes. In Figure 23 (a) and Figure 24 (a), the crest displacement trends and values for both dams closely align across the three software systems in the D model. For the DF model in Koyna, the trend closely matches with minor variations in magnitude, as depicted in Figure 23 (b). However, there are discrepancies in the time of occurrence of the maximum displacement among the three solution procedures. These differences become more pronounced in the DF model for Pine Flat, as observed in Figure 24 (b). In the case of the DR and DFR models for Koyna, the solutions from Abaqus A and ADRFS v1 yield the most consistent and least variable results, while the solutions from Abaqus M and EAGD-84 exhibit higher variation, as seen in Figure 23 (c) and (d). Similarly, for Pine Flat, solutions from Abaqus A, ADRFS v1, and Abaqus M consistently provide consistent and less variable results, while the solution from EAGD-84 shows higher variation, as shown in Figure 24 (c) and (d). The variation in results between the two dams highlights the critical importance of selecting the appropriate solution procedure. Moreover, it underscores the influence of each dam's specific behavior under seismic conditions, influenced by factors such as geometry, material properties, and loading conditions.

Table 7. Maximum crest displacement in (m) for scenarios S1 and S2 across different solution procedures and model complexities

Scenario (x=)	Model complexity (y=)	Koyna dam				Pine Flat dam			
		Software (z=)							
		1	2	3	4	1	2	3	4
S1	1	0.042	0.042	0.039	-	0.027	0.030	0.033	-
S1	2	0.037	0.039	0.035	-	0.026	0.038	0.034	-
S1	3	0.045	0.051	0.049	0.050	0.041	0.043	0.057	0.042
S1	4	0.056	0.046	0.029	0.050	0.031	0.043	0.056	0.042
S2	1	0.046	-	0.042	-	0.029	-	0.036	-
S2	2	0.035	-	0.039	-	0.028	-	0.036	-
S2	3	0.047	-	0.046	0.048	0.031	-	0.058	0.044
S2	4	0.059	-	0.027	0.048	0.045	-	0.058	0.044

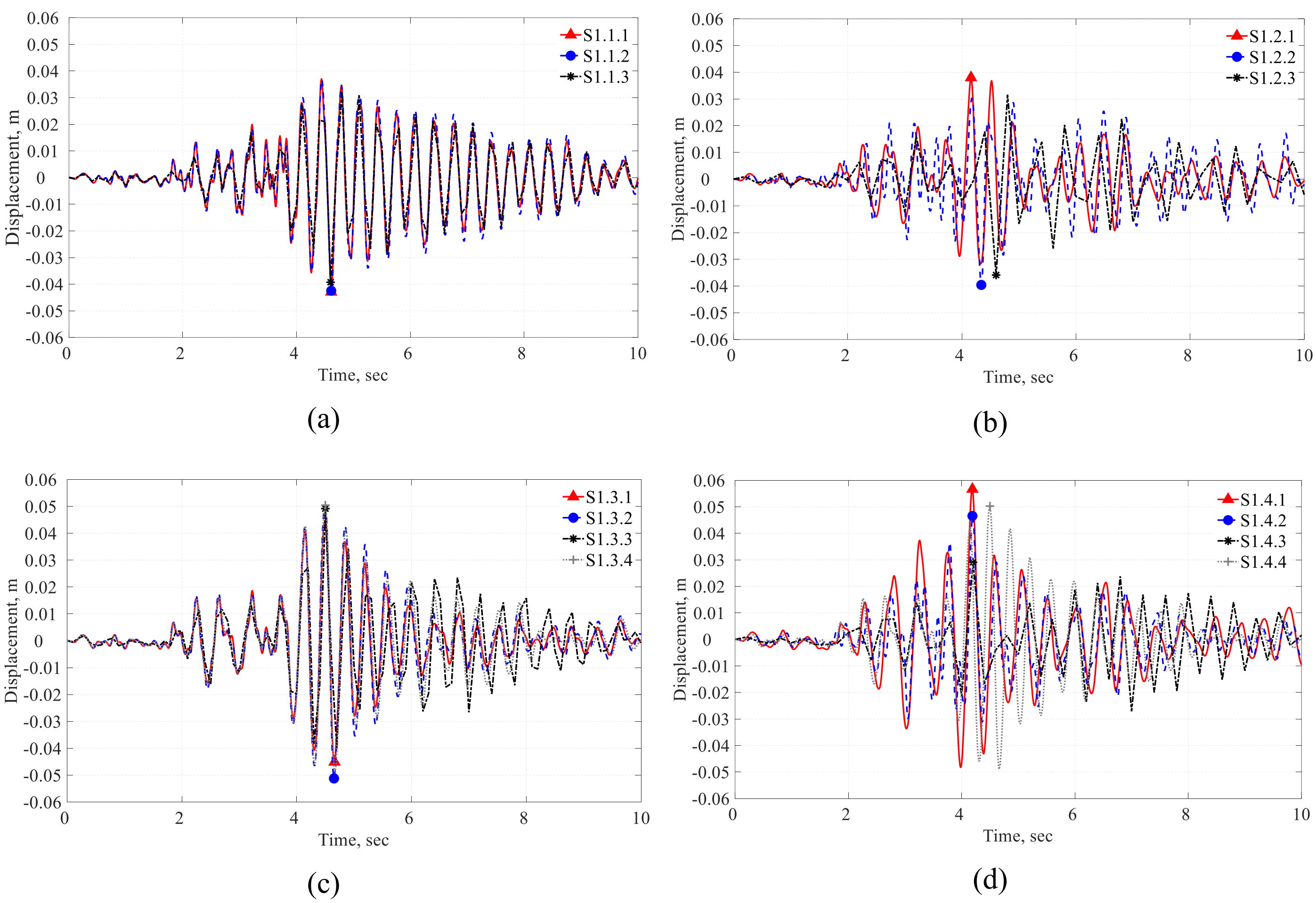


Figure 23. Koyna dam horizontal time displacement for S1 scenario: (a) D, (b) DF, (c) DR, and (d) DFR

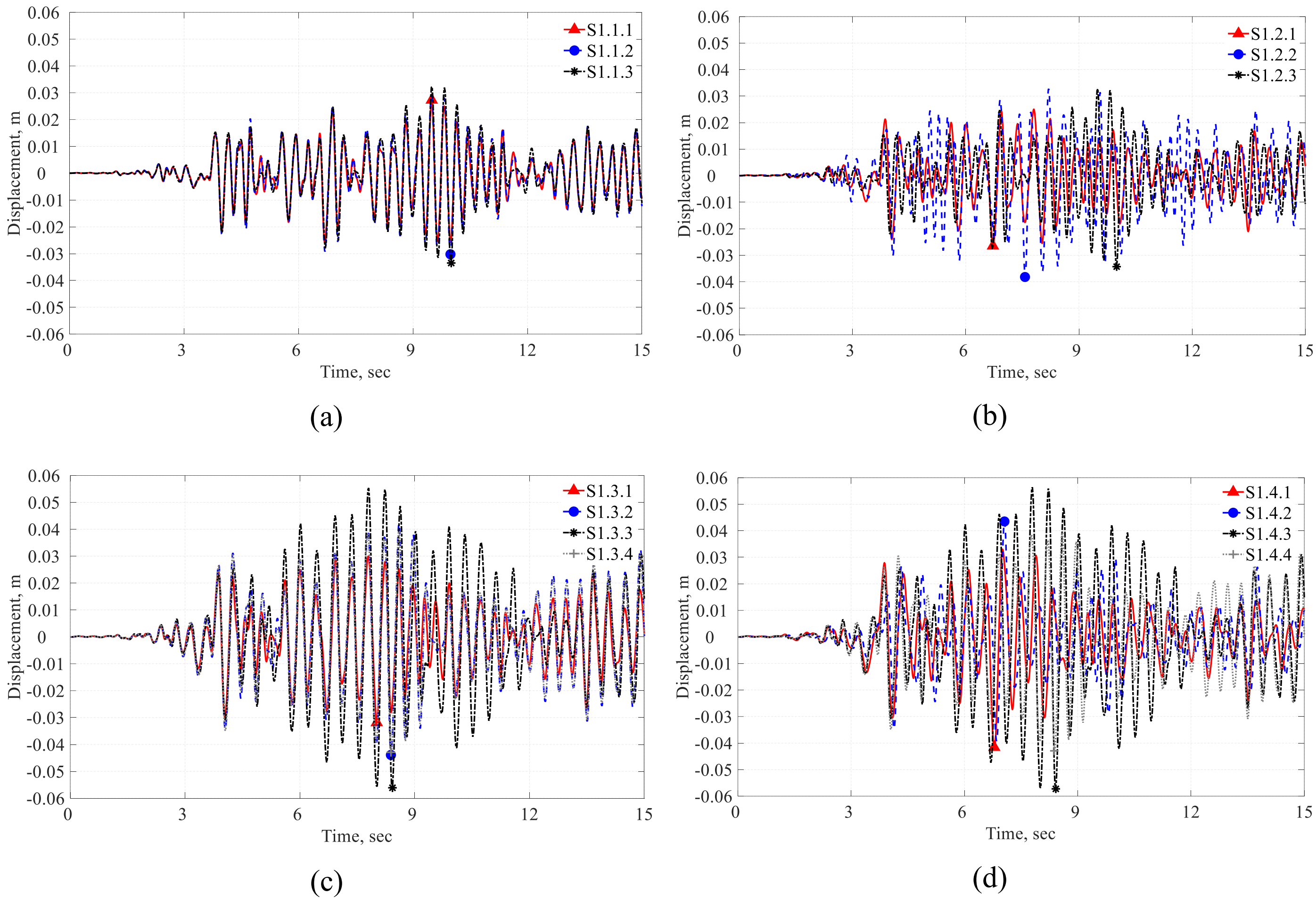


Figure 24. Pine Flat horizontal time displacement for S1 scenario: (a) D, (b) DF, (c) DR, and (d) DFR

Similarly, Figure 25 and Figure 26 illustrate the displacement histories for scenario S2. In line with S1, when only the body of the dam is considered in the model, the crest displacement trends and magnitudes closely match across all the software systems for both dams, as shown in Figure 25 (a) and Figure 26 (a). However, for Pine Flat dam, the time of occurrence of maximum displacement slightly varies across the software systems, as observed in Figure 26 (a). For the Koyna DF model, there is a close match in trend and magnitude, although the maximum displacement occurs at different periods, as depicted in Figure 25 (b). Similarly, for Pine Flat dam, there is a trend-wise match, but the variations in magnitude and the time when the maximum displacement occurs are more significant, as shown in Figure 26 (b). In the DR model, consistency in magnitude and trend can be observed for the Koyna dam in Figure 25 (c), while significant discrepancies are evident for the Pine Flat Dam in Figure 26 (c). The DFR model exhibits consistent trends but substantial variations in magnitude for both dams, as depicted in Figure 25 (d) and Figure 26 (d). The Abaqus A solution provides the most consistent response across the solution procedures for both dams, regardless of the model complexity.

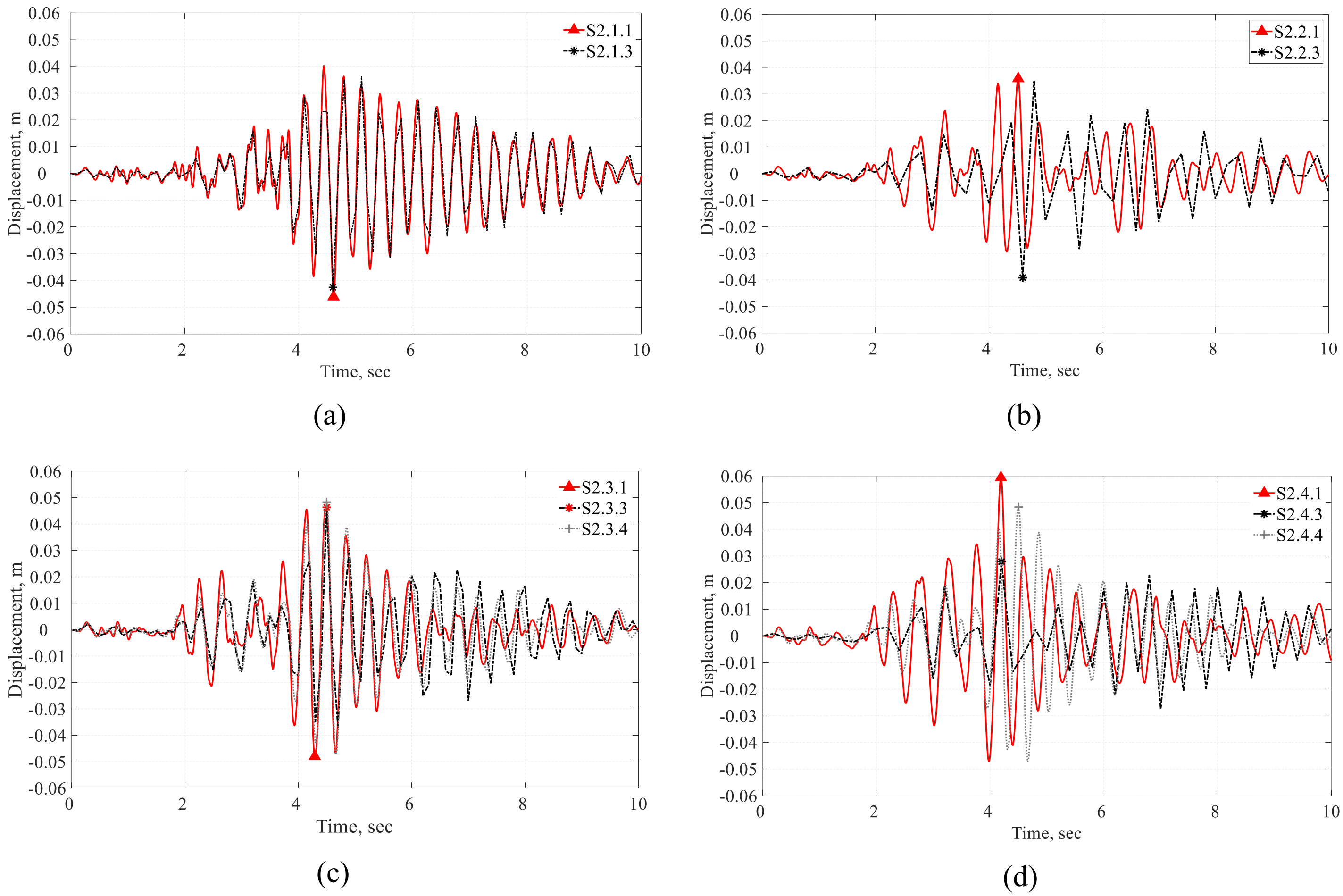
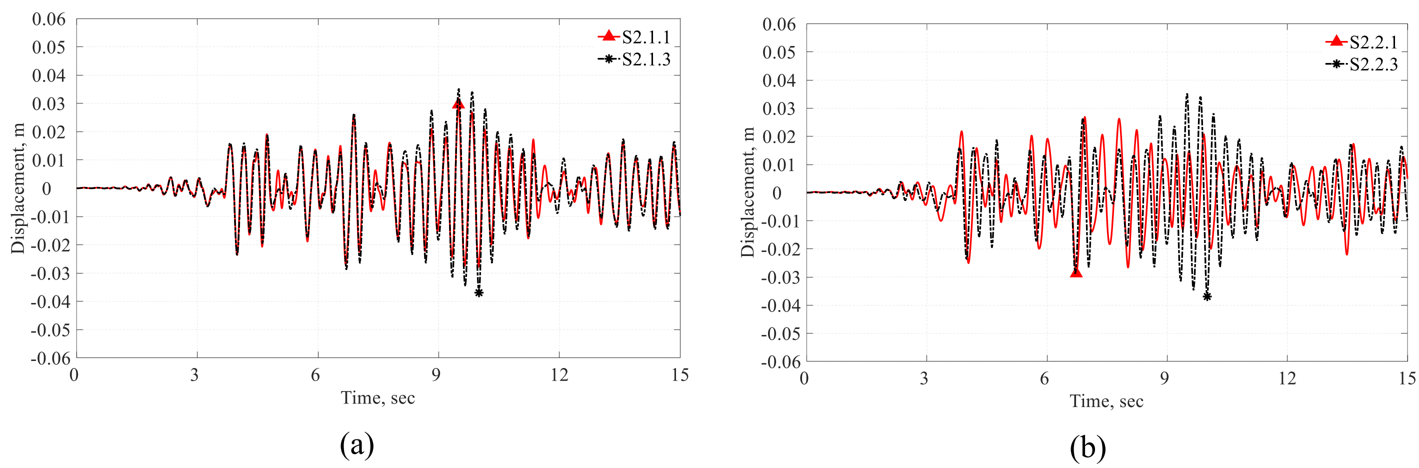
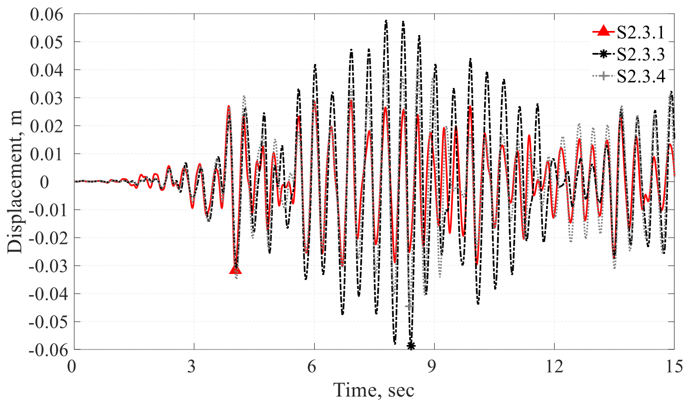
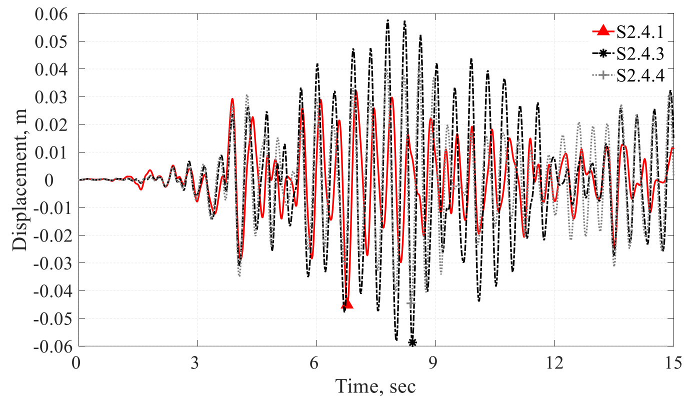


Figure 25. Koyna dam horizontal time displacement for S2 scenario: (a) D, (b) DF, (c) DR, and (d) DFR





(c)



(d)

Figure 26. Pine Flat dam horizontal time displacement for S2 scenario: (a) D, (b) DF, (c) DR, and (d) DFR

4.5.9. Displacement histories S3 and S4

To further assess the variation between different modeling approaches, a comparison between linear and nonlinear analysis was conducted, as shown in Table 8. Comparing scenarios S3 and S4, Table 8 highlights a significant increase in displacement magnitude within the D and DF models for both dams. This difference underscores the importance of considering both horizontal and vertical ground motion components. The heightened crest displacement observed in scenario S4, compared to scenario S3, can be attributed to the influence of the vertical seismic component. When a dam experiences both horizontal and vertical seismic forces, their complex interaction can induce an anti-gravity-like effect, temporarily reducing the dam's effective weight. Consequently, the dam exhibits higher displacements due to an increased dynamic response. As in the previous section, Figure 27 and Figure 28 depict the displacement time histories for scenario S3. For the Koyna dam, in the D and DF models, nonlinear analysis reveals inelastic behavior compared to linear analysis, evidenced by the disparity between both curves, as shown in Figure 27 (a) and (b). Conversely, for the Pine Flat dam, in the D and DF models, the trends and magnitudes closely match between linear and nonlinear analysis, as indicated in Figure 28 (a) and (b), suggesting that the dynamic behavior of the dam during the Taft earthquake remains within the elastic range. In the DR and DFR models for the Koyna dam, the magnitude of displacement is lower in the nonlinear analysis compared to the linear analysis, as illustrated in Figure 27 (c) and (d). Conversely, for the Pine Flat dam, the magnitude of displacement is higher in the nonlinear analysis compared to the linear analysis, as depicted in Figure 28 (c) and (d). It is noteworthy that the observed displacement values in nonlinear analysis can be either higher or lower compared to the linear analysis. The lower displacement in nonlinear analysis can be attributed to possible damage and stress redistribution in the structure. Moreover, it is observed that for the Koyna dam, the nonlinear displacement values are generally lower than in the linear analysis, indicating closer conformity to the reported damage state in the real structure. However, for the Pine Flat dam, both linear and nonlinear analyses show similar displacement values, indicating elastic behavior and less damage. Variations in displacement can also be observed in the DR and DFR models, particularly with the Abaqus M in both linear and nonlinear analyses. However, the Abaqus A solution provides consistent results across both linear and nonlinear analyses.

Table 8. Maximum crest displacement in (m) for scenarios S3 and S4 across different solution procedures and model complexities

Scenario (x=)	Model complexity (y=)	Koyna		Pine Flat	
		Software (z=)			
		3	4	3	4
S3	1	0.040	-	0.035	-
S3	2	0.042	-	0.035	-
S3	3	0.035	0.043	0.066	0.043
S3	4	0.037	0.044	0.077	0.044
S4	1	0.051	-	0.043	-
S4	2	0.047	-	0.043	-
S4	3	0.035	0.040	0.054	0.044
S4	4	0.037	0.040	0.077	0.046

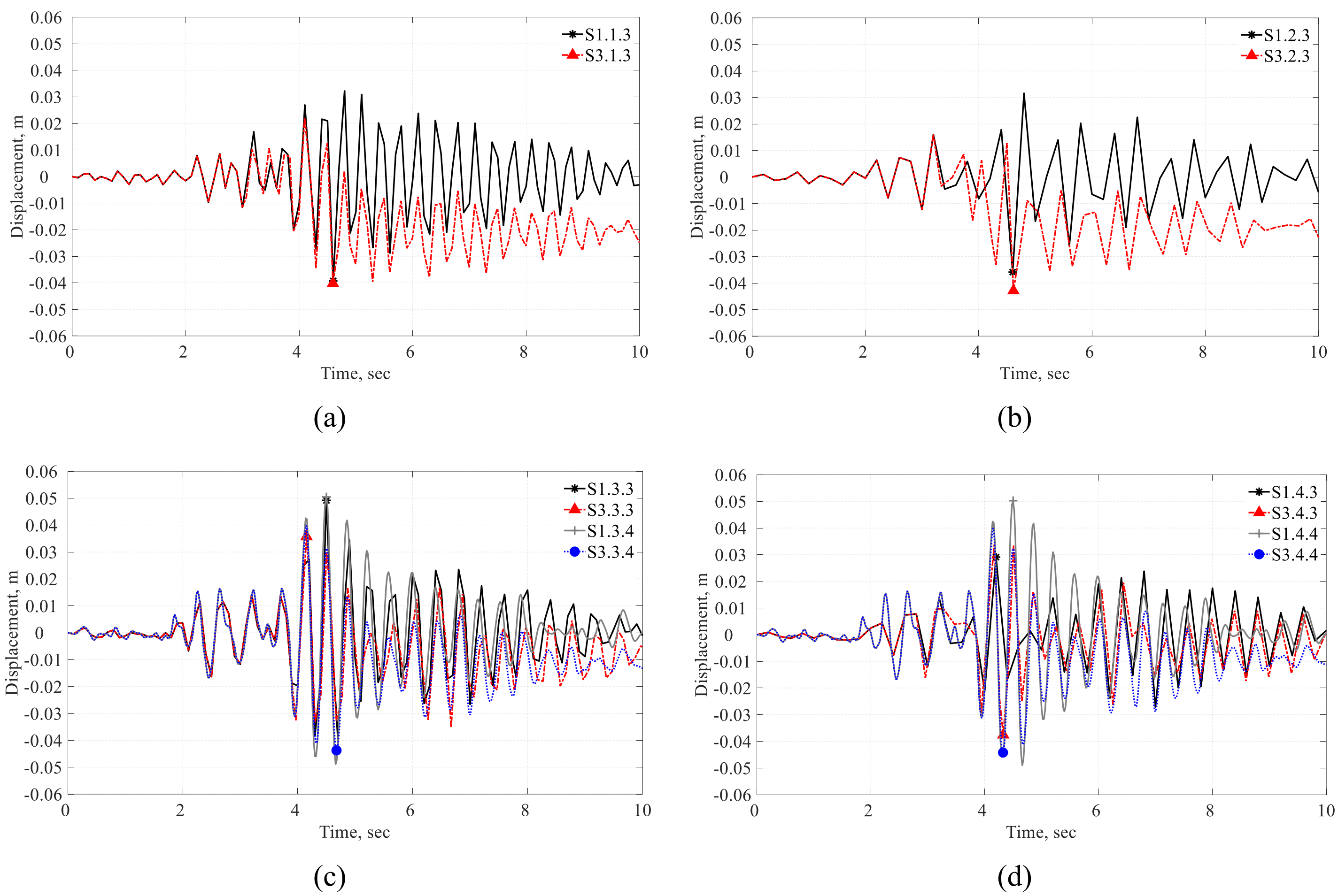


Figure 27. Koyna dam horizontal time displacement: (a) D, (b) DF, (c) DR, and (d) DFR, linear (S1) vs. nonlinear analysis (S3) considering horizontal ground motion component only.

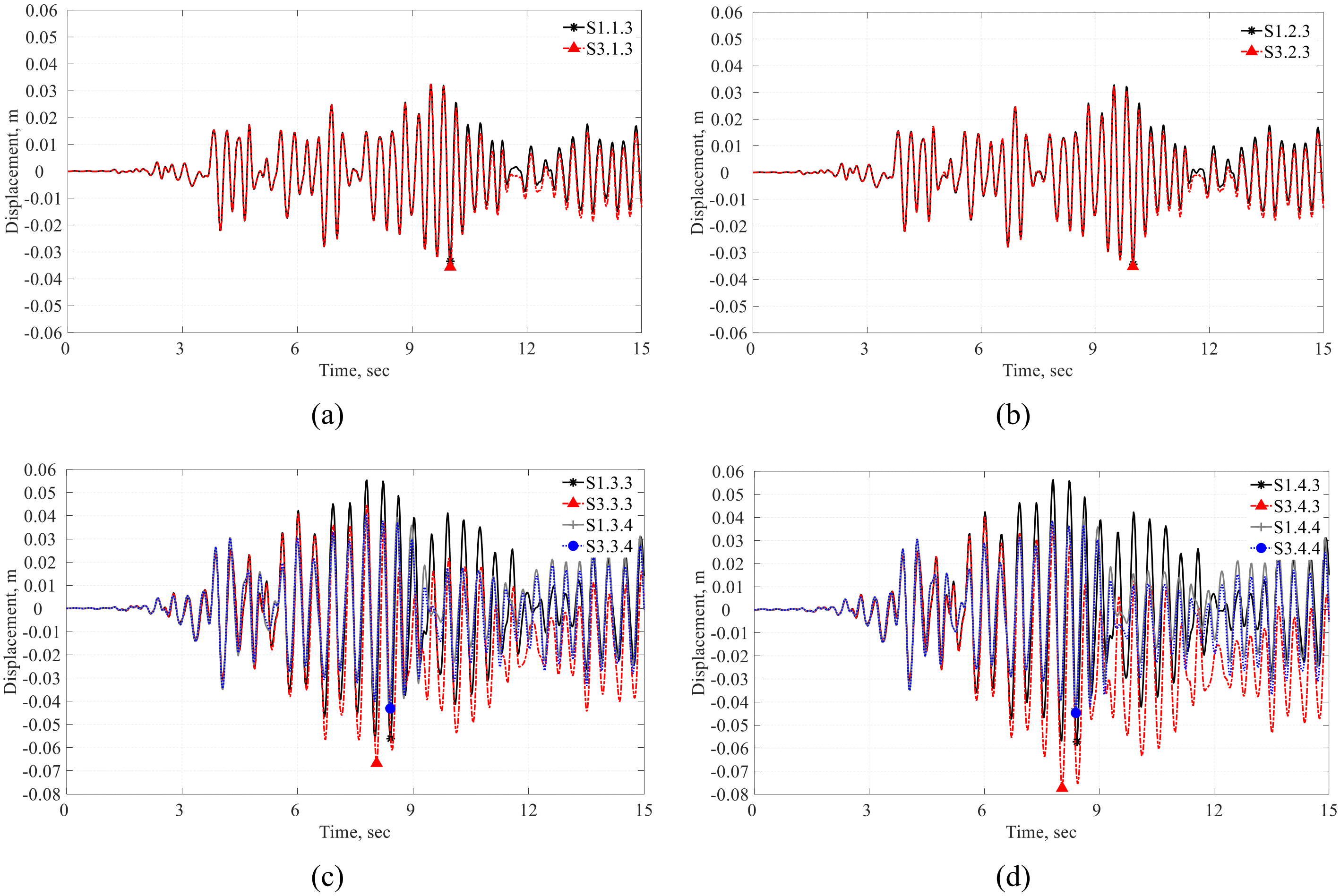
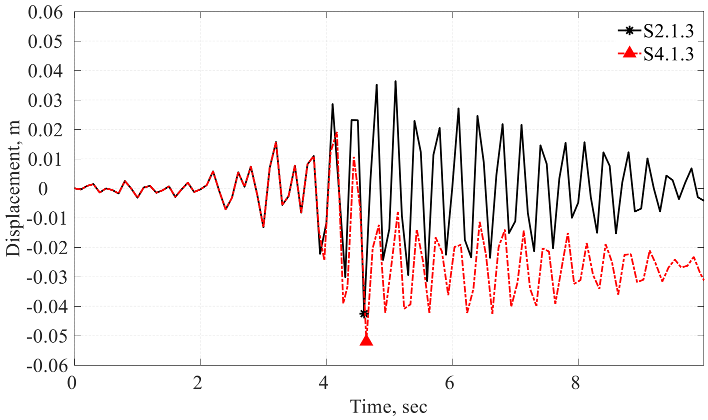
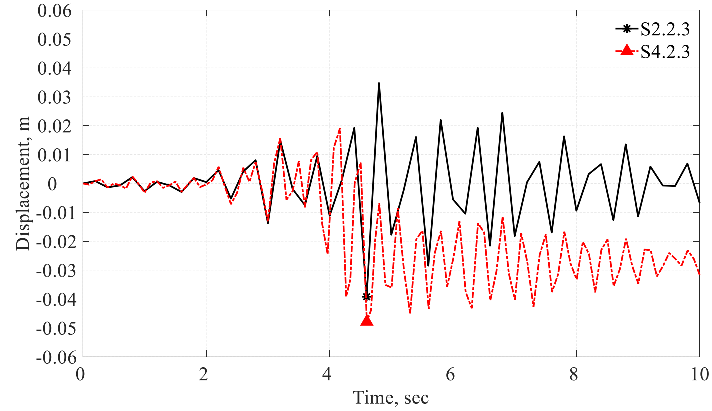


Figure 28. Pine Flat dam horizontal time displacement: (a) D, (b) DF, (c) DR, and (d) DFR, linear (S1) vs. nonlinear analysis (S3) considering the horizontal ground motion component

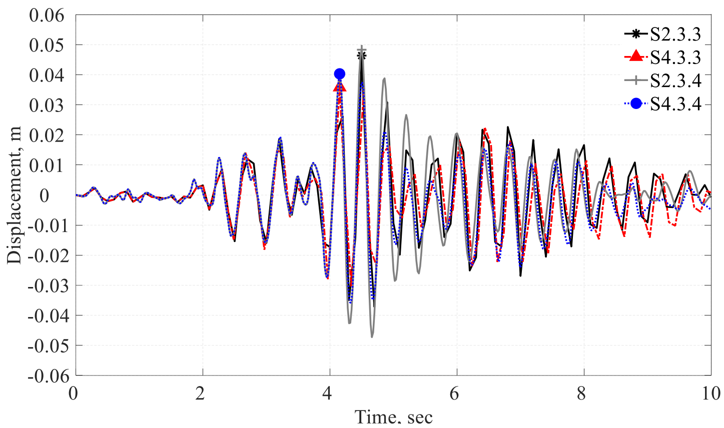
Indeed, the observed inelastic behavior of the D and DF models, depicted in Figure 29 (a), (b) and Figure 30 (a), (b), underscores the importance of considering the reservoir empty condition. The dynamic response of the dams is significantly influenced by the presence or absence of reservoir water. Furthermore, when the reservoir is filled, there is an elevated displacement in the DFR model of the Pine Flat dam compared to the Koyna dam. This indicates that the dynamic response is intensified in the Pine Flat dam due to the presence of reservoir water. Conversely, in the case of the Koyna dam, the dynamic response appears to be damped, suggesting that the presence of reservoir water mitigates the magnitude of the displacement.



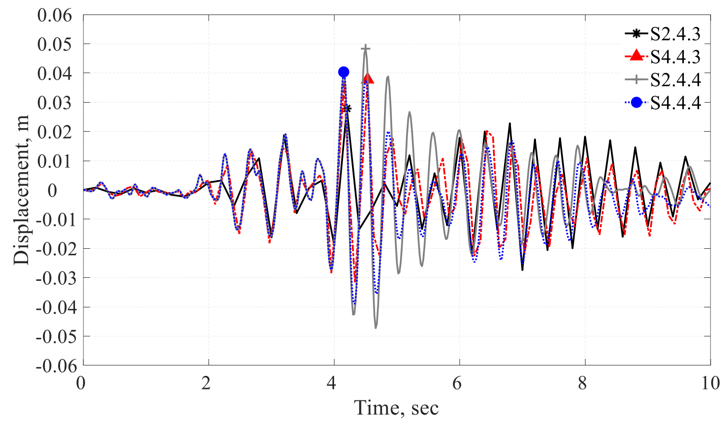
(a)



(b)

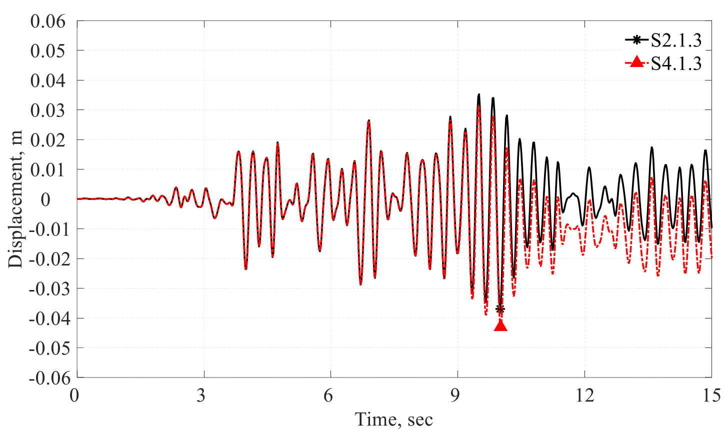


(c)

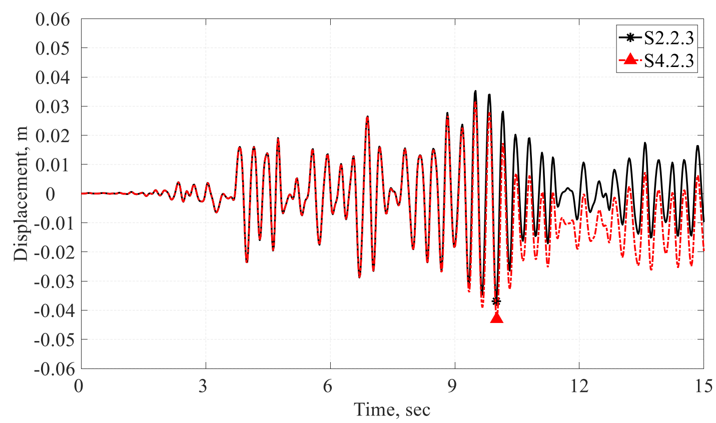


(d)

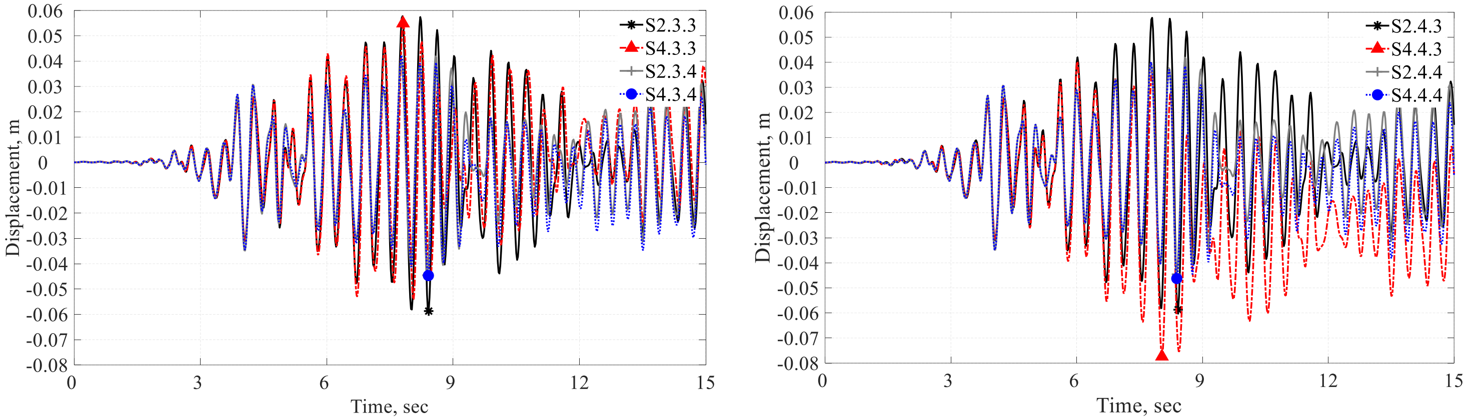
Figure 29. Koyna dam horizontal time displacement: (a) D, (b) DF, (c) DR, and (d) DFR, linear (S2) vs. nonlinear analysis (S4) considering horizontal and vertical ground motion components



(a)



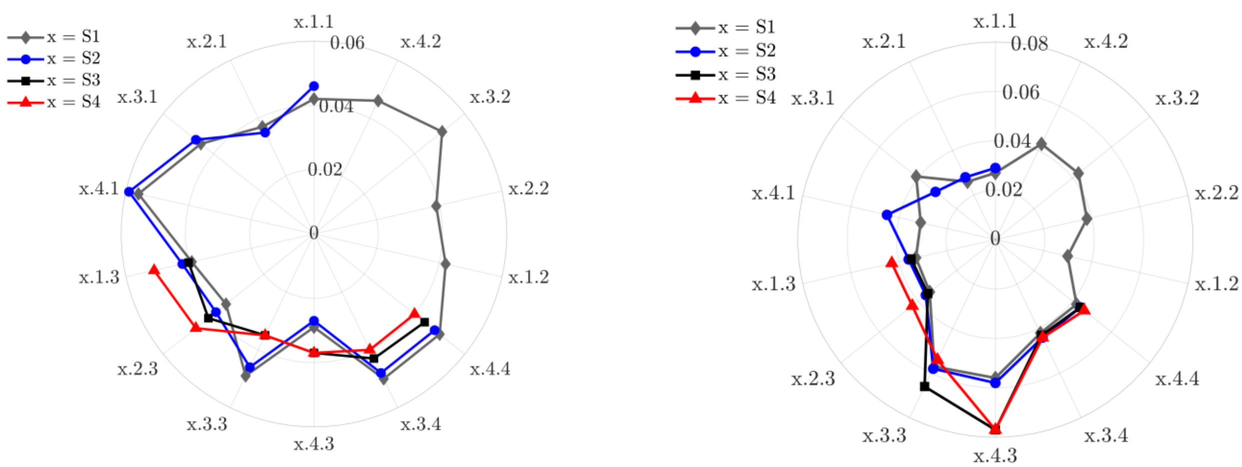
(b)



(c) (d)

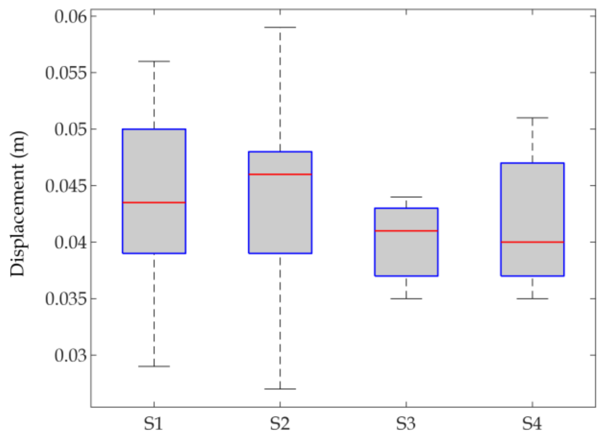
Figure 30. Pine Flat dam horizontal time displacement: (a) D, (b) DF, (c) DR, and (d) DFR, linear (S2) vs. nonlinear analysis (S4) considering horizontal and vertical ground motion components

Figure 31 and Figure 32 serve to summarize the key findings of this section, providing a comparison of the maximum crest displacement across scenarios S1 to S4. From Figure 31, it is evident that discrepancies exist between all four scenarios, with Pine Flat exhibiting more pronounced variation compared to Koyna. Additionally, the influence of vertical ground motion appears to have a relatively minor impact on displacement values when contrasted with scenarios incorporating nonlinearities and increased model complexity. Figure 32 illustrates the displacement variation for both Koyna and Pine Flat dams across all considered scenarios. It becomes apparent that the presence of nonlinearity significantly affects crest displacement, with Pine Flat Dam exhibiting a wider range and higher variability. These observations underscore the necessity of supplementing linear analysis with nonlinear approaches to gain a comprehensive understanding of structural response, particularly in seismic conditions.

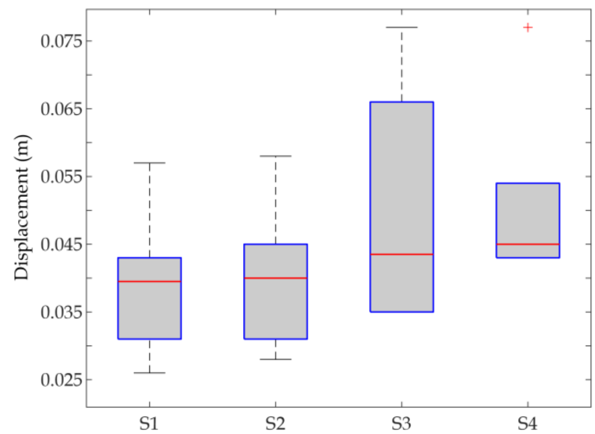


(a) (b)

Figure 31. Crest displacement (a) Koyna Dam, (b) Pine Flat Dam



(a)



(b)

Figure 32. Displacement variation among scenarios, (a) Koyna Dam, (b) Pine Flat Dam

4.6. Comparison among software tools

In addition to the discussed variations in seismic analysis results, it's crucial to consider the computational burden imposed by each software, as this factor can significantly impact the feasibility of using a particular software for routine safety assessments versus critical, in-depth analyses. In terms of ease of use, EAGD-84 emerges as the most accessible option, followed by ADRFS v1, while Abaqus is perceived as more complex. However, the pivotal consideration lies in the time required for simulation. EAGD-84 typically offers the shortest analysis time, ranging from 20 to 30 seconds per simulation, rendering it suitable for routine safety assessments where rapid evaluations are paramount. ADRFS v1 falls in the middle ground concerning computational time, ranging from 40 to 60 seconds per simulation. In contrast, Abaqus, while renowned for its power and precision, often demands more time, with analyses ranging from 90 to 150 seconds per simulation. Consequently, it might be reserved for critical cases or detailed assessments where computational resources are more manageable. Engineers must carefully weigh the computational demands of each software against their specific analysis requirements, available resources, and the urgency of the assessment. This ensures the selection of the most suitable tool to guarantee both safety and efficiency in dam safety evaluations.

4.7. Verification with ICOLD benchmark study

The recent study by Hariri-Ardebili (2023) extensively explores modeling variabilities in the seismic assessment of dams. In that study, results from a series of twenty DFR models (2D, 3D slice, and full 3D) of a benchmark problem from the 15th ICOLD International Benchmark Workshop and the 2018 USSD benchmark workshop were utilized to evaluate modeling variability and uncertainty (ICOLD 2019; USSD 2018). While our present study considers twenty-four different models with increasing complexity, it complements the findings of Hariri-Ardebili (2023), and the results are synergistic. For the benchmark concrete gravity dam problem on Pine Flat dam studied in ICOLD (2019) and USSD (2018), the modal analysis results and dam crest displacement variations found in our study are quite consistent with comparable scenarios reported in those benchmarks, considering the disparities in input parameters (such as slight differences in reservoir level, foundation dimensions, and material properties) and inherent modeling assumptions in each software tool used here. It's important to note disparities in material properties, specifically σ_{cu} and σ_{to}, between our current study (22.41 MPa, 2.24 MPa) and those used in Hariri-Ardebili (2023) (28.0 MPa and 2.0 MPa), respectively. Similarly, variations in foundation geometry are evident, with our current study employing dimensions of 412 m by 206 m, contrasting with Hariri-Ardebili (2023) where dimensions of 700 m by 122 m were used. The reservoir level considered in the present study is 290.02 m vs 278.57 m in Case A2 (ICOLD 2019; USSD 2018). Lastly, differences in Rayleigh viscous damping parameters for the dam in our current study employ α = 0 and β = 0.004333, while Hariri-Ardebili (2023) uses α=0.751 and β=0.0005. A cross-validation of the findings for comparable cases of the current study was made with the benchmarks from ICOLD (2019) and USSD (2018). The outcomes, for comparable scenarios, indicate that the results of our study fall within the broad range of results presented in those benchmarks. Table 9 presents a comparison of modal parameters for DFR models (scenarios, y=4, z=3 and y=4, z=4) of our present article with Case A2 presented in ICOLD (2019) and USSD (2018).

Table 9. Comparison of modal parameters with the 15th ICOLD International Benchmark Workshop [188], [227]

Mode	Natural frequency (Hz)			St. Deviation
	Present study[1]	Present study[2]	ICOLD Benchmark[3]	ICOLD Benchmark[3]
1	1.90	1.81	2.15	0.34
2	3.67	3.04	3.28	0.63
3	3.76	3.32	3.91	0.79
4	4.86	3.54	4.51	0.88

[1]scenario, y=4, z=3 and [2]scenario, y=4, z=4 and [3]Case A2 of 15th ICOLD International Benchmark Workshop

Scenario S1.4.4 in our current study corresponds to Case D-3 in ICOLD (2019) and USSD (2018). The maximum crest displacement for scenario S1.4.4 (0.042 m) in the present study falls within the reported range for Case D-3 in ICOLD (2019) and USSD (2018). Similarly, scenario S3.4.4 in our study matches Case E-1 in ICOLD (2019) and USSD (2018). The maximum crest displacement values for S3.4.4 (0.044 m) align with those of Case E-1 and fall within the reported range in ICOLD (2019) and USSD (2018). The reasonable variation in outcomes can be attributed to differences in considered material properties, reservoir level, and foundation dimensions. Additionally, there may be variations in the modeling approaches adopted by different participants. While a large number of models can provide an improved understanding and quantification of modeling uncertainty compared to a scenario with fewer analysis models, selecting fewer but carefully chosen models for progressive analysis with increasing complexity could be beneficial when there is some prior knowledge of the modeling uncertainty and the desired level of accuracy.

4.8. Concluding remarks

The parametric study conducted in this research sheds light on the critical role of numerical simulations in evaluating the seismic performance of dams. By focusing on two case study dams with similar geometries but distinct material and loading characteristics, we aimed to understand the variations in system response resulting from different solution procedures and model complexities. The study encompassed four scenarios (S1 to S4), each escalating in model complexity and utilizing varying solution procedures. Through a systematic comparison, we aimed to discern the impact of these factors on modal parameters and crest displacement across the scenarios.

Key findings from our study, consistent with those of previous benchmark studies, include:

1. In scenarios considering only the dam body, modal parameters and crest displacement histories align well across different software systems, indicating reliable performance in simpler models.
2. Discrepancies arise in crest displacement values between simplified approaches like the added mass method and more accurate acoustic element modeling, emphasizing the importance of considering fluid-structure interaction accurately.
3. The choice of reservoir modeling significantly influences results, with acoustic elements providing a more accurate representation of fluid-structure interaction compared to the added mass approach.
4. Despite adopting isotropic and homogeneous material properties and boundary conditions for the foundation, variations in results across models indicate the impact of each tool's implementation of soil-structure interaction.
5. Maximum crest displacement shows increasing variation with increasing modeling complexity, underlining the importance of progressive simulation for understanding system behavior thoroughly.
6. Nonlinear effects are more pronounced for scenarios with an empty reservoir, particularly for the Koyna dam, which lacks the damping effects of water during seismic events.
7. The use of nonlinear analysis and acoustic elements for reservoir modeling yields more consistent results across scenarios and dams.
8. EAGD-84 and ADRFS v1 offer ease of use and quicker turnaround for preliminary safety assessments, while Abaqus or similar software is recommended for comprehensive safety evaluations.

Based on these findings, several recommendations emerge for dam safety assessments:

1. For initial screenings or routine evaluations, simpler methods like 2D modeling with EAGD-84 and ADRFS v1 are effective.
2. Compliance with regulatory standards necessitates a mix of methods, with more complex analyses reserved for dams with high-risk profiles.
3. In the design and retrofitting stages, detailed analyses with Abaqus or similar tools are essential for ensuring structural resilience.
4. Understanding variations across different methods is crucial to avoid the pitfalls of overly simplistic approaches and to develop effective action plans in emergency response scenarios.

Future studies can explore additional factors such as joint opening/closing, base sliding, nonlinear contact modeling, and heterogeneous foundation simulation to further refine modeling techniques and understand variations in system response comprehensively.

Chapter 5

Ground motion selection

This chapter delves into the uncertainties that arise from selecting ground motion and their effects on assessing the seismic risk assessment of concrete gravity dams. The Pine Flat DFR model serves as a case study for seismic risk analysis. The lognormal fragility function corresponding to three limit states is utilized to construct failure probability curves. The Concrete Damaged Plasticity (CDP) model is used for material non-linearity in the dam, and the Drucker Prager failure model is employed for the foundation. The reservoir is modeled using acoustic elements, and a nonlinear time-history analysis is conducted. Next, the chapter explores the effects of ground motion selection techniques and Record-to-Record (RTR) variability on fragility assessment. To address epistemic and aleatory uncertainties, two unique ground motion selection techniques, ASCE 7-16 and Conditional Mean Spectrum (CMS), grounded in distinct theoretical frameworks, are employed. RTR variability is considered within a return period and across different periods for aleatory uncertainty. The study selects 110 ground motions to ensure the robustness of the analysis. The fragility assessment of a 2D DFR system takes into account the nuances of ground motion across different periods, providing a thorough understanding of their collective impact. Fragility curves, developed through stress, displacement, and damage area ratio-based indices, give a comprehensive view of the influence of ground motion selection techniques and RTR variations on the fragility assessment of the concrete gravity dam. This investigation also identifies critical failure modes in the context of seismic vulnerability. A quantitative risk assessment is conducted for the two identified failure modes, namely failure at the neck and failure at the dam's base. The report estimates the loss of life and economic damage for both failure modes and demonstrates the impact of the ground motion selection technique. By managing these uncertainties, engineers and decision-makers can make more informed decisions about dam design, assessment, and retrofit, ultimately enhancing their safety and resilience.

5.1. Introduction

In the domain of structural engineering, dams play a pivotal role in ensuring the essential functions of water supply, flood control, and power generation for communities globally. Meanwhile, the performance and maintenance of the existing dams during their life cycle need to be monitored. However, the resilience of these massive structures faces persistent challenges, particularly in regions prone to heightened seismic activities. Gravity dams situated in regions prone to seismic activity face the potential for substantial damage during intense earthquakes, exemplified by instances like the Koyna Dam in India, the Sefid Rud Dam in Iran, and the Pine Flat Dam in the United States [228]. With a global inventory of over 61000 large dams, concerns about the safety of aging structures have become a widespread issue. Many of these dams, constructed decades ago, are now well into their fifth or sixth decade of service, underscoring the critical need for robust evaluations and modernization initiatives [2]. Recent studies highlight the urgency of these assessments and retrofitting procedures, especially considering that the average age of large dams in the United States, a country with a substantial dam infrastructure, is now 65 years and steadily increasing [5]. The pressing concern is further amplified by the potential consequences of dam failures, ranging from loss of life to economic setbacks and environmental devastation, emphasizing the paramount importance of dam safety. Recent advancements in understanding seismic risks reveal that many dams no longer meet updated safety standards. This convergence of aging infrastructure, emerging challenges, evolving seismic load estimation methods, and heightened societal safety expectations necessitates a thorough reassessment and enhancement of seismic analysis techniques for dams [229].

In the past ten years, there has been a notable surge in comprehending seismic hazards, and evaluation techniques leading to heightened attention on seismic safety protocols for existing dams. Within this framework, deterministic methods are frequently criticized for being overly conservative and, in certain cases, deemed unsafe. Such perspectives arise from their inclination to neglect the numerous uncertainties inherent in structural analysis. This limitation is further accentuated by the dependence on extreme load scenarios characterized by exceptionally low probabilities of occurrence. To address these limitations and establish a more rational approach to assessing the safety of concrete gravity dams, there is a growing need for procedures that can prioritize risks effectively. Furthermore, a shift toward a probabilistic framework is imperative. Such an approach enables the comprehensive management of the diverse sources of uncertainty that can significantly influence dam performance and the decisions associated with it [100].

Earthquake-induced damage poses a dual threat to dams, impacting both their regular functioning and overall safety. Consequently, there is a critical need to delve into methodologies for evaluating the seismic performance of gravity dams. Given the uncertainties inherent in seismic effects and structural resistances, a more rational approach involves assessing structural seismic performance through the lens of seismic fragility. In essence, seismic fragility is commonly defined as the probabilities associated with structures attaining or surpassing specific damage states (DS) under varying levels of ground motion intensity [230]. Within the probabilistic paradigm, fragility analysis emerges as a promising solution. Seismic fragility assessment of dams represents a pivotal aspect of ensuring the structural resilience of these critical infrastructures under seismic events. The essence of fragility analysis lies in comprehending how dams respond to varying levels of seismic intensity. This assessment helps in gauging the structural vulnerabilities and informs risk mitigation strategies. Seismic fragility assessments employ diverse methodologies, ranging from judgmental and empirical approaches to analytical techniques and hybrid models. These methods intricately define the parameters influencing a dam's response under seismic stressors. The assessment revolves around the definition of damage states or limit states, crucial thresholds that demarcate the transition from functional to non-functional states. Determining these states is a nuanced process, considering the complex interplay of material properties, structural geometry, and ground motion dynamics. The process of fragility assessment operates amidst a web of uncertainties. These uncertainties, both aleatory (inherent randomness) and epistemic (knowledge-based), significantly impact the assessment's accuracy. Factors like seismic ground motion variability, modeling uncertainties, and limited data availability introduce complexity. Additionally, fragility analysis is seamlessly integrated into broader seismic risk assessments, offering a granular perspective on a dam's vulnerability. Fragility curves, emerging from meticulous analyses, serve as indispensable tools in risk assessment, providing insights into failure probabilities at different seismic intensities. In this intricate landscape of seismic fragility assessment, understanding the fundamentals, methodologies, damage states, and uncertainties is paramount. Through a detailed exploration of these aspects, a comprehensive comprehension of dam fragility assessments emerges, laying the foundation for informed decision-making and resilient infrastructural design. At the heart of this evolution lies the complex process of ground motion selection. Selecting appropriate ground motions is beset with uncertainties, ranging from the inherent variability in seismic events to uncertainties introduced by different attenuation equations and selection methods.

5.2. Background

In the domain of structural engineering, the seismic fragility assessment of dams stands as a critical pursuit, driven by the imperative to comprehend and mitigate the vulnerabilities of these essential structures in the face of seismic forces. Over the past decade, seismic fragility analysis has garnered increasing attention, evolving as a captivating subject that scrutinizes the resilience of dams under earthquake-induced stresses. This review embarks on an exploration of pivotal contributions in the literature, traversing diverse methodologies and studies that have shaped our understanding of how dams respond to varying levels of seismic intensity. From probabilistic analyses and fragility curves to considerations of material uncertainties and ground motion selections, the literature offers insight, laying the foundation for a nuanced comprehension of seismic risks in dam engineering.

Araujo and Awruch et al. [231] performed a probabilistic analysis for seismic assessment of the dam-reservoir-foundation system, applying artificially generated ground motions, and considering various limit states such as sliding, concrete crushing, and cracking failure modes. Ellingwood et. al., [232] studied the fragility analysis of concrete gravity dams. Basic fragility concepts are presented, and databases required to support the fragility assessment are identified. The method is illustrated using a concrete monolith from the Bluestone Dam in West Virginia, designed in the late 1930s. Tekie and Ellingwood,[230] investigated fragility curves for a gravity dam, considering various limit states such as material failure at the toe and neck, sliding at the dam-foundation interface, and deflection of the crest near the dam heel. The seismic analysis involved twelve ground motions scaled to a range of 0.1g to 1.2 g. Their findings indicated the potential for sliding along the dam-foundation interface and tensile cracking at the dam's neck during an earthquake with a magnitude equivalent to the maximum credible earthquake (MCE) defined by the U.S. Army Corps of Engineers. Lupoi and Callari, [233] Constructed fragility curves for Japan's Kasho Dam, which endured the Western Tottori earthquake in the year 2000. The evaluation focused on an operational limit state, encompassing varying reservoir water levels, and scrutinizing the effects of material uncertainties. Ghanaat et al. [234] utilized non-linear time-history analysis with Latin Hypercube Simulation (LHS) for developing the fragility curves for two failure modes, i.e., sliding at the dam base and sliding at the lift joint. Baker, [235] estimated fragility functions using multiple stripe analysis and Incremental dynamic analysis, highlighting the superior efficiency of multiple stripe analysis over the incremental approach. The article also introduces a method to calibrate structural fragility functions directly from nonlinear time-history responses, eliminating the need for extensive simulations. Bernier et al.,[236] the majority of existing fragility assessments for concrete dams commonly employ identical records across all intensity levels and frequently choose them with a target spectrum that is deemed insufficient. To enhance the fragility assessment, it is suggested to utilize the Conditional Spectrum (CS) method within a multiple stripes analysis [95]. This method was utilized to enhance the fragility assessment of an eastern Canadian concrete gravity dam, demonstrating its superiority compared to conventional methods. The investigation involved analyzing the interaction among the dam, foundation, and reservoir, taking into account variations in model parameters. Subsequently, fragility curves were formulated using nonlinear time-history analysis, following the methodology proposed by Tekie and Ellingwood [230]. Hariri-Ardebili et al., [237] explored fragility curves for gravity dams subjected to solely horizontal and combined horizontal and vertical ground motions, determining that the addition of a vertical component elevates the likelihood of failure. Hariri-Ardebili et. al.,[238] address the probabilistic seismic demand model (PSDM) which is the relationship between the intensity measure (IM) (such as spectral acceleration) and the engineering demand parameter (EDP) (such as displacement and crack ratio i.e., the ratio of crack length to the total crack path). When the results of the cloud analysis are aggregated, then one can plot the seismic fragility curve which is the probability of EDP exceedance in terms of the IM parameter. Ansari et. al.[239], conducted a vulnerability assessment using fragility curves on a typical concrete gravity dam. The fragility function was developed based on crest displacement which may be an effective and viable health monitoring tool specific to the concrete gravity dam. The seismic risk of concrete dams may be assessed using various numerical techniques, ranging from simplified methods to linear and nonlinear ones. Hariri-Ardebili et. al., [240] propose a random version of a simplified response spectrum method (involving equivalent static lateral forces [ESLFs]) for gravity dams employing propagating uncertainties through the input parameters. Alembagheri, [241] the efficiency of vector-valued intensity measures for predicting the seismic demand in gravity dams is investigated. The

Folsom gravity dam-reservoir coupled system is selected and numerically analyzed under a set of two hundred actual ground motions. The probabilistic seismic behavior of the dam is investigated by calculating its fragility curves employing scalar and vector IMs considering the effect of zero response values. Segura et. al. [242] propose a methodology for the proper modelling and characterization of the uncertainties to assess the seismic vulnerability of a dam-type structure. It also includes all the required analyses and verifications of the numerical model before performing a seismic fragility analysis and generating the corresponding fragility curves. In recent years, probabilistic methods, such as fragility analysis, have emerged as reliable tools for the seismic assessment of dam-type structures. Segura et. al., [100] present the development of up-to-date fragility curves for the sliding limit states of gravity dams in Eastern Canada using a record selection method based on the generalized conditional intensity measure (GCIM) approach. Utilizing the spectral acceleration at the fundamental period of the dam-reservoir-foundation system, $S_a(T_i)$, as an intensity measure parameter, they conducted multiple stripe analyses for fragility curve development. Deng-Hong Chen et al. [243] studied damage processes and failure modes of roller compacted concrete gravity dams using Incremental dynamic analysis, identifying potential failure locations at which functional failure may occur are mostly found in the stress concentration of the dam slope, the boundary of the rolling section, the junction between the dam and dam foundation, and the top of the corridor. Sevieri et. al. [244] discusses the main issues behind the application of performance-based earthquake engineering to existing concrete dams, with particular emphasis on the fragility analysis. After a critical review of the most relevant studies on this topic, the analysis of an Italian concrete gravity dam is presented to show the effect of epistemic uncertainties on the calculation of seismic fragility curves. Segura et al., [229] explored viable metamodels for seismic evaluation of gravity dams for use in fragility analysis, identifying key parameters influencing fragility analysis estimates. Gavabar and Alembagheri [245] generated seismic fragility curves for three gravity dams i.e., Pine Flat Dam (United States), Koyna Dam (India), and Shafarood Dam (Iran), observing better seismic performance for the Shafarood dam under seismic excitations. Ganji et al. [246] evaluated the effect of uncertainties in the mechanical properties of foundations on the seismic response of the DFR system, highlighting the importance of deconvolution. Tidke et. al.,[247] For the fragility analysis of the Koyna dam, using a 2D DFR model with a layered foundation, ground motions are picked according to the Conditional Mean Spectrum approach. An Incremental Dynamic Analysis (IDA) method is used in which each ground motion is scaled at different intensity levels and directly these ground motions are adopted for the time-history analysis. In fragility analysis, the seismic risk of a gravity dam can be evaluated better using PGA and ASI as compared to PGV. Li et. al., [108] study fuzzy seismic fragility analysis of gravity dams considering spatial variability of material parameters. A mathematical model for describing the fuzziness of damage states threshold is presented. The seismic performance of the aged-concrete gravity dam (aged-CGD) by safety assessment based on the reliability index is the main focal point of this study. Nahar et. al. [248] studied the effective safety assessment of an aged concrete gravity dam based on the reliability index in a seismically induced site. To investigate the aging effect, the hygro-chemo-mechanical model has been taken for different years consideration.

5.3. Ground motion selection

In recent years, considerable research efforts have been devoted to enhancing the process of ground motion selection procedures for seismic analyses, considering the unique geological characteristics of each seismically active region. The importance of selecting input ground motions tailored to specific seismic site conditions must be emphasized, given the inherent diversity in geological settings across regions. A seismic hazard analysis was conducted for Pine Flat Dam, located in California, USA using the USGS tool [249]. The Central Valley of California is surrounded by several faults San Andreas fault: California's largest fault, is located in the west. The San Andreas fault is a right-lateral strike-slip transform fault that extends roughly 750 miles through California. It forms the tectonic boundary between the Pacific Plate and the North American Plate. The San Andreas fault can create earthquakes as big as magnitude 8.

The ground motion selection in this study was carried out using the ASCE 7-16 and Conditional Mean Spectrum (CMS) method. ASCE 7-16 provides guidelines for selecting ground motions applicable to seismic designs of various structures, including dams. ASCE 7 provides a framework to establish the ground motions and the newest edition (ASCE 7-16, 2016) provides more guidance in the ways ground motions are to be specified in terms of the acceptable hazard and risk levels as well as criteria for appropriate ground motions to be used in the response history procedures [250]. This method adheres to a risk-consistent approach, ensuring that the chosen ground motions maintain a probability of exceeding the design limit state equal to the predetermined probability of exceedance. ASCE 7-16 requires a minimum of 11 ground motion time histories for each target spectrum. ASCE 7-16 allows the use of ground motions scaled to scenario spectra as an alternative to the risk-targeted uniform hazard spectrum. In the ASCE 7-16 edition ground motions were selected based on spectral matching in between 0.2T to 2.0T with the target spectrum, where T used to be the fundamental period of the structure in the fundamental mode for the direction of response being analyzed. The current selection process uses the risk-targeted uniform hazard spectrum as the target spectrum.

Similarly, the Conditional Mean Spectrum (CMS) method [98] has become widely utilized for selecting ground motions in dam fragility analyses. This technique aligns the mean spectrum of chosen ground motions with a predefined target spectrum at the structure's fundamental period. Typically, this target spectrum is derived through Probabilistic Seismic Hazard Analysis (PSHA) specific to the dam site. The CMS approach is an efficient tool for ground motion selection introduced by Baker [98]. This approach provides the mean spectrum, serving as the target spectrum for ground motion selection. The calculation procedure for the spectrum is detailed [251]. Jayaram et al. [95] presented an algorithm for ground motion selection where motions are aligned with the target spectrum mean and variance. Subsequently, this algorithm was refined [252]. Bernier et al. [236] conducted an enhanced fragility analysis of a gravity dam, incorporating the CMS method proposed by Jayaram et al. [95].

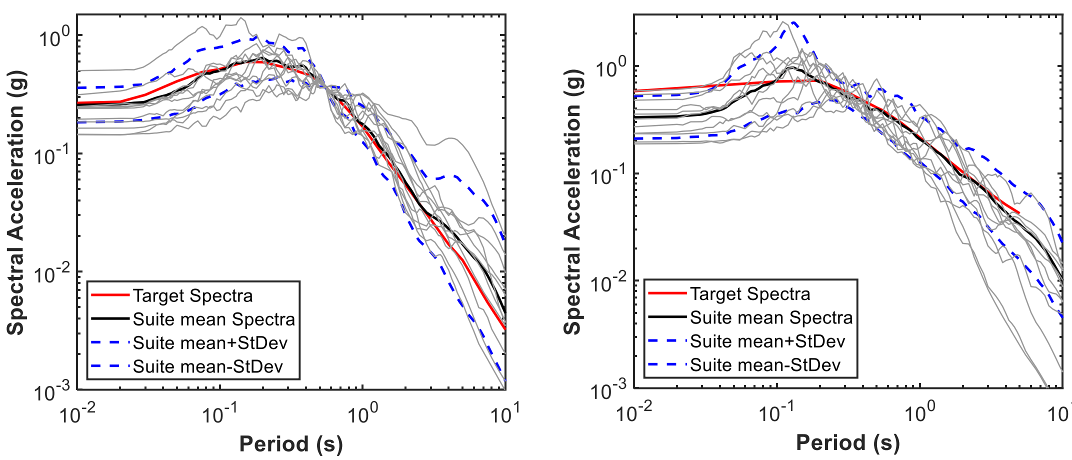
Utilizing the U.S. Geological Survey (USGS) tool [249], a seismic hazard analysis was conducted for Pine Flat Dam in California, USA. This analysis meticulously outlined potential earthquake scenarios across varied intensity levels, defined in terms of horizontal spectral acceleration at the structure's fundamental period. Spectral accelerations were chosen for return periods of 475,975, 2475, 5000, and 10000 years. Ground motion selection was performed using the Pacific Earthquake Engineering Research Centre (PEER) ground motion database [253]. The Probabilistic Seismic Hazard Analysis (PSHA) for the dam's location, specifically for the 0.50-second spectral period and considering a shear wave velocity of Vs_{30} = 760 m/s (B/C boundary) [254], was carried out to generate the Uniform Hazard Spectrum (UHS).

For the UHS development, the conterminous U.S. 2014 (update) (v4.2.0) model [255] in the USGS tool was utilized. This model provided essential disaggregation information for 11 attenuation equations. The obtained disaggregation data were instrumental in developing the target spectrum and selecting ground motions using the CMS method. Specifically, the disaggregation information corresponding to the Campbell & Bozorgnia (2014) attenuation equation [256] in the PEER ground motion database closely aligned with the UHS at the target period.

The target spectrum in the PEER ground motion database was generated using specific input parameters. These included a damping ratio of 5%, specifying the region as global/California, a magnitude of 6.42, and an R_{jb} (distance from the fault) of 46.13 km. Record selection criteria involved considering fault type as strike-slip. The fundamental period of the dam foundation reservoir (DFR) system, set at 0.551 seconds, was used as the conditioning period. For ASCE 7-16, magnitudes between 6 to 7.5, and R_{jb} values between 10 to 50 km were considered during spectrum generation. Each selection method comprised 55 ground motions, consisting of 11 unique motions per return period across five return periods.

Figure 33 (a) shows the mean target spectrum or CMS, alongside the CMS ± conditional σ spectra and the spectra of the selected ground motions, where σ is the standard deviation. It's noteworthy that all these chosen ground motions fall within the CMS +/- conditional σ range, ensuring their suitability for the analysis. This stringent selection process guarantees that the chosen ground motions closely align with the specific seismic characteristics of the site.

ASCE 7-16 establishes a comprehensive framework for selecting ground motions. The latest edition offers detailed guidelines on how to specify these motions concerning acceptable hazard and risk levels. It mandates a minimum of 11 ground motion time histories for each target spectrum. ASCE 7-16 also allows the use of ground motions scaled to scenario spectra, providing an alternative to the risk-targeted uniform hazard spectrum. In this edition, ground motions were chosen based on spectral matching between 0.2T to 2.0T, where T represents the fundamental period of the structure in its fundamental mode for the analyzed response direction [250]. In the ASCE 7-16 process, the risk-targeted uniform hazard spectrum serves as the target spectrum. Figure 33 (b) shows the mean target spectrum, along with the ± σ spectra and the spectra of the chosen ground motions. Appendix A contains detailed information about the ground motions selected based on the CMS for various return periods. Similarly, Appendix B provides comprehensive details of the ground motions chosen by ASCE 7-16 standards across different return periods.



(a) (b)

Figure 33. (a) CMS 1 in 5000 years, (b) ASCE 7-16 1 in 5000 years

The ground motion selection techniques used in the current study reflect a focused approach to understanding the variation in seismic response of the system under study. By employing this method, the research aligns with contemporary practices in seismic analysis, ensuring that the ground motions used in the study are both representative of the site-specific seismic hazard and consistent with the latest advancements in the field. This approach enhances the reliability and relevance of the seismic vulnerability assessment, providing valuable insights into the seismic behavior of structures under different seismic loading scenarios.

5.3.1. Comparison of ASCE 7-16 and CMS

In recent years, extensive research has been conducted on the procedure for selecting ground motions in seismic analysis. Considering the diverse geological conditions of earthquake-prone regions, the careful selection of input ground motions is crucial. It is imperative to choose ground motions with characteristics that align with the specific seismic site conditions of the region under consideration. Non-linear seismic analysis of the structure requires the right selection of GMs, which can provide a real scenario during an earthquake. The ASCE 7-16 and the Conditional Mean Spectrum (CMS) method are both used for ground motion selection. Both methods approach the problem in different ways [98], [257]. The ASCE 7-16 method is based on probabilistic seismic hazard analysis (PSHA), which considers all possible earthquakes that could occur at a site, along with their probabilities of occurrence, to estimate ground motions. This method tends to give higher Peak Ground Acceleration (PGA) values as it considers worst-case scenarios [257]. On the other hand, the CMS method is a deterministic approach that selects ground motions based on a specific scenario (like a particular earthquake on a known fault) [257]. This method might give lower PGA values as it considers a specific scenario rather than all possible scenarios. The CMS method has been suggested by ASCE/SEI 7-16 to decrease the dispersion between response accelerations [257]. The differences in the PGA values between the ASCE and CMS methods can be attributed to the different approaches these methods use for ground motion selection.

The variability within a return period for both methods can be due to the inherent uncertainty in predicting ground motions. Factors like the local geology, distance from the seismic source, and the type of earthquake can all influence the actual ground motion at a site. The variability across return periods can be due to the increasing severity of the ground motions considered. Longer return periods correspond to more severe (but less likely) earthquakes, leading to higher PGA values. From Figure 34, the median PGA values for ASCE 7-16 are generally higher than those for CMS across all return periods. The ASCE method seems to predict higher ground accelerations, which could lead to a more conservative safety assessment. However, the CMS method, with its generally lower PGA values, might be more representative of the actual ground motions that might occur. It appears that the ASCE method generally predicts a larger spread of PGA values compared to the CMS method. This could be because the ASCE method considers a wider range of possible earthquake scenarios. This suggests that the ground motion selection method can significantly impact the PGA, and in turn, the dynamic analysis. In summary, while ASCE 07-16 provides a standard approach that can be applied broadly across many types of structures and sites, CMS offers a more tailored approach, particularly useful for site-specific analyses and structures with unique dynamic characteristics. Both techniques aim to ensure that the seismic inputs used in structural analyses are representative of the actual seismic hazards that structures might face.

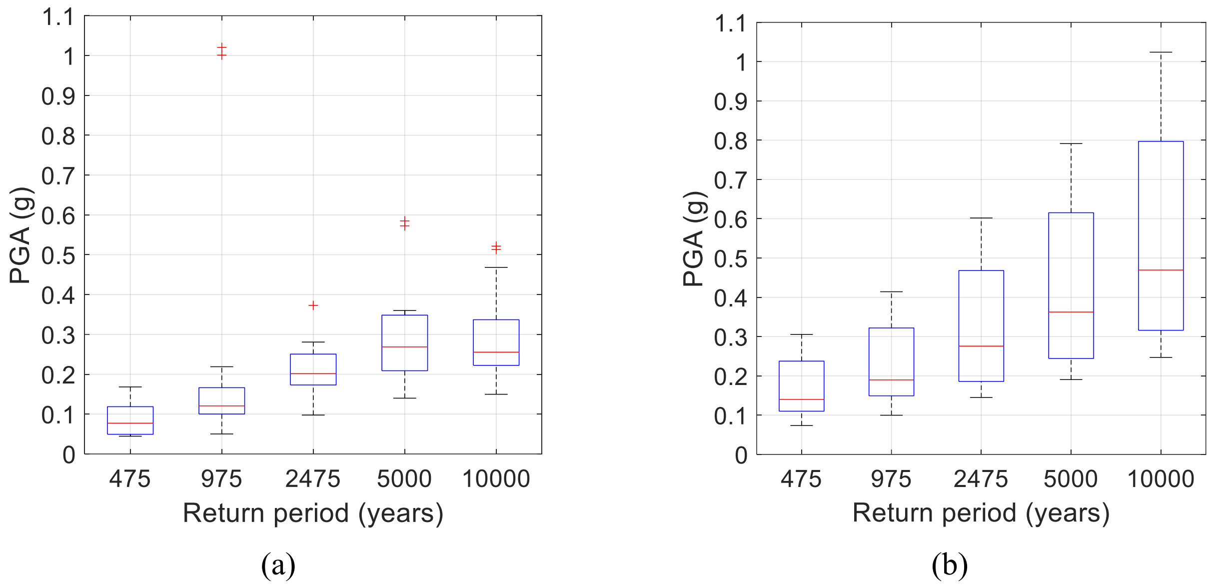


Figure 34. Comparison of variation of (a) PGA values for CMS and (b) PGA values for ASCE 7-16

5.3.2. Impact of RTR variability

Record-to-record variability refers to the differences in the seismic response of a structure due to variations in the characteristics of ground motions, even if they have the same magnitude and distance characteristics. For structures like concrete gravity dams, which are highly sensitive to seismic loading, RTR variability can significantly affect the reliability of the fragility assessment. Different ground motions can produce vastly different stress responses and deformation patterns in such structures. Studies have shown that ignoring RTR variability can either underestimate or overestimate the seismic vulnerability of dams. Accurate modeling of RTR variability is crucial for understanding the probabilistic seismic hazard and for developing robust fragility curves for these structures.

5.4. Case study

This section provides an overview of the chosen case study Pine Flat Dam. This dam was well-studied and its geometric, dynamic, and material properties are reported widely in the existing literature [222], [258], [259], making it an ideal candidate for this investigation. Pine Flat Dam, located in California, USA, plays crucial roles in water storage, hydroelectric power generation, and flood control. Pine Flat Dam presents a height of 130 m and a crest length of 561 m; it is comprised of 36 monoliths, each measuring 15.25 m wide, along with an additional 12.2 m wide block.

5.4.1. Numerical model

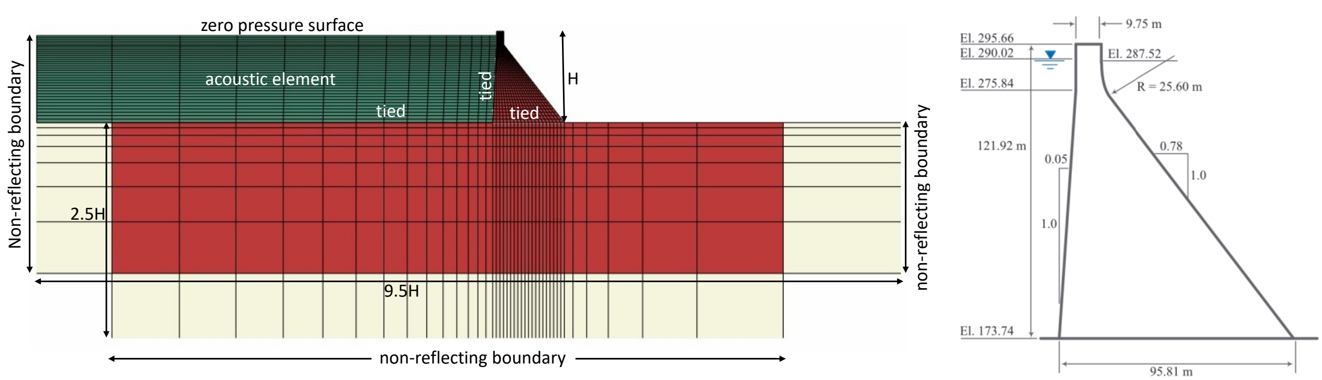
The numerical simulation of the coupled DFR system, as well as the monolith of the Pine Flat dam, is shown in Figure 35 (a), (b). The simulation was conducted using the Abaqus 2022 standard version [260]. The model incorporates both fluid-structure and soil-structure interaction. The reservoir is represented using acoustic elements (AC2D4), while the concrete dam and rock foundation utilize plain stress elements (CPS4R). Infinite elements (CINPE4) are employed for peripheral elements of the foundation. The CPS4R is a general-purpose 2D element used for standard problems in structural mechanics, while CINPE4 is designed for simulating wave propagation in infinite domains. Damping in the dam and foundation is implemented using Rayleigh viscous damping. Tie contacts are established between the dam, foundation, and reservoir, and non-reflecting boundary conditions are defined at the periphery of the foundation and the truncating end of the reservoir. Additionally, a zero-pressure surface is defined at the top of the reservoir. The material properties considered in the numerical simulation are detailed in Table 10. The model incorporates material nonlinearity through the concrete damage plasticity (CDP) model, with specific properties outlined in Table 11.

The nonlinear dynamic analysis focuses on a singular loading scenario, encompassing self-weight, hydrostatic thrust, hydrodynamic effects, and seismic loads. Seismic loading is applied in combinations with both horizontal components either as H_1V or H_2V. Here, the ground motions have been applied at the base of the dam. Alternatively, they could be deconvoluted and applied to the base of the foundation [197]. These analyses maintained consistent parameters, including the dam's geometry, material properties, reservoir level, foundation size, and contact characteristics, ensuring a uniform evaluation. This investigation does not take into account the effects of uplift, silt pressure, and aging, despite their potential impact on seismic performance.

The extensive simulations considering the ground motion variation yielded essential data, including the maximum principal stress history at the neck and heel, crest displacement history, and tensile damage area ratio (DAR). This evaluation provided a robust foundation for understanding the dam's response under varied seismic conditions, enabling comprehensive risk assessments, and strengthening the overall safety protocols of the Pine Flat dam.

Table 10. Elastic material properties of the dam, foundation, and reservoir for Pine Flat Dam [261]

Material properties	Concrete	Foundation	Reservoir
Density (ρ)	2482 kg/m^3	2640 kg/m^3	1000 kg/m^3
Modulus of elasticity (E)	22407 MPa	22407 MPa	-
Bulk modulus (K)	-	-	2070 MPa
Poisson’s ratio	0.2	0.333	-
Rayleigh damping Alpha (α)	-	1.64	-
Rayleigh damping Beta (β)	0.004333	0.00668	-



(a) (b)

Figure 35. (a) Considered Abaqus DFR model (b) Cross-section

5.4.2. Concrete damaged plasticity (CDP) model

Concrete damage plasticity (CDP) stands out as a widely adopted material model in finite element analysis, offering a means to simulate concrete behavior across a spectrum of loading conditions. It effectively captures inelastic deformation and the accumulation of damage in concrete structures, providing a comprehensive characterization of both tensile and compressive responses, as shown in Figure 19, in Chapter 4. In assessing the nonlinear response of the concrete dam to seismic forces, the concrete damaged plasticity model was used in the Abaqus software. The damaged plasticity model, initially introduced by Lubliner et al. [262], serves to depict the nonlinear material behavior of concrete. Lee and Fenves [263] expanded on this model by incorporating yield function and damage variables, specifically addressing tensile and compressive damage to characterize various failure states. Subsequently, Lee and Fenves [264] applied the concrete damaged plasticity (CDP) model in the seismic analysis of a gravity dam. The CDP model was extensively used by various researchers for the damage assessment of concrete gravity dams [203], [265], [266], [267]. The CDP parameters as used in this study are shown in Table 11.

Table 11. CDP properties for the Pine Flat Dam

ψc*	σ_{co} (MPa)	σ_{cu} (MPa)	σ_{to} (MPa)	e	R
36.31°	12.08	22.41	2.24	0.1	1.16

* ψ_c: dilatation angle; σ_{co}: compressive initial yield stress; σcu: compressive ultimate yield stress; σ_{to}: tensile failure stress; e: flow potential eccentricity and R: ratio of the initial equibiaxial to the uniaxial compressive yield stress.

The CDP model in Abaqus is a continuum, plasticity-based, damage model used to simulate the nonlinear, inelastic behavior of concrete. It is particularly effective in earthquake engineering and structural dynamics for modeling concrete structures under cyclic loading and seismic events. The CDP model accounts for the degradation of the material stiffness due to both tensile and compressive plastic straining. The CDP model in Abaqus combines isotropic damage mechanics and plasticity theory. It is designed to represent the irreversible damage and stiffness degradation in concrete due to cracking in tension and crushing in compression [260].

The yield criterion for the CDP model is an extension of the Drucker-Prager yield criterion. It is represented in compression as shown in Equation 9 and tension as shown in Equation 10.

$$f_c(\sigma, q_t, q_c) = q_c\left(\frac{3J_2}{I_1^2}\right)^{1/2} + \frac{I_1}{3} - \sigma_c \leq 0 \qquad 9$$

$$f_t(\sigma, q_t, q_c) = q_t\left(\frac{3J_2}{I_1^2}\right)^{1/2} - \sigma_t \leq 0 \qquad 10$$

f_c and f_t are the yield functions for compression and tension, respectively, σ is the stress state, J_2 is the second invariant of the deviatoric stress tensor, I_1 is the first invariant of the stress tensor, q_t and q_c are tension and compression hardening parameters. σ_c and σ_t are the uniaxial compressive and tensile strengths of concrete.

The CDP model introduces two damage variables, $'d_t'$ and $'d_c'$ for tension and compression, respectively, can be seen in Figure 19 (a) and (b). These variables range from 0 (undamaged material) to 1 (fully damaged material). The stress-strain relationship in the CDP model is expressed by the following Equation 11.

$$\sigma = (1-d)\bar{\sigma} = (1-d)D_0 : (\varepsilon - \varepsilon^{pl}) \quad 11$$

The initial elastic stiffness matrix of the material is denoted by D0; σ represents the stress tensor, and $\bar{\sigma}$ stands for the effective stress tensor; d is a scalar representing the damage variable; ε^{pl} refers to the plastic strain. The process to determine the failure surface incorporates two hardening variables: the equivalent plastic strain in tension (ε_t^{pl}) and the equivalent plastic strain in compression (ε_c^{pl}). Under uniaxial loading conditions, the damage variable 'd' is divided into tensile and compressive scalar damage variables, indicated as dt and dc, respectively. The relationships between stress and strain for uniaxial tension and compression are depicted in Equations 12 and 13.

$$\sigma_t = (1-d_t)\sigma_e = (1-d_t)D_0 \times \left(\varepsilon_t - \varepsilon_t^{pl}\right) \quad 12$$

$$\sigma_c = (1-d_c)\sigma_e = (1-d_c)D_0 \times \left(\varepsilon_c - \varepsilon_c^{pl}\right) \quad 13$$

The stress-strain relationship of concrete under uniaxial tensile and compressive loading is shown in Figure 19 (a) and (b), respectively. Figure 19 (c) shows the tension damage curve for concrete, where the scalar damage variable in tension (d_t) changes with cracking displacement. However, the compressive crushing failure is not considered in the present study. Table 11 shows the material properties of the CDP model, which gives non-linear material behavior to the concrete.

5.5. Validation of modal parameters

The initial phase of the investigation involved validating the numerical model used in this study against the comprehensive analyses and findings reported for the Pine Flat Dam during the 15th ICOLD International Benchmark Workshop. The comparison of modal parameters, as presented in the following Table 12, falls comfortably within the range of values previously reported, underscoring the reliability and consistency of the model employed. In this analysis, a reservoir level of 290.02 m was adopted, aligning with Case A2 specified in the 15th ICOLD International Benchmark Workshop. It should be noted, however, that discrepancies exist between the foundation dimensions and material properties used in the current study and those detailed in the workshop's findings.

Table 12. Comparison of modal parameters with the 15th ICOLD International Benchmark Workshop [227], [188]

Mode	Natural frequency (Hz)		St. Deviation
	Present study	ICOLD Benchmark[1]	ICOLD Benchmark[1]
1	1.81	2.15	0.34
2	3.04	3.28	0.63
3	3.32	3.91	0.79
4	3.54	4.51	0.88

DFR model considered in this study and [1]Case A2 of the 15th ICOLD International Benchmark Workshop

5.5.1. Methodology

Figure 36 presents a detailed framework for the seismic performance and risk assessment of the Pine Flat Dam, integrating several critical steps to ensure a comprehensive evaluation. The process begins with the creation of a coupled two-dimensional (2D) DFR model, designed to accurately simulate the complex interactions within the dam system during seismic events. This model serves as the foundation for the subsequent analysis and evaluation stages. The selection of ground motions is a pivotal step in the assessment process, with a suite of 110 ground motion records chosen for five distinct return periods. This selection is grounded in the CMS and ASCE 7-16 procedures, ensuring a diverse and representative set of seismic inputs that reflect both site-specific seismic hazard profiles and industry-standard practices. Following the selection of ground motions, the framework involves performing nonlinear dynamic analyses of the 2D DFR system under the influence of these selected ground motion records. This analysis aims to capture the dam's structural response focusing on stress at the neck and heel, damage area ratio, and displacement across the different return periods. These structural response parameters are critical in understanding the dam's behavior under seismic loading and in identifying potential vulnerabilities. Central to the seismic performance evaluation is the definition of limit state functions, which are based on the dam's potential failure modes and performance objectives. These functions enable the calculation of the probability of exceeding each limit state at given intensity levels, providing a quantitative measure of the dam's seismic vulnerability. To quantitatively represent the dam's vulnerability to seismic events, a probabilistic distribution, typically lognormal, is fitted to the probability of failure data. This step results in the generation of fragility curves for each limit state, offering a statistical perspective on the likelihood of exceeding specific damage thresholds under seismic loading. The fragility curves are then utilized to assess the impact of variations in ground motion selection techniques and RTR variability. This analysis highlights the influence of different seismic inputs on the dam's seismic performance, underscoring the importance of ground motion selection in seismic risk assessments.

An additional step involves developing an influence line diagram for risk estimation, focusing on failure modes at the neck and heel of the dam. This approach, following the provisions set forth by the USACE in 2011, provides a targeted analysis of critical dam components that are susceptible to seismic-induced failures. Finally, the framework culminates in the estimation of potential loss of life and economic damage, translating the technical findings of the seismic performance and risk assessment into tangible societal and economic impacts. This holistic approach not only enhances the understanding of the Pine Flat Dam's seismic vulnerabilities but also facilitates informed decision-making regarding risk mitigation, emergency preparedness, and resource allocation for dam safety enhancements.

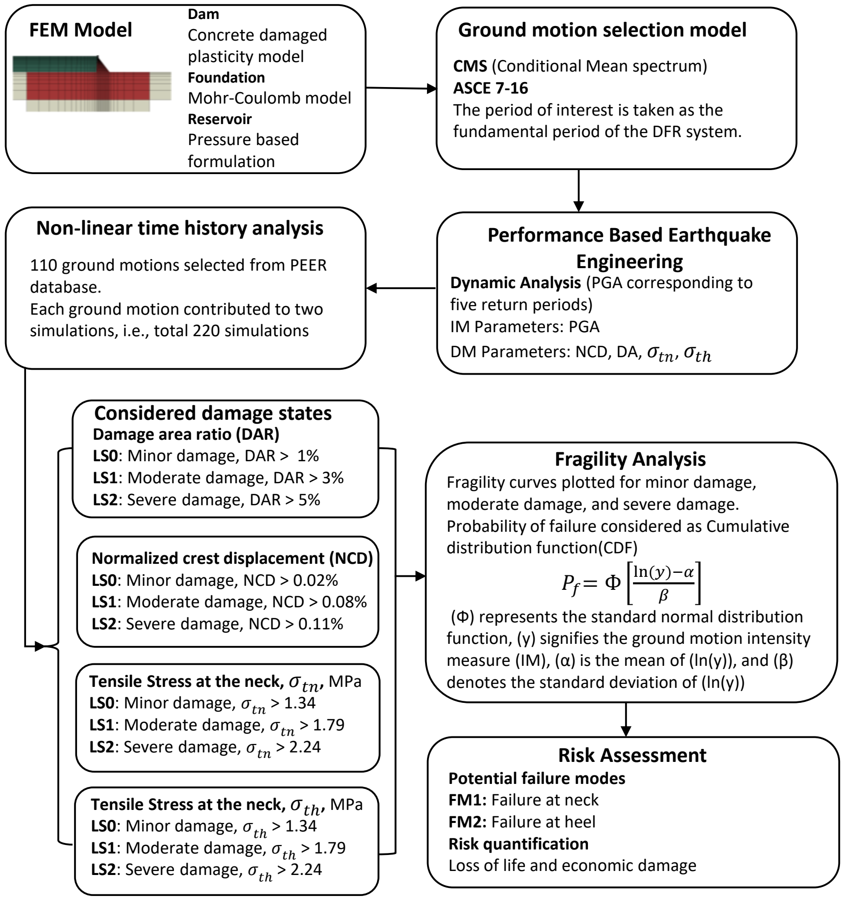


Figure 36. Outline of adopted methodology for fragility assessment

5.5.2. Inference of results

Figure 37 illustrates the comparative variation of structural response parameters and seismic demand characterized by return periods. This analysis is integral to understanding the seismic behavior of concrete gravity dams, particularly in terms of displacement, damage, and stress distribution. The variation of the crest displacement indicates a discernible trend showing an increase in displacement values with longer return periods. This trend is expected as higher return periods typically correspond to more intense seismic events, which would naturally induce larger displacements in dam structures. In this context, the ASCE 7-16 method predicts a larger crest displacement than the CMS, accompanied by a greater degree of variation. This increased variability may reflect the method's sensitivity to seismic intensity or may incorporate a broader set of seismic parameters that result in a more conservative estimate. The damage area ratio (DAR) plot further complements the understanding of structural performance under seismic loading. The DAR is seen to increase with the return period, reflecting a more extensive area of damage for more significant seismic events. The variation in DAR is substantial for both methods, which may be indicative of the inherent uncertainties in predicting the extent of damage due to seismic forces. This variability also underscores the stochastic nature of seismic events and the resultant structural response. Figure 37 (a) to (d) shows the variation of major principal stress at the neck and heel providing insights into the material stress states under seismic loading. There is an upward trend in stress values, approaching the limiting tensile strength as the return period increases.

This is consistent with the understanding that more significant seismic events generate higher stress levels within dam structures. Notably, the variation in stress diminishes with the increase in return period. This reduction in variation could be attributed to the material reaching its performance limits, whereupon further increases in seismic demand do not proportionally increase the stress due to the possibility of stress redistribution or the initiation of damage mechanisms that relieve stress concentrations. The data suggests a complex interplay between seismic demand and dam response, emphasizing the need for comprehensive seismic risk assessment approaches that can capture the variability in response parameters. The trend of increasing stress values nearing the material's tensile limits is particularly concerning, as it highlights the risk of structural failure or significant damage in rare but possible extreme seismic events. The results underscore the importance of employing advanced probabilistic methods such as fragility assessment in seismic risk assessment and the necessity of integrating these findings into engineering practices to ensure the resilience and safety of concrete gravity dams against seismic hazards.

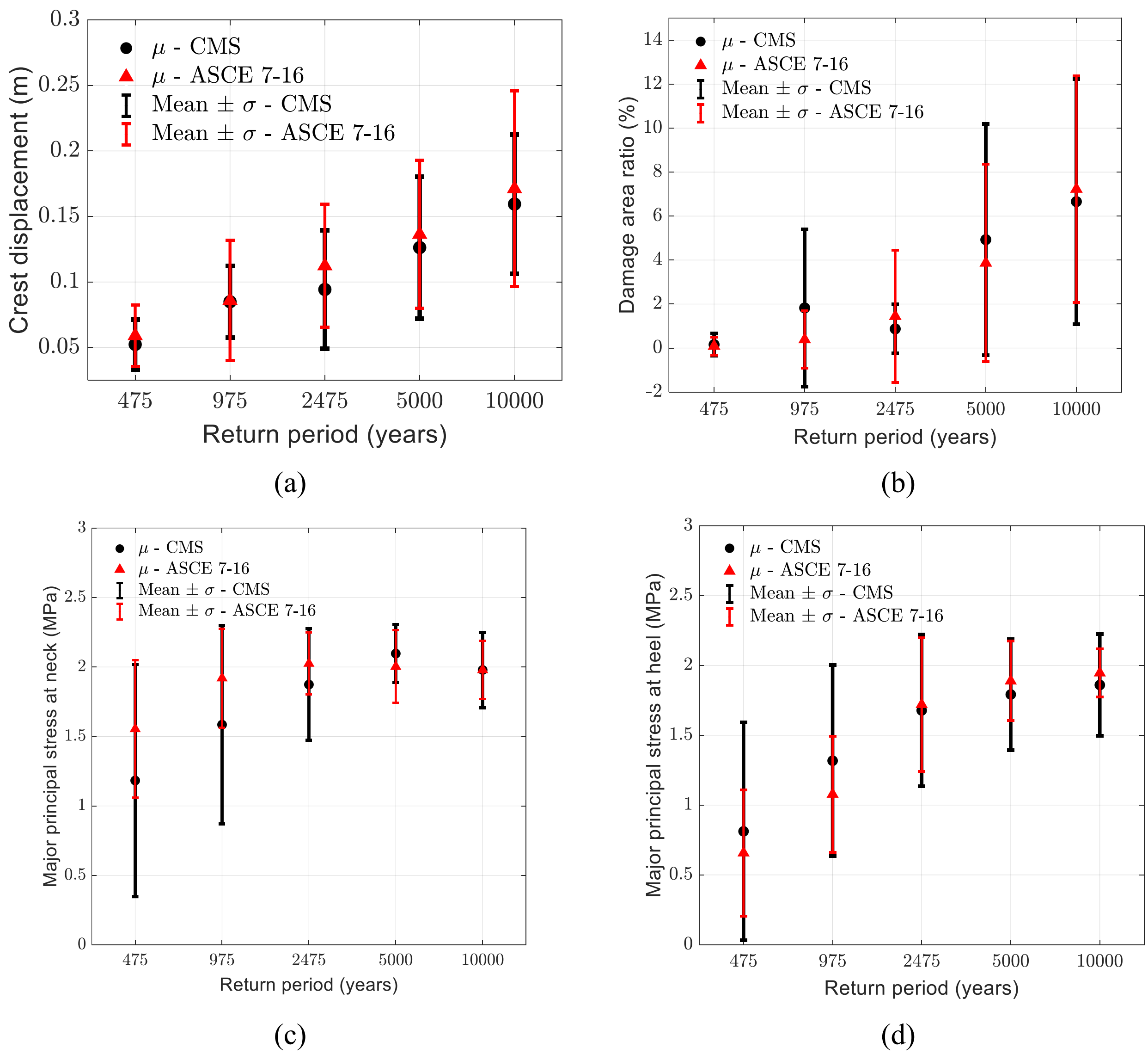


Figure 37. Comparison of variation of (a) displacement (b) damage area ratio (c) stress at neck (d) stress at the heel

5.6. Fragility analysis

In this study, a seismic risk assessment for a gravity dam was conducted, focusing on the influence of ground motion variations within and across various return periods, as well as the selection procedure. The approach involves developing fragility curves based on damage indices based on crest displacement, tensile stress, and damage area ratio. This enables nuanced comprehension and quantification of the variations in dam performance. The goal is to enhance our understanding of the system's behavior, providing valuable insights to mitigate the post-seismic consequences effectively.

5.6.1. Damage indices

In fragility analysis, damage indices are quantitative measures used to assess the severity of damage or deformation in a structure under specific loading conditions. These indices are crucial for developing fragility curves, which depict the probability of a structure experiencing different levels of damage given a certain intensity of loading, such as ground motion in seismic analysis. Common damage indices in fragility analysis include crest displacement, stress, and damage area ratio. Crest displacement measures the maximum horizontal displacement of the crest or top of a structure during an event. It is often used in dam fragility assessments to evaluate the structural response. Stress-based damage indices consider the distribution and magnitude of stress within a structure. Different stress components, such as tensile or compressive stress, may be assessed to gauge potential damage. The damage area ratio, index quantifies the ratio of the damaged area to the total area of the structure. It provides a spatial measure of damage distribution and severity. These indices help in categorizing the damage into different levels, such as minor, moderate, or severe, and are instrumental in developing fragility curves. The fragility curves, in turn, offer a probabilistic representation of the structural response under varying loading conditions, aiding in risk assessment and mitigation strategies.

5.6.2. Damage limit states

The key parameters under investigation are crest displacement, stress at the neck and heel, and damage area ratio, which are vital indicators of the dam's structural integrity. The crest displacement values were normalized with respect to the height of the dam. Normalized crest displacement (NCD) was calculated using Equation 14. The Damage Area Ratio (DAR) quantifies the percentage of the dam cross-sectional area that experiences damage due to the exceedance of tensile stress during seismic events, as shown in Equation 15. Elements with DAMGET values ranging from 0.6 to 1 are considered damaged. The damaged cross-sectional area is determined by summing the areas of these elements. Figures C.1 and C.2 in Appendix-C display the tensile damage plots, highlighting the damaged elements. Excessive crest displacement not only signifies potential damage to the dam itself but also raises concerns about the integrity of ancillary structures. Similarly, the exceedance of tensile stress combined with inelastic duration at the neck (σ_{tn}) and heel (σ_{th}) region shows material failure, propagation of crack path, and the risk to structural integrity. The neck of a gravity dam is a critical area where the structure is relatively thinner. Excessive tensile stresses here could be indicative of potential structural vulnerabilities. The heel of the dam is where the dam meets the foundation. Elevated tensile stresses at the heel could suggest issues related to the interaction between the dam and its foundation, potentially impacting stability, due to interface cracking and increased uplift pressure. Crest displacement, stress exceedance at neck and heel, and damage area ratio, when combined with ground motion return periods, facilitate the development of fragility curves. These curves serve as probabilistic representations of the likelihood of specific damage states occurring. In this study, limit states as a function of the crest displacement, stress exceedance, and DAR were defined.

$$NCD = \frac{crest\ displacemnt(m)}{height\ of\ the\ dam(m)} \quad 14$$

$$DAR = \frac{\text{dam cross section area that is damaged}}{total\ \text{cross section area of dam}} \quad 15$$

The three considered limit states (LS_0, LS_1, and LS_2) represent progressively increasing levels of damage to the concrete gravity dam, each indicative of different degrees of structural impairment as per the Performance-Based Earthquake Engineering (PBEE) guidelines. LS_0, or Minor damage, corresponds to the lowest performance level, signifying the presence of superficial or minor issues that do not significantly compromise the dam's overall integrity. This might include hairline cracks, surface abrasions, or localized imperfections that, while necessitating attention, do not pose an immediate threat to the structure. Moving up the performance levels, LS_1, or Moderate Damage, signifies a more pronounced level of impairment. In this state, structural elements experience notable distress, with cracks and deformations surpassing superficial characteristics. While the dam remains stable, restorative actions become imperative to prevent further deterioration. Finally, LS_2, or Severe Damage, represents the highest performance level on the scale and a critical condition where the structural integrity of the dam is significantly compromised. This involves extensive cracking, deformations, and potential instability. Immediate and comprehensive remediation is essential to avert catastrophic failure. These limit states provide a systematic framework for assessing and addressing the evolving condition of the dam, allowing for timely interventions at different stages of structural distress, thereby enhancing the dam's overall seismic resilience. The considered damage limit states in this analysis are provided in Table 13.

Table 13. Damage limit states

Limit State	Range			
LS_0- Minor damage	DAR > 1%	NCD > 0.02%	$\sigma_{tn} > 1.34$ MPa	$\sigma_{th} > 1.34$ MPa
LS_1- Moderate damage	DAR > 3%	NCD > 0.08%	$\sigma_{tn} > 1.79$ MPa	$\sigma_{th} > 1.79$ MPa
LS_2- Severe damage	DAR > 5%	NCD > 0.11%	$\sigma_{tn} > 2.24$ MPa	$\sigma_{th} > 2.24$ MPa

Damage area ratio (DAR), Normalized crest displacement (NCD), Tensile stress at neck and heel (σ_{tn}, σ_{th})

5.6.3. Fragility framework

Fragility analysis is a crucial technique in assessing the vulnerability of engineered systems to specific events, often used in seismic engineering and other fields where structural integrity is paramount [230]. The fragility function, $P_f(y)$, as shown in Equation 16 indicates the likelihood of structural failure given a specific ground motion intensity measure (IM) level. In this context, y represents the demand variable measured in the same units as the IM. D is the probability of exceeding a failure threshold. di refers to different damage states, such as minor, moderate, and severe (IM) representing the Intensity measure parameters.

$$P_f(y) = P[D > d_i | IM = y] \quad 16$$

In the context of a gravity dam, the fundamental failure modes encompass sliding, overturning, tensile cracking, and compressive crushing. In this study, the structural limit states considered are tensile crack failure and normalized crest displacement, as proposed in the previous section. To construct fragility curves, the log-normal cumulative distribution function (CDF) is employed. The failure probability (P_f) can be calculated using Equation 17.

$$P_f = \Phi\left[\frac{\ln(y) - \alpha}{\beta}\right] \qquad 17$$

In this equation, Φ represents the standard normal distribution function, and α and β are the mean and the standard deviation of the lognormal CDF, respectively.

5.6.4. Fragility function

The fragility curves generated for the 5-intensity-level correspond to five return periods. In each of the 22 nonlinear dynamic analyses conducted for each return period, combined H_1V or H_2V ground motion records were utilized. This resulted in a total of 110 analyses per selection method. For each simulation, NCD, stress at the neck, heel, and DAR were computed. Table 14 and Table 15 provide a summary of the fraction of collapse, i.e., samples where stress, NCD, and DAR values exceeded the limit state, for CMS and ASCE 7-16 respectively. The limit states were considered based on tensile stress, DAR, and NCD as detailed in section 5.6.2. The results from Table 14 and Table 15, representing the five fragility point estimates, were used to develop fragility curves for the three considered limit states.

Table 14. Fraction of collapse for CMS

Return Period (Years)	1in10000	1in5000	1in2475	1in975	1in475
DAR Limit state					
LS_0	18/22	16/22	8/22	7/22	2/22
LS_1	15/22	11/22	8/22	7/22	1/22
LS_2	12/22	9/22	4/22	3/22	1/22
NCD Limit state					
LS_0	22/22	19/22	16/22	11/22	2/22
LS_1	16/22	15/22	15/22	9/22	2/22
LS_2	17/22	16/22	15/22	9/22	2/22
Tensile stress at the Neck					
LS_0	21/22	21/22	20/22	15/22	12/22
LS_1	21/22	18/22	16/22	12/22	6/22
LS_2	20/22	12/22	10/22	9/22	4/22
Tensile stress at the Heel					
LS_0	20/22	20/22	17/22	13/22	4/22
LS_1	16/22	14/22	12/22	7/22	3/22
LS_2	10/22	8/22	7/22	4/22	3/22

Table 15. Fraction of collapse for ASCE 7-16

Return Period (Years)	1in10000	1in5000	1in2475	1in975	1in475
DAR limit state					
LS_0	20/22	17/22	7/22	1/22	1/22
LS_1	17/22	8/22	2/22	1/22	0/22
LS_2	16/22	3/22	1/22	1/22	0/22
NCD Limit state					
LS_0	22/22	22/22	20/22	18/22	13/22
LS_1	18/22	15/22	12/22	5/22	4/22
LS_2	14/22	11/22	6/22	4/22	2/22
Tensile stress at the Neck					
LS_0	22/22	21/22	21/22	19/22	15/22
LS_1	20/22	20/22	18/22	18/22	8/22
LS_2	15/22	15/22	12/22	12/22	6/22
Tensile stress at the Heel					
LS_0	22/22	20/22	17/22	6/22	2/22
LS_1	17/22	17/22	11/22	1/22	1/22
LS_2	10/22	9/22	6/22	1/22	0/22

5.6.5. Fragility curves

Figure 38 (a) and (b) shows the fragility curves based on DAR for CMS and ASCE 7-16. The fragility curves depict a progressive shift from minor to severe damage states as the return period increases, aligning with the expected behavior of the dam structure under seismic loading. Across all limit states, the fragility results show an increased probability of exceeding the damage states as the return period increases. CMS appears to be more sensitive to lower intensity levels than ASCE 7-16, especially evident in LS_1. CMS predicts slightly higher failure probabilities than ASCE 7-16 for similar return periods. This indicates that for the same ground motion, the structure is more likely to experience damage at lower return period values when using CMS. Similarly, Figure 38 (c) and (d) shows the fragility curves based on NCD for CMS and ASCE 7-16. NCD fragility curves show similar trends for minor damages (LS0), aligning closely with DAR-based fragility curves. For moderate damages (LS_1), DAR and NCD fragility show differences, especially in CMS predictions. NCD tends to predict higher probabilities of moderate damage than DAR. Similarly, for severe damage (LS_2), the difference between DAR and NCD is more pronounced. The fragility estimates based on NCD show higher probabilities for severe damage compared to those based on DAR. Here, NCD-based fragility appears to provide more conservative estimates, especially for moderate and severe damages, compared to DAR. Considering that, the choice between DAR and NCD should be made based on the desired level of conservatism and the risk tolerance of the project. Further as observed in DAR-based fragility, CMS tends to be more conservative across all limit states, especially for moderate and severe damages. Depending on the specific requirements of the project and the acceptable level of risk, the DAR or NCD-based fragility, or a hybrid type can be selected for a comprehensive and accurate evaluation of a structure's vulnerability.

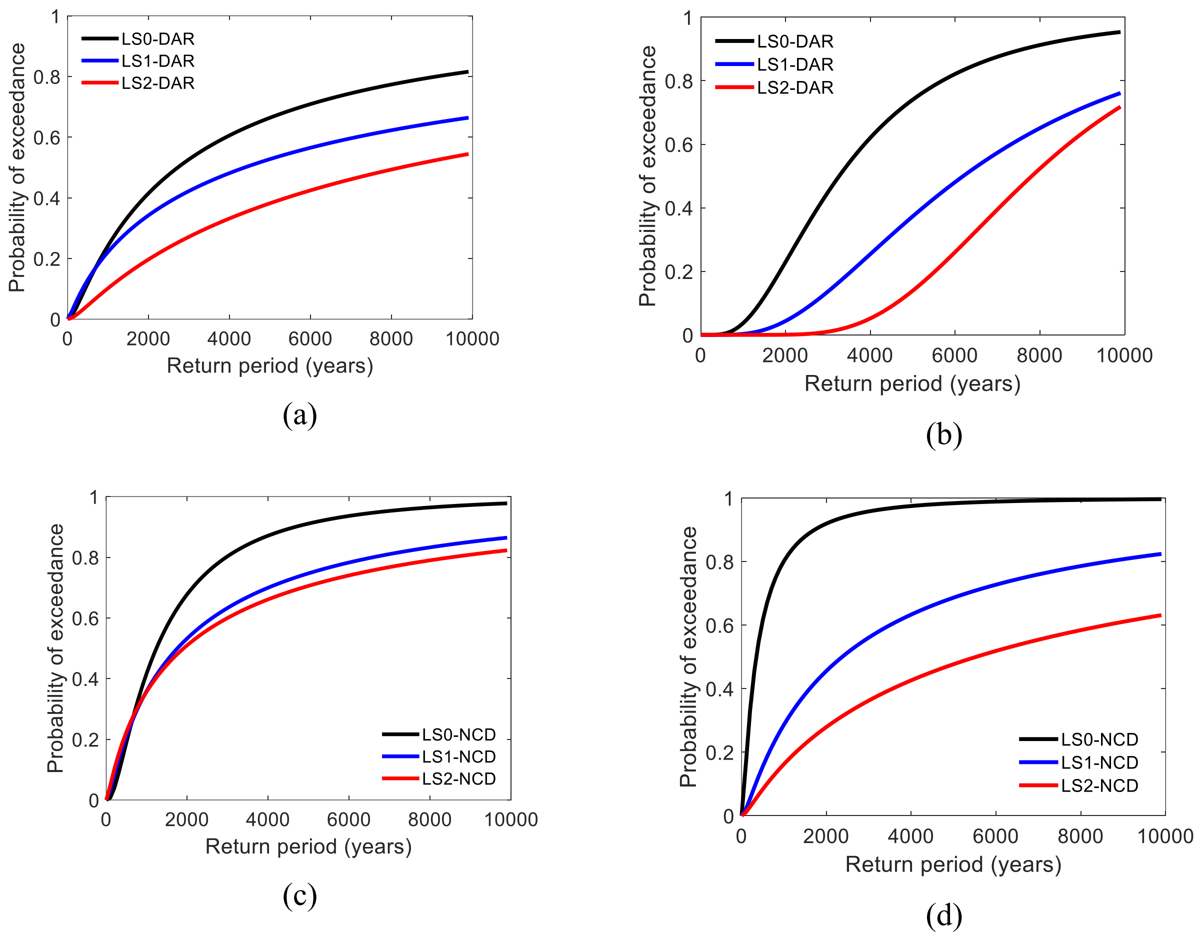


Figure 38. Fragility curves (a) CMS-DAR, (b) ASCE 7-16-DAR, (c) CMS-NCD (d) ASCE-NCD

Figure 39 presents the fragility curves for tensile stress at heel and neck regions, contrasting the predictions between CMS and ASCE 7-16. Upon examining the fragility curves for tensile stress at the heel and neck various comparative inferences were drawn between the CMS and the ASCE 7-16 approaches. Firstly, both methods indicate an increase in the probability of exceedance with the return period, which is a common trend in seismic risk assessment, as it correlates higher return periods with more severe ground motions. As shown in Figure 39 (a) and (b), for the heel, the CMS-derived fragility curves consistently reside above those of ASCE 7-16 across all limit states (LS_0, LS_1, LS_2), suggesting a higher likelihood of exceedance for a given return period. This implies that the CMS methodology may be capturing a more conservative view of seismic vulnerability or that it possibly incorporates additional factors not fully accounted for by ASCE 7-16. Notably, the CMS method differentiates more distinctly between the performance of different limit states, hinting at its sensitive response to changes in seismic intensity. As shown in Figure 39 (c) and (d), shifting focus to the neck region, we observe an augmented vulnerability as the fragility curves for both CMS and ASCE 7-16 show a higher probability of exceedance compared to those for the heel. This heightened risk could be attributed to the intrinsic characteristics of the neck region, which might include factors such as higher stress concentrations, that can exacerbate the response to seismic loading. Comparatively, the CMS method again suggests a more vulnerable scenario for the neck than ASCE 7-16, aligning with the observations made for the heel. This consistent pattern reinforces the notion that CMS might be incorporating a broader range of uncertainties or site-specific conditions that accentuate the seismic risk profile. Lastly, the neck region's pronounced fragility is evident across both CMS and ASCE 7-16, albeit more so with CMS. This higher susceptibility necessitates diligent consideration in seismic risk assessments and underlines the importance of targeted investigation into the factors contributing to the neck's increased risk, which is crucial for the formulation of effective mitigation, maintenance, and retrofit strategies.

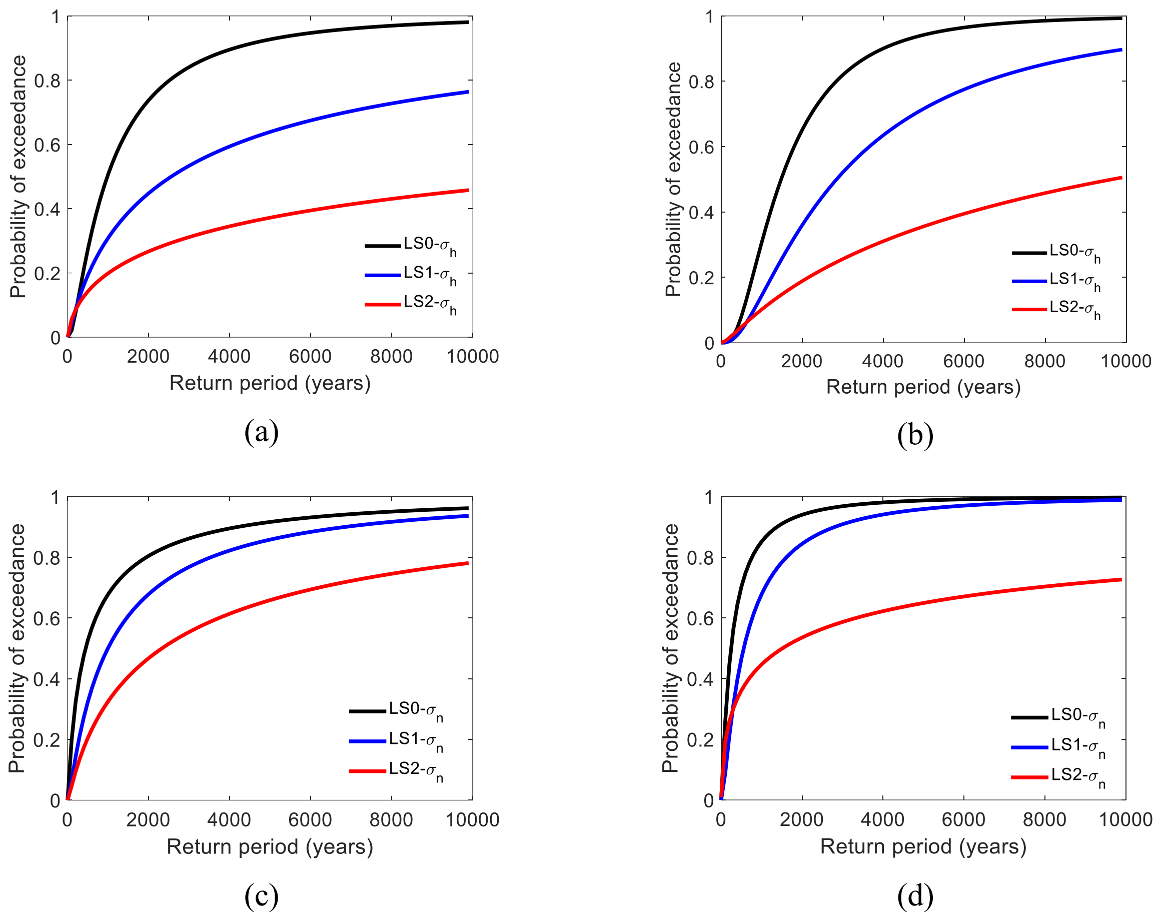
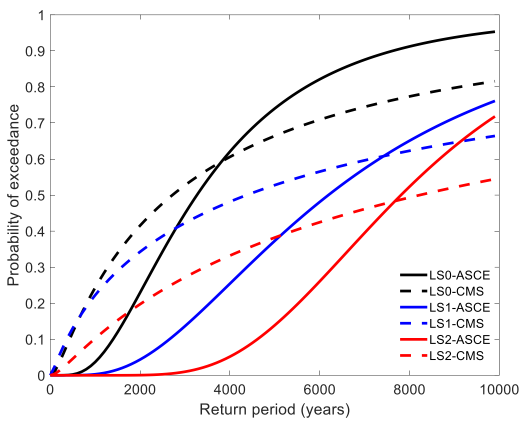


Figure 39. Fragility curves (a) CMS-Heel, (b) ASCE 7-16-Heel, (c) CMS-Neck (d) ASCE-Neck

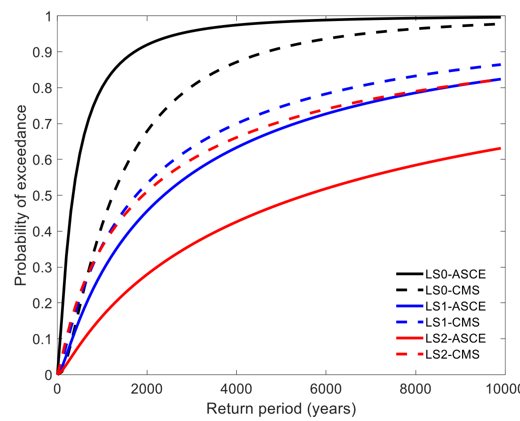
The combined interpretation of NCD, DAR, and stress at the neck and heel provides a comprehensive understanding of a concrete dam's seismic vulnerability. NCD, reflecting the extent of crest movement, reveals how the dam responds to ground motion, with higher NCD values signifying greater displacement and potential for structural damage. DAR, on the other hand, offers insights into the overall damage within the cross-section, pinpointing potential failure locations like the neck and heel. Stress data at these critical regions adds another layer, indicating how seismic forces affect the dam's structural integrity. By analyzing these parameters collectively, a holistic view of the dam's behavior under seismic stress can be obtained. For instance, high NCD coupled with elevated DAR and critical stress levels at the neck and heel regions can signal a heightened risk of severe structural damage. Conversely, lower values across these parameters may imply a more resilient dam.

5.6.6. Impact of the record selection method

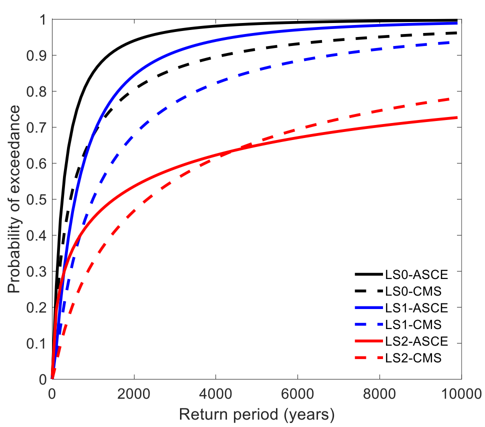
Figure 40 (a) to (d) shows the comparison of DAR, NCD, stress at the neck, and heel fragility curves based on ASCE 7-16 and CMS. The choice of ground motion selection based on ASCE 7-16, or CMS depends upon the project-specific risk tolerance and the desired level of conservatism in the analysis. ASCE 7-16 provides reliable fragility estimates for minor and moderate damages, making it suitable for structures where conservative estimates are acceptable. CMS exhibits a more cautious approach, especially for severe damage states, making it valuable when a more conservative risk assessment is necessary. For minor and moderate damages: both methods offer reasonable predictions, but CMS leans towards a more conservative estimate, which could be advantageous in risk-averse scenarios. Similarly, for severe damages, CMS provides a more conservative estimate, which might be essential for critical structures where understanding worst-case scenarios is crucial. The divergence between the methods underscores the importance of understanding and addressing uncertainties in seismic fragility assessments. Careful consideration of site-specific parameters and ground motion records is vital in producing accurate predictions, especially for critical infrastructures like dams. This analysis highlights the significance of comprehensively evaluating different limit states and considering multiple methodologies to obtain a holistic view of a structure's vulnerability under seismic stress. It emphasizes the need for a nuanced approach, considering both the practical implications and the level of conservatism required for a given engineering scenario.



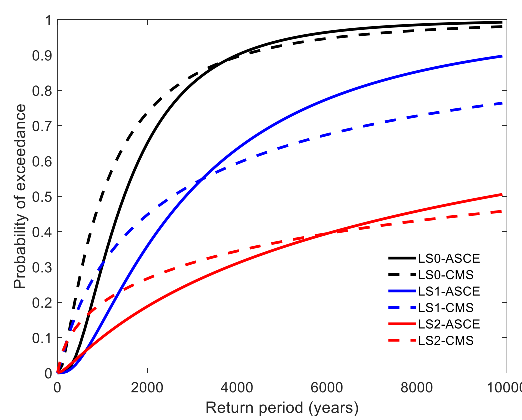
(a)



(b)



(c)



(d)

Figure 40. Fragility curves comparison between ASCE 7-16 and CMS, (a) DAR, (b) NCD, (c) stress at neck (d) stress at the heel

5.7. Risk assessment

Throughout its lifespan, a dam faces the full spectrum of potential ground motion intensities at its specific location, as defined by the site-specific seismic hazard curve. Risk can be characterized in two ways: first, as the likelihood of any structure failing owing to any reasonable cause, such as a breach of a predefined limit state or other cause, and second, as the ensuing losses due to such failures [40]. Event tree analysis (ETA) in the case of quantitative risk assessment (QRA) is used to account for input uncertainties and determine individual and total failure probability for the selected failure mode [33], [128]. So, in a way the integration of all three components as shown in Equation 2, Chapter 1 i.e., probability of a particular load obtained through the seismic hazard curve, system response given the load obtained through fragility curves, and the consequences assessment based on guideline provisions provide insight into systems risk. The estimated risk may then be validated against acceptable risk criteria (ALARP) to evaluate the adequacy of the system's existing safety and reliability of the system or to implement additional safety measures. The risk curve is displayed as pairs f-N and f-D. The acceptable level of risk varies and is determined by economic, environmental, social, and technological factors.

The seismic risk assessment in this article considers two distinct failure modes, which are determined based on the outcomes of the fragility assessment. These failure modes encompass failure at the neck (now onwards called as FM_1) and failure at the base of the dam (now onwards called as FM_2). To ensure comprehensive risk assessment, the annual risk, including considerations for loss of life and economic damage, measured as the annual probability of experiencing the specified failure modes, was carefully evaluated. This assessment involved convolving the fragility functions with the hazard curve derived from probabilistic seismic hazard analysis (PSHA) to calculate the unconditional probabilities of exceeding these specified failure scenarios. The mean hazard curve was derived in a discrete manner, involving the calculation of the annual rate of exceedance at specified hazard levels. Additionally, an analytical representation of the hazard curve was developed to facilitate seismic safety assessments through analytical or numerical integration, allowing for the propagation of uncertainty within the hazard model. In cases where the hazard data at the dam site did not exhibit a linear relationship in log-log space, a hyperbolic function was employed to approximate the hazard curve, following the approach proposed by Bradley et al.[268]. This function offers a good approximation for both linear and nonlinear hazard data within the range of adopted intensity levels, although it may not extrapolate accurately. It is mathematically expressed in Equation 18. The intensity level at $S_a(T_1)$, T_1=0.551 sec and the annual probability of exceedance as used in this study is shown in Table 16.

$$\hat{v} = \alpha \exp\left\{\beta\left[ln\left(\frac{S_a(T_1)}{\gamma}\right)\right]^{-1}\right\} \tag{18}$$

Table 16. Intensity level vs Annual rate of exceedance

Intensity level, CMS	0.165 g	0.220 g	0.290 g	0.410 g	0.540 g
Intensity level, ASCE 7-16	0.231 g	0.325 g	0.497 g	0.671 g	0.885 g
Annual rate of exceedance	1.96×10^{-3}	9.42×10^{-4}	3.66×10^{-4}	1.80×10^{-4}	8.99×10^{-5}

Equation 19 shows the probability of unconditional failure. Similarly, the consequences assessments based on guideline recommendations carried out for estimating the loss of life and economic damage due to the two failure modes. It is important to note this investigation does not consider the non-failure risk.

$$P_{f,\,\text{unc}} = \int_{Sa(T_1)} (1 - P[LS \mid \text{IM}, Sa(T_1)]) \left|\frac{\mathrm{d}\hat{v}}{\mathrm{d}Sa(T_1)}\right| \mathrm{d}Sa(T_1) \qquad 19$$

$(1 - P[LS \mid \text{IM}, Sa(T_1)])$ is obtained from the fragility function, and $\left|\frac{\mathrm{d}\hat{v}}{\mathrm{d}Sa(T_1)}\right|$ is the PDF of the median hazard at the dam site. The fragility curves for limit state LS_2, for failure at neck and heel as shown in Figure *39* for both CMS and ASCE 7-16 is considered. Table 16 presents the risk estimated as the annual probability of exceeding each damage limit state. The study assumes reservoir level as a constant value when a seismic event occurs. The reservoir volume of Pine Flat Dam is 1.23 km^3 at elevation 290.01 m, maximum water depth of 131 m. The dam break peak discharge curve vs. pool level obtained from empirical relations as proposed by [269], [270], shown in Equation 20.

$$Q_p = 0.607.\, V_w^{0.295}.\, h_w^{1.24} \qquad 20$$

Where Q_p is the predicted peak discharge in m^3/s, V_w is the volume of stored water at the moment of failure in m^3 and h_w is the pool level in the reservoir calculated from the lower point of the final breach where the water level is expressed in meters. The peak discharge in case of failure at the base is estimated as 106154 m^3/s, considering the reservoir level at 290.01 m. Similarly, the peak discharge in case of failure at the neck is estimated as 7812 m^3/s, considering the reservoir level at 275.84 m. Table 17 summarizes the estimated failure discharge.

Table 17. Reservoir level vs Peak discharge

Failure mode	Reservoir level (m)	Peak discharge, Q_p(m^3/s)
FM_1	290.01	106154
FM_2	275.84	7812

The assessment of both loss of life (LOL) and economic damage is focused on the direct consequences caused by the flood wave. Estimations for LOL resulting from the peak discharge Q_p, associated with the considered failure modes are derived from established methodologies such as those proposed by Graham [271] and the work of I. Escuder-Bueno et al.[272]. The population at risk is assumed in this calculation to be 0.1 million. Additionally, it's important to note that the analysis does not factor in any warning time scenarios, primarily due to the inherent uncertainty regarding the timing of seismic events. The assessment of economic impacts resulting from a specific flood event entails several steps. Initially, it involves the calculation of the overall value of land use, which encompasses the total expenses that would be incurred if all structures and agricultural resources within the examined area were to be damaged or destroyed by the flood. Subsequently, these estimated costs are applied to a depth-damage curve as proposed by Huizinga et al. [273], which establishes a relationship between the maximum flood depth and the corresponding cost of destruction. By multiplying the extent of damage by the economic value associated with the destruction, this study computes the estimation of economic consequences resulting from the flood event under consideration.

The quantitative risk assessment was carried out using the iPresas Calc tool [60]. The Influence diagram for the seismic risk scenario is shown in Figure 41. There are four different types of nodes taking a specific input used for developing the influence diagram. The seismic node takes input as Intensity level vs Annual rate of exceedance, values as shown in Table 16. The pool level considers the single reservoir level as 290.01 m, during the seismic event. The individual failure probabilities are calculated with Equation 19, using the fragility function for LS2 as shown in Table 14 and Table 15, and act as input for failure nodes for FM_1 and FM_2. The Failure node takes input as the level of collapse, corresponding to an annual exceedance rate of 8.99 x 10^{-5}. The peak discharge as used in node Q_p is shown in Table 17. Finally, the LOL and economic damage are estimated, corresponding to the failure discharge. The failure event timing (day and night) is taken with equal probability, accordingly, the LOL and economic damage are estimated. The f-N pairs for LOL and economic damage with their associated failure probability are shown in Figure 42. From Table 18, it can be seen that the failure probability of the neck region is higher compared to base failure across both CMS and ASCE 7-16. It can also be seen that the individual risk of FM_1 is higher in ASCE 7-16, however, in FM_2 CMS produces a higher failure probability. The total failure risk of the system with ground motion selected using CMS is higher compared to ASCE 7-16.

Table 18. Estimated individual and total risk

Failure mode	CMS Individual risk	CMS Total risk	ASCE 7-16 Individual risk	ASCE 7-16 Total risk
FM_1	1.09 x 10^{-4}	1.75 x 10^{-4}	1.43 x 10^{-4}	1.69 x 10^{-4}
FM_2	6.61 x 10^{-5}		2.57 x 10^{-5}	

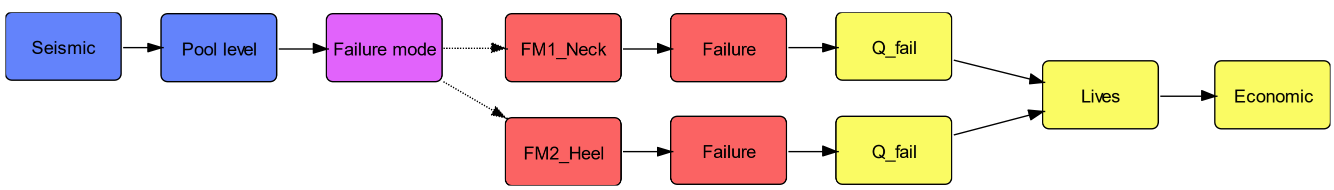
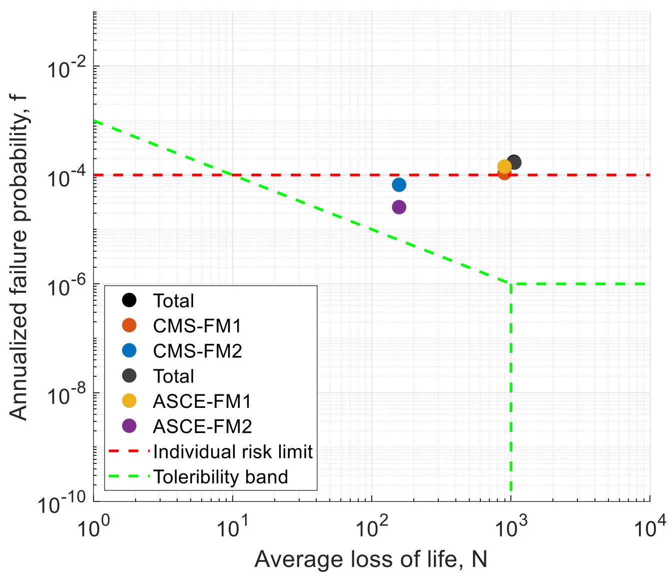
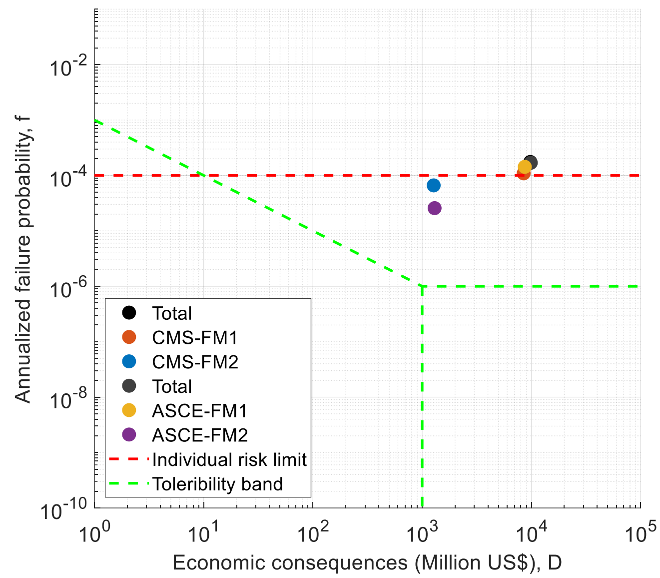


Figure 41. Influence diagram for the seismic risk



(a)



(b)

Figure 42. (a) f-N pair for average loss of life, and (b) f-D pair for economic consequences

5.7.1. Results inference on risk assessment

The comparative analysis of failure mechanisms at the neck and heel reveals that heel failure, characterized by complete block failure, results in higher levels of loss of life (LOL) and economic damage, despite its lower occurrence probability compared to neck failure. The use of CMS as a ground motion selection method increases the probability of these critical events, subsequently elevating the risk of LOL and economic impacts. This indicates the significant influence of ground motion selection techniques on the outcomes of individual and overall failure modes. The prevailing approach to risk assessment involves the use of analytical formulas to predict failure or peak discharge under selected failure scenarios. Similarly, this investigation adopts the depth damage curves introduced by Huizinga et al.[273] for quantifying LOL and economic losses. This study aims to showcase how risk assessment outcomes vary with different ground motion selection methods. Nevertheless, the accuracy of estimating LOL and economic losses could be enhanced through comprehensive dam breach analysis, utilization of actual topographic data, and population density within the study area. Specifically, within the United States context, incorporating tools like HAZUS [274] developed by FEMA could refine the estimations of LOL and economic impacts. Moreover, given that fragility assessments are crucial for determining the failure likelihood of specific failure modes, which are affected by ground motion variability and epistemic uncertainties such as material characteristics and modeling decisions, meticulous attention is required in their thorough analysis and integration into the model to reduce outcome variability.

5.8. Concluding remarks

This study presents a comprehensive analysis of the seismic fragility of concrete gravity dams, with a specific focus on Pine Flat Dam. By employing advanced simulation techniques and considering two distinct ground motion selection methods ASCE 7-16 and CMS the research addresses critical epistemic and aleatory uncertainties in seismic risk assessment. The findings underscore the significant impact of ground motion selection and RTR variability on the fragility assessment of dams. The conclusions are as follows,

1. Utilizing a comprehensive suite of ground motions is essential for a thorough seismic fragility assessment. It allows for a more robust understanding of a structure's response under various seismic scenarios, helping to identify critical failure modes and enhancing the reliability of risk assessments.
2. Incorporating a range of return periods in fragility analysis is crucial. It provides insights into the structure's performance across different levels of seismic hazard, helping engineers and decision-makers evaluate the long-term safety and resilience of the dam.
3. Considering multiple damage indices, such as Normalized Crest Displacement (NCD), Damage Area Ratio (DAR), and stresses at critical locations like the neck and heel, offers a more comprehensive view of structural vulnerability. Each index highlights specific aspects of damage, contributing to a more holistic assessment.
4. The choice of ground motion selection method, whether it's CMS or ASCE 7-16, significantly influences fragility assessment outcomes. It can lead to variations in predicted failure probabilities, which underscores the importance of selecting an appropriate method tailored to the project's objectives and site-specific conditions.
5. The increased vulnerability observed at the neck region compared to the heel underscores the necessity for targeted investigations into the factors contributing to this heightened risk. Such inquiries are pivotal for devising effective mitigation, maintenance, and retrofit strategies.
6. Fragility assessments are integral to risk assessments. The ground motion selection method directly affects risk evaluations, including the estimation of loss of life and economic damage. Therefore, careful consideration of ground motion selection is vital for making informed decisions regarding dam safety and resilience.

This study underscores the significance of adopting a comprehensive and adaptable approach to seismic risk assessment for concrete gravity dams. It emphasizes the intricate interplay between ground motion selection, return periods, and damage indices, all of which significantly influence fragility assessment and subsequent risk evaluations. By incorporating a diverse range of ground motions, considering various return periods, and evaluating multiple damage indices, engineers and decision-makers gain a holistic understanding of the intricate dynamics governing dam behavior under seismic forces. This knowledge empowers them to make informed and proactive choices aimed at fortifying dam safety and proactively mitigating potential risks. Furthermore, this research contributes to a deeper comprehension of seismic vulnerabilities and potential failure modes, underscoring the need for bespoke seismic assessment approaches. These findings provide a robust foundation for future studies, particularly in investigating the impact of material aging, foundation heterogeneity, and more complex failure modes. Beyond advancing the field of seismic engineering, this work serves as an invaluable resource for bolstering the resilience and safety of dam infrastructures against the ever-present threat of seismic events.

Chapter 6

Material degradation

This chapter explores the impact of construction heterogeneity, environmental exposure, aging, and variability in ground motion record-to-record (RTR) on the seismic fragility assessment of a concrete gravity dam. It systematically addresses epistemic uncertainties stemming from material property variations and aleatory uncertainties linked to RTR variability within and across different return periods. Utilizing the conditional mean spectrum (CMS) method, the study selects 55 ground motions spanning five return periods, ranging from 475 to 10000 years, with 11 ground motions corresponding to each period. A comprehensive set of 990 nonlinear simulations was carried out using a coupled 2D Dam-Foundation-Reservoir (DFR) system, incorporating variation in material property and RTR in ground motions. This study considers only material nonlinearity, implemented using the CDP model. Each simulation considers gravity load, hydrostatic, and hydrodynamic impact corresponding to a fixed reservoir level, along with the effect of combined horizontal and vertical ground motion. The stress at neck, heel, and crest displacement was extracted from these simulations. Subsequently, this study develops fragility curves based on stress and displacement damage indices for three distinct limit states, each correlating to a specific damage level of the structure. These fragility curves provide an integrated view of the impacts of material uncertainty, aging-related degradation, and RTR variations on the dam's seismic fragility, crucially quantifying these influences. Further, as shown in Chapter 5, these variations in fragility will influence any subsequent risk assessment and decision-making process. So, this signifies careful consideration of the material heterogeneity and degradation due to aging. The findings of this case study are pivotal in showing the dynamic changes in system response as concrete gravity dams age. These insights are crucial for effectively planning disaster mitigation strategies, informing rehabilitation initiatives, and enhancing structural health monitoring protocols. By integrating advanced probabilistic methods and acknowledging the evolving nature of seismic risk, this study contributes significantly to the seismic safety of these aging infrastructures.

6.1. Introduction

The seismic performance assessment of aging dams, particularly concrete gravity dams (CGDs), is a complex and increasingly vital field of study within civil and structural engineering. According to the International Commission on Large Dams (ICOLD), concrete gravity dams account for about a quarter of the global portfolio of large dams, which includes more than 61,000 dams [2]. The average age of concrete gravity dams is estimated to be around 50 years, as most of them were built before 1970. As these structures age, they are subject to many factors that can significantly impact their integrity and functionality. One of the primary concerns is the degradation of materials due to aging processes. The construction of CGD predominantly involves plain cement concrete, a choice that directly influences its long-term durability and performance. One of the primary functions of these dams is to support the reservoir water they retain. This continuous contact with water, over the typical design life of around 100 years, exposes the concrete to various hydro-chemo-mechanical actions, leading to a gradual but significant degradation in its strength. Over time, factors such as moisture and heat transport, freeze-thaw actions, chemically expansive reactions, and corrosion of reinforcing steel contribute to the deterioration of concrete, leading to a reduction in strength and an increase in porosity and crack propagation [275], [276]. Material uncertainty, stemming from the inherent heterogeneity in construction materials and methods, further complicates these aging effects, introducing variability in the structural response of these dams [277].

Environmental exposure varies significantly across different geographic locations, affecting the rate and nature of degradation. Additionally, the seismic performance of aging dams is influenced by the variability in ground motion characteristics, which can be highly site-specific and unpredictable. This uncertainty is compounded by the outdated design practices prevalent at the time of construction of many older dams. These designs, often based on now-obsolete seismic hazard assessments and technological limitations, may not adequately address current safety standards or seismic risk profiles [230], [278]. The impact of climate change adds another layer of complexity to the seismic assessment of aging dams. Changes in weather patterns, such as increased frequency and intensity of extreme weather events, can exacerbate existing vulnerabilities and lead to unforeseen loading conditions on these structures [127]. In light of these challenges, a significant body of research has emerged, focusing on the degradation of concrete materials in the context of dam safety and performance [102], [279]. These studies highlight the critical need for updated methodologies and approaches in assessing the seismic performance of aging dams. The International Commission on Large Dams (ICOLD) has recognized the significance of aging in dams and provided guidelines and recommendations to address these concerns [280], [281]. These guidelines underscore the importance of regular and comprehensive assessments, incorporating modern analysis techniques and updated seismic risk evaluations. The seismic performance assessment of aging dams, therefore, requires an integrated approach that considers material degradation, construction heterogeneity, environmental exposure, ground motion variability, updated design practices, and the impact of climate change. This holistic perspective is essential for ensuring the safety and resilience of these critical infrastructures in the face of evolving challenges and risks.

6.2. Background

The seismic performance assessment of aging concrete gravity dams has undergone significant evolution over the past three decades, reflecting an intensified focus on research efforts due to the increasing number of dams nearing or exceeding their design life. With many concrete gravity dams in service for over 50 years, important advances in the methodologies for evaluating natural phenomena hazards have necessitated the revision of design-basis events upwards. This systematic literature review highlights the significant progress in research methodologies and findings aimed at understanding and mitigating the risks associated with aging dam infrastructure. The advancements in this field are pivotal in ensuring the safety and sustainability of such critical infrastructure against seismic hazards, underscoring the importance of continuous research and development in this area.

Bhattacharjee et. al.,[101] study seismic cracking and energy dissipation in concrete gravity dams. A finite element method for seismic fracture analysis of concrete gravity dams is presented. The influences of global or local degradation of the material fracture resistance on the seismic cracking response of concrete dams were also studied. Ghrib et. al., [102] discuss the local approach of the fracture using damage mechanics concepts to evaluate the seismic response of concrete gravity dams. A 60 m concrete gravity dam is therefore selected and subjected to ground motion typical of eastern North America. Cervera et. al.,[103], study seismic evaluation of concrete dams via continuum damage models. A general methodology for the analysis of large concrete dams subjected to seismic excitation is outlined. The mechanical behavior of concrete is modeled using an isotropic damage model which allows for tension and compression damage and exhibits stiffness recovery upon load reversals. Tekie et. al.,[230] present a methodology for developing fragilities of concrete gravity dams to assess their performance against seismic hazards. An approach to include the time-dependent degradation of concrete owing to environmental factors and mechanical loading in terms of isotropic damage index is presented by Gogoi et. al.,[282]. The performance of an aged dam with a known percentage of isotropic or orthotropic damage due to seismic excitation is studied. Bayraktar et. al.,[283] study the effect of reservoir length on the seismic performance of gravity dams to near- and far-fault ground motions. The effect of reservoir length on the seismic performance of gravity dams to near and far fault ground motions is investigated. It is seen from the analysis results that the seismic behavior of the concrete gravity dams is considerably affected by the length of the reservoir. The fracture procedures include the extended finite element method with cohesive constitutive relations, the crack band finite element method with plastic-damage relations, and the finite element Drucker−Prager elastoplastic model by Pan et. al.,[104]. The applicability and suitability of the three procedures for seismic cracking analysis of gravity and arch dams are discussed. A study on the failure process of high concrete dams subjected to strong earthquakes is crucial to the reasonable evaluation of their seismic safety. Zhong et. al., 2011 [105] studied seismic failure modeling of concrete dams considering the heterogeneity of concrete. For using the proposed model, no knowledge of the cracking route needs to be known beforehand, and no re-meshing is required. Nayak et. al., 2013 [277] investigate the evolution of tensile damages in aged concrete gravity dams, which is necessary to estimate the safety of existing dams towards future earthquake forces. Zhang et. al., 2013 [284] present results of a study aimed at evaluating the near-fault and far-fault ground motion effects on nonlinear dynamic response and seismic damage of concrete gravity dams including dam-reservoir-foundation interaction. Nonlinear dynamic response and seismic damage analyses of the selected concrete dam subjected to both near-fault and far-fault ground motions are performed. A new concept to determine the state of the damage in concrete gravity dams is introduced. The Pine Flat concrete gravity dam has been selected for the purpose of the analysis and its structural capacity, assuming no sliding plane and rigid foundation, has been estimated using the two well-known methods: nonlinear static pushover (SPO) and incremental dynamic analysis (IDA) by Alembagheri et. al., 2013 [285]. It is concluded that the SPO and IDA can be effectively used to develop indexes for seismic performance evaluation and damage assessment of concrete gravity dams. Wang et. al., 2015 [286] In order to bridge the gap between duration definitions and multi-component seismic excitations used for simulation, a concept of integrated duration is proposed. Wang et. al., 2016 [286] study a general definition of integrated strong motion duration and its effect on seismic demands of concrete gravity dams. A general integrated duration definition for multi-component seismic excitations is proposed based on the existing concept of strong motion duration. The results also reveal the effects of vertical seismic excitations on the seismic response of concrete gravity dams and emphasize the necessity to consider vertical motions in seismic performance assessment of such infrastructures. Hariri-Ardebili et. al., 2018 [287] present the results of a study that considers the spatial distribution of random variables in the context of random field theory. The uncertainty and dispersion of the seismic responses are quantified in each model; it is found that concrete heterogeneity affects the seismic performance evaluation and should be considered in a structural assessment and risk analysis. Gorai et. al., [106] deal with the time history analysis of dam-reservoir-foundation coupled system using finite element technique under near field and far field ground motions. Along with the comparative study of seismic response of Koyna dam, qualitative assessment of the seismic performance of the dam are also evaluated. Nahar et. al., [107] propose an approach to assess and predict the seismic risk of existing concrete gravity dams (CGDs) considering the aging effect. The seismic risk assessment captures here the nonlinear dynamic behavior of a concrete gravity dam through fragility analysis. Sevieri et. al., [244] discuss the main issues behind the application of performance-based earthquake engineering to existing concrete dams, with particular emphasis on the fragility analysis. After a critical review of the most relevant studies on this topic, the analysis of an Italian concrete gravity dam is presented to show the effect of epistemic uncertainties on the calculation of seismic fragility curves. Zhao et. al., [288] propose a coupled chemo-mechanical model to predict the seepage dissolution effect on the aging deformation of concrete dams. Nahar et. al., [248] studied the effective safety assessment of an aged concrete gravity dam based on the reliability index in a seismically induced site. To investigate the aging effect, the hygro-chemo-mechanical model has been taken for different years consideration. Li et. al., [108] study fuzzy seismic fragility analysis of gravity dams considering spatial variability of material parameters. A mathematical model for describing the fuzziness of damage states threshold is presented. Lastly, "Ageing water infrastructure: An emerging global risk" by the UNU Institute for Water, Environment and Health (UNU-INWEH) in January 2021 [289]. This report synthesizes the prevailing challenges associated with aging dams, underscoring the urgency for adopting performance-based engineering approaches and advanced analytical models to address the multifaceted risks posed by aged concrete gravity dams.

The chronicle of seismic performance assessment for aging concrete gravity dams reveals a profound evolution of methodologies and insights, from the initial studies on seismic cracking to the recent advances addressing aging effects and performance-based engineering. The comprehensive report by UNU-INWEH on aging water infrastructure serves as a capstone to this journey, highlighting the pressing global challenge of aging dams. This literature review not only maps out the trajectory of past research efforts but also emphasizes the critical need for ongoing innovation and investigation. As the field looks to the future, it remains essential to refine and expand upon these foundational studies to safeguard the resilience and functionality of these vital structures against the backdrop of seismic threats and the inevitable march of time.

6.3. Case study

This section delves into the Pine Flat Dam, selected for this case study due to its extensive examination and the broad documentation of its geometric, dynamic, and material properties within the scholarly community, as indicated by the existing literature [222], [258], [259]. Located in California, USA, the Pine Flat Dam is instrumental in fulfilling several critical functions, including water storage, hydroelectric power generation, and flood control. These multifaceted roles underscore the dam's significance within the region's infrastructure ecosystem. The numerical simulation of this study incorporates a two-dimensional DFR model of the Pine Flat Dam, with its cross-section of block 16 depicted in Figure 35 (a) and (b). The dam has a height of 130 m from the deepest foundation block and extends across a crest length of 561 m. Its structure includes 36 monoliths, each with a width of 15.25 m, supplemented by an additional block measuring 12.2 m in width. This detailed modeling approach, capturing the dam's geometrical layout and structural components, provides a solid foundation for the investigation. The choice of Pine Flat Dam, with its well-documented specifications and critical operational roles, offers a comprehensive framework for examining the impact of various factors on dam safety and performance, particularly in the context of seismic vulnerability and resilience considering the impact of aging.

6.3.1. Methodology

Figure 43 illustrates the comprehensive framework utilized for the seismic performance assessment of the coupled DFR system. This updated framework expands upon the one presented in Chapter 5, Figure 36, by incorporating distinct limit state values for tensile strength at the neck and heel. Additionally, it utilizes a comprehensive suite of 990 simulations to accommodate the impacts of aging and construction heterogeneity on material properties. This evaluation process encompasses several carefully designed steps to ensure a thorough analysis of the system's seismic resilience. Initially, a two-dimensional (2D) model of the DFR system is developed to accurately represent the physical characteristics and behavior of the dam under seismic loading. Following this, a selection of ground motion records for five distinct return periods using the conditional mean spectrum (CMS) procedure, ensuring the ground motions are appropriately matched to the seismic hazard profile of the dam's location. The core of the assessment involves conducting nonlinear dynamic analyses of the 2D DFR model. This step accounts for both material uncertainty and the degradation of material properties due to aging, with the analyses performed considering the selected suite of ground motion records. The outcomes of these analyses provide insights into the structural response of the dam, including stress and displacement measures, under seismic excitation.

Subsequently, the process involves defining limit state functions that capture the potential failure modes and performance objectives of the dam. These functions serve as benchmarks for assessing the dam's ability to withstand seismic events, allowing for the calculation of the probability of exceeding each limit state at various intensity levels. This step is crucial for understanding the dam's vulnerability to seismic forces. To quantitively express the seismic vulnerability, a probabilistic distribution, such as the lognormal distribution, is fitted to the collected probability of failure data. This fitting process results in the derivation of fragility curves for each limit state, offering a visual and statistical representation of the dam's likelihood to meet or exceed specific performance thresholds under seismic loading. Lastly, these fragility curves are employed to evaluate the impacts of variations in material properties and record-to-record (RTR) variability on the dam's seismic performance. By integrating the effects of material property changes due to aging and the inherent variability in seismic ground motions, this comprehensive approach allows for a nuanced understanding of how these factors influence the seismic resilience of the dam. This adopted methodology not only enhances the assessment of the dam's seismic performance but also aids in identifying potential areas for improvement and mitigation strategies to enhance the dam's seismic safety.

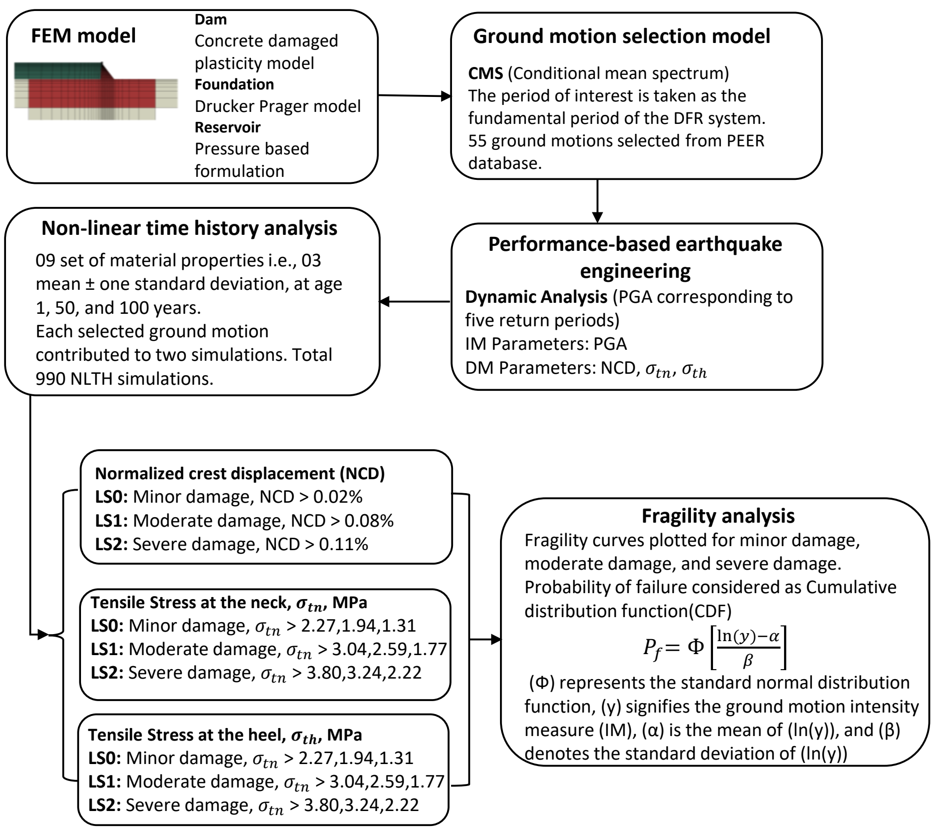


Figure 43. Outline of adopted methodology for fragility assessment

6.3.2. Ground motion selection

In recent years, the seismic engineering community has placed a significant emphasis on refining ground motion selection procedures for seismic analyses. This focus stems from the understanding that each seismically active region has unique geological and seismotectonic characteristics, which must be accurately reflected in the seismic assessment of structures, particularly for critical infrastructures like dams. The selection of input ground motions that are representative of specific seismic site conditions is crucial, given the inherent diversity in geological settings across various regions. This process directly impacts the accuracy and reliability of seismic vulnerability assessments. There exist ground motion selection methods such as conditional mean spectrum (CMS), generalized conditional intensity measure (GCIM), and ASCE 7-16 procedure. Among the various ground motion selection methods, the CMS method, utilized in the current study, stands out for its ability to account for site-specific seismic hazard information. The CMS method is particularly effective in ensuring that the selected ground motions are consistent with the probabilistic seismic hazard at a site, providing a spectrum that is conditioned on a target spectral acceleration value at a particular period. The selection of the CMS method in the current study reflects a focused approach to understanding the seismic response of the system under investigation. By employing this method, the research aligns with contemporary practices in seismic analysis, ensuring that the ground motions used in the study are both representative of the site-specific seismic hazard and consistent with the latest advancements in the field.

The CMS method [98] has become widely utilized for selecting ground motions in dam fragility analyses. This technique aligns the mean spectrum of chosen ground motions with a predefined target spectrum at the structure's fundamental period. Typically, this target spectrum is derived through Probabilistic Seismic Hazard Analysis (PSHA) specific to the dam site. The CMS approach is an efficient tool for ground motion selection introduced by Baker [98]. This approach provides the mean spectrum, serving as the target spectrum for ground motion selection. The calculation procedure for the spectrum is detailed [251]. Jayaram et al. [95] presented an algorithm for ground motion selection where motions are aligned with the target spectrum mean and variance. Subsequently, this algorithm was refined [252]. Bernier et al. [236] conducted an enhanced fragility analysis of a gravity dam, incorporating the CMS method proposed by Jayaram et al. [95].

A seismic hazard analysis was conducted for Pine Flat Dam, located in California, USA using the USGS tool. The Central Valley of California is surrounded by several faults San Andreas fault: California's largest fault, is in the west. The San Andreas fault is a right-lateral strike-slip transform fault that extends roughly 750 miles through California. It forms the tectonic boundary between the Pacific Plate and the North American Plate. The San Andreas fault can create earthquakes as big as magnitude 8. Utilizing the U.S. geological survey (USGS) tool [249], a seismic hazard analysis was conducted for Pine Flat Dam in California, USA. This analysis meticulously outlined potential earthquake scenarios across varied intensity levels, defined in terms of horizontal spectral acceleration at the structure's fundamental period. Spectral accelerations were chosen for return periods of 475,975, 2475, 5000, and 10000 years. Ground motion selection was performed using the Pacific Earthquake Engineering Research Center (PEER) ground motion database [253]. The probabilistic seismic hazard analysis (PSHA) for the dam's location, specifically for the 0.50-second spectral period and considering a shear wave velocity of Vs_{30} = 760 m/s (B/C boundary) [254], was carried out to generate the uniform hazard spectrum (UHS).

For the UHS development, the conterminous U.S. 2014 (update) (v4.2.0) model [255] in the USGS tool was utilized. This model provided essential disaggregation information for 11 attenuation equations. The obtained disaggregation data were instrumental in developing the target spectrum and selecting ground motions using the CMS method. Specifically, the disaggregation information corresponding to the Campbell & Bozorgnia (2014) attenuation equation [256] in the PEER ground motion database closely aligned with the UHS at the target period.

The target spectrum in the PEER ground motion database was generated using specific input parameters. These included a damping ratio of 5%, specifying the region as global/California, a magnitude of 6.42, and an R_{jb} (distance from the fault) of 46.13 km. Record selection criteria involved considering fault type as strike-slip. The fundamental period of the DFR system, set at 0.551 seconds, was used as the conditioning period. A total of 55 ground motions were selected, consisting of 11 unique motions per return period across five return periods (475 to 10000 years). Figure 33 (a), in Chapter 5, shows the mean target spectrum or CMS, alongside the CMS ± conditional σ spectra and the spectra of the selected ground motions, where σ is the standard deviation. It's noteworthy that all these chosen ground motions fall within the CMS +/- conditional σ range, ensuring their suitability for the analysis. This stringent selection process guarantees that the chosen ground motions closely align with the specific seismic characteristics of the site.

6.3.3. Numerical model

The numerical simulation was performed using the Abaqus 2022 standard version. The model is thoroughly developed to account for the complexities of fluid-structure interaction (FSI) and soil-structure interaction (SSI), elements critical to understanding the dynamic behavior of dams under various loading conditions. In simulating the reservoir, acoustic elements (AC2D4) were chosen for their capability to accurately represent the fluid dynamics within the reservoir, capturing the essential aspects of wave propagation and pressure distribution against the dam structure. The concrete dam and its underlying rock foundation are modeled using plane stress elements (CPS4R), chosen for their effectiveness in standard structural mechanics problems where the stress is assumed constant through the thickness. Additionally, to simulate the boundless expanse surrounding the foundation and accurately capture seismic wave propagation effects, infinite elements (CINPE4) are utilized for the peripheral foundation elements. The CPS4R element is recognized for its general applicability in two-dimensional structural analyses, making it an ideal choice for representing the solid mechanics of the dam and foundation. Conversely, the CINPE4 element is specifically designed to model wave propagation in infinite domains, ensuring that seismic waves' effects are realistically captured as they dissipate from the dam into the surrounding geological media. To accurately simulate the damping characteristics of the dam and foundation materials, Rayleigh viscous damping was implemented, as shown in Equation 21. This approach models damping as a linear combination of the mass matrix (M) and stiffness matrix (K), with α and β serving as the constants of proportionality for mass and stiffness contributions, respectively. This method allows for a nuanced representation of damping effects, crucial for predicting the dam's dynamic response to seismic loading accurately.

$$[C] = \alpha[M] + \beta[K] \qquad 21$$

The material properties for Pine Flat Dam as shown in Table 19 are used for the model validation purpose. Subsequently, the impact of aging and material heterogeneity on seismic performance was incorporated into the simulation, with the specific parameters and their variations due to aging processes detailed in Table 20. To adeptly capture the nonlinear behaviors of materials under seismic loading, the model employed the concrete damage plasticity (CDP) model. Material properties as used in CDP are shown in Table 21. The core of the simulation revolved around a comprehensive nonlinear dynamic analysis, examining the dam's response under a carefully constructed loading scenario. This scenario included the self-weight of the structure, hydrostatic thrust from the reservoir water, hydrodynamic effects resulting from water movement during seismic events, and direct seismic loads. These seismic loads were applied, incorporating both horizontal and vertical components, identified as H_1V or H_2V to simulate the multidirectional nature of seismic forces. Here, the ground motions have been applied at the base of the dam. Alternatively, they could be deconvoluted and applied to the base of the foundation [197]. Acknowledging the inevitable variability in material properties due to aging and the inherent heterogeneity in construction practices, the simulation was carefully developed to ensure a uniform evaluation framework. This simulation maintained consistent parameters across simulations, including the dam's geometric configuration, reservoir level, foundation dimensions, and contact characteristics between the structural elements. While the model explicitly focused on these parameters, it did not extend to the effects of uplift and silt pressure, recognizing their relevance but choosing to concentrate on the primary factors influencing seismic performance. The outcomes of these simulations, which considered variations in material properties and ground motion inputs, provided insights. Key findings included detailed histories of maximum principal stress at critical locations such as the dam's neck and heel, as well as displacement histories along the crest. These results lay a foundation for understanding the seismic behavior of the Pine Flat Dam, factoring in the influence of aging.

Table 19. Elastic material properties of dam, foundation, and reservoir for Pine Flat dam [261]

Material properties	Concrete	Foundation	Reservoir
Density (ρ)	2482 kg/m^3	2640 kg/m^3	1000 kg/m^3
Modulus of elasticity (E)	22407 MPa	22407 MPa	-
Bulk modulus (K)	-	-	2070 MPa
Poisson's ratio	0.2	0.333	-
Rayleigh damping Alpha (α)	-	1.64	-
Rayleigh damping Beta (β)	0.004333	0.00668	-

6.3.4. Material properties with the effect of aging

To comprehend the impact of material degradation due to ageing, changes in the concrete's characteristics over time are inferred based on the concrete mix detailed in Washa et al.'s [290] experimental study. The concrete exhibited a 28-day compressive strength of 36.3 MPa. In Equation 22, the initial value E_i is taken as 32660 MPa, as noted by Mandal (2017). The formula for calculating the degraded elastic modulus, as suggested by Azizan et al. [291], incorporates factors such as initial porosity, chemical porosity, and mechanical porosity. This proposed equation as shown in Equation 22 has been employed in the current study to examine the effects of aging on the elastic modulus of the concrete in the case study dam. The variation in the elastic modulus for the degraded concrete is derived using Equations 22 and 23, respectively, and these variations are depicted in Figure 44.

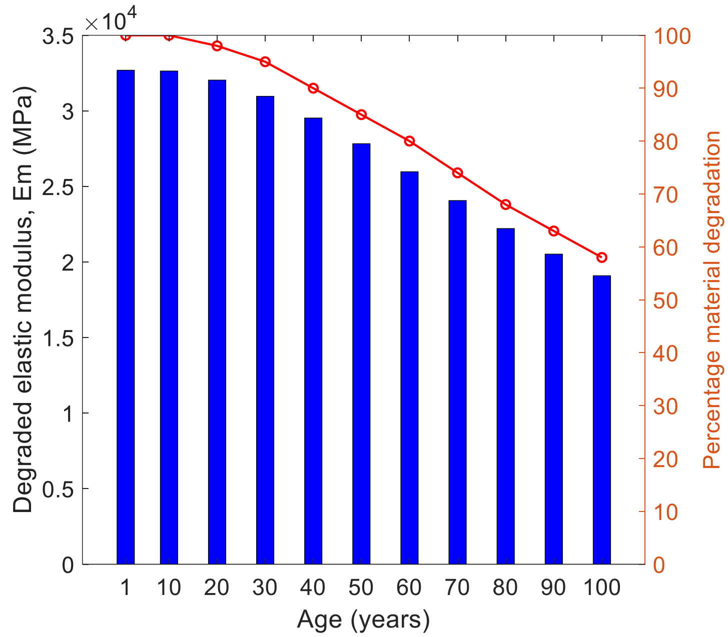


Figure 44. Material degradation due to aging

The tensile strength at the initial stage is calculated using Equation 25, while the tensile strength at subsequent ages is determined using Equation 24. Table 20 and Table 21 show the properties of concrete as it degrades over time along with heterogeneity. A significant reduction in both the modulus of elasticity and tensile strength of the concrete is evident, a result of ongoing deterioration. Consequently, when assessing the seismic behavior of the aged DFR system, the properties of the concrete as shown in Table 20 and Table 21 are incorporated as key input parameters.

$$E_m(t) = 0.0175t^3 - 3.4054t^2 + 29.807t + E_i \quad 22$$

The un-degraded elastic modulus of concrete E_0 can be obtained from the relation, where f (t) is the compressive strength at that particular age.

$$E_0 = 5000\sqrt{f(t)} \quad 23$$

The estimate of the tensile strength of degraded concrete is necessary as it is required for performance assessment. The variation of the tensile strength of concrete is considered the same as the changes in elastic modulus [292] and is given by

$$f_t = f_{t0}\left(\frac{E_m}{E_{t0}}\right) \quad 24$$

where f_{t0} and E_{t0} is the initial tensile strength and elastic modulus of the concrete. f_t is the tensile strength of degraded concrete. The initial tensile strength [293] is obtained from the following expression for normal-weight concrete.

$$f_{t0} = 0.294f_c^{0.69} \quad 25$$

Table 20. Material properties of dam considering the impact of aging

Age (years)	1			50			100		
	$\mu + \sigma$	μ	$\mu - \sigma$	$\mu + \sigma$	μ	$\mu - \sigma$	$\mu + \sigma$	μ	$\mu - \sigma$
Modulus of elasticity, E_m (MPa)	37978	32686	26353	32330	27825	22434	22181	19091	15391

6.3.5. Concrete damaged plasticity (CDP) model

Concrete damage plasticity (CDP) stands out as a widely adopted material model in finite element analysis, offering a means to simulate concrete behavior across a spectrum of loading conditions. It effectively captures inelastic deformation and the accumulation of damage in concrete structures, providing a comprehensive characterization of both tensile and compressive responses, as shown in Figure 19, in Chapter 4. In assessing the nonlinear response of the concrete dam to seismic forces, the concrete damaged plasticity model was used in the Abaqus software. The damaged plasticity model, initially introduced by Lubliner et al. [262], serves to depict the nonlinear material behavior of concrete. Lee and Fenves [263] expanded on this model by incorporating a yield function and damage variables, specifically addressing tensile and compressive damage to characterize various failure states. Subsequently, Lee and Fenves [264] applied the Concrete Damaged Plasticity (CDP) model in the seismic analysis of a gravity dam. The CDP model was extensively used by various researchers for the damage assessment of concrete gravity dams [203], [265], [266], [267]. The CDP parameters used in this study are shown in Table 21.

Table 21. CDP properties with aging impact

Age (years)	Variation	σ_{co} (MPa)	σ_{cu} (MPa)	σ_{to} (MPa)	e	R	ψ_c^*
1	$\mu + \sigma$	26.43	49.04	5.13	0.1	1.16	36.31°
	μ	19.58	36.32	3.80	0.1	1.16	36.31°
	$\mu - \sigma$	12.73	23.61	2.47	0.1	1.16	36.31°
50	$\mu + \sigma$	22.50	41.74	4.37	0.1	1.16	36.31°
	μ	16.67	30.92	3.24	0.1	1.16	36.31°
	$\mu - \sigma$	10.83	20.10	2.10	0.1	1.16	36.31°
100	$\mu + \sigma$	15.44	28.64	3.00	0.1	1.16	36.31°
	μ	11.44	21.22	2.22	0.1	1.16	36.31°
	$\mu - \sigma$	7.43	13.79	1.44	0.1	1.16	36.31°

* ψ_c: dilatation angle; σ_{co}: compressive initial yield stress; σ_{cu}: compressive ultimate yield stress; σ_{to}: tensile failure stress; e: flow potential eccentricity and R: ratio of the initial equibiaxial to the uniaxial compressive yield stress.

The Concrete Damage Plasticity (CDP) model in Abaqus is a continuum, plasticity-based, damage model used to simulate the nonlinear, inelastic behavior of concrete. It is particularly effective in earthquake engineering and structural dynamics for modeling concrete structures under cyclic loading and seismic events. The CDP model accounts for the degradation of the material stiffness due to both tensile and compressive plastic straining. The CDP model in Abaqus combines isotropic damage mechanics and plasticity theory. It is designed to represent the irreversible damage and stiffness degradation in concrete due to cracking in tension and crushing in compression [260]. The yield criterion for the CDP model is an extension of the Drucker-Prager yield criterion. It is represented in compression as shown in Equation 26 and tension as shown in Equation 27.

$$f_c(\sigma, q_t, q_c) = q_c \left(\frac{3J_2}{I_1^2}\right)^{1/2} + \frac{I_1}{3} - \sigma_c \leq 0 \qquad 26$$

$$f_t(\sigma, q_t, q_c) = q_t \left(\frac{3J_2}{I_1^2}\right)^{1/2} - \sigma_t \leq 0 \qquad 27$$

f_c and f_t are the yield functions for compression and tension, respectively, σ is the stress state, J_2 is the second invariant of the deviatoric stress tensor, I_1 is the first invariant of the stress tensor, q_t and q_c are tension and compression hardening parameters. σ_c and σ_t are the uniaxial compressive and tensile strengths of concrete. The CDP model introduces two damage variables, 'd_t' and 'd_c' for tension and compression, respectively, which can be seen at Figure 19 (a) and (c). These variables range from 0 (undamaged material) to 1 (fully damaged material). The stress-strain relationship in the CDP model is expressed by the following Equation 28.

$$\sigma = (1-d)\bar{\sigma} = (1-d)D_0 : (\varepsilon - \varepsilon^{pl}) \qquad 28$$

The initial elastic stiffness matrix of the material is denoted by D_0; σ represents the stress tensor, and $\bar{\sigma}$ stands for the effective stress tensor; d is a scalar representing the damage variable; ε^{pl}refers to the plastic strain. The process to determine the failure surface incorporates two hardening variables: the equivalent plastic strain in tension ε_t^{pl} and the equivalent plastic strain in compression ε_c^{pl}. Under uniaxial loading conditions, the damage variable 'd' is divided into tensile and compressive scalar damage variables, indicated as d_t and d_c, respectively. The relationships between stress and strain for uniaxial tension and compression are depicted in Equations 29 and 30.

$$\sigma_t = (1-d_t)\sigma_e = (1-d_t)D_0 \times \left(\varepsilon_t - \varepsilon_t^{pl}\right) \qquad 31$$

$$\sigma_c = (1-d_c)\sigma_e = (1-d_c)D_0 \times \left(\varepsilon_c - \varepsilon_c^{pl}\right) \qquad 32$$

The relationship between stress and strain for concrete subjected to uniaxial tensile and compressive forces is depicted in Figure 19 (a) and (c), respectively. Figure 19 (b) illustrates the curve for tension damage in concrete, highlighting how the scalar damage variable in tension d_t varies with the cracking displacement. It's important to note that the aspect of compressive crushing failure is not included in this current analysis. Material properties relevant to the Concrete Damage Plasticity (CDP) model, which are instrumental in defining the non-linear behavior of concrete, are detailed in Table 21.

6.4. Model validation

6.4.1. Validation of modal parameters

The initial stage of this research involved validating the numerical model against the comprehensive and well-documented studies of Pine Flat Dam from the 15th ICOLD International Benchmark Workshop. This validation is evidenced in Table 22, where the modal parameters are estimated using the material properties listed in Table 19, and these comparisons fall within the ranges reported in studies. It's important to note that the material properties presented in Table 19 were exclusively utilized for the validation of modal parameters. For the remainder of the analysis, the study shifts focus to the material properties affected by aging, as detailed in Table 20 and Table 21. This transition underscores the model's accuracy while adapting to study the aging impact on the dam's structural integrity. A reservoir level of 290.02 m is considered in this study which is similar to the Case A2 of the 15th ICOLD International Benchmark Workshop. However, there exists variation in the foundation dimension, and material properties considered in both the studies.

Table 22. Comparison of modal parameters with the 15th ICOLD International Benchmark Workshop [227], [188]

Mode	Natural frequency (Hz)		St. Deviation
	Present study	ICOLD Benchmark[1]	ICOLD Benchmark[1]
1	1.81	2.15	0.34
2	3.04	3.28	0.63
3	3.32	3.91	0.79
4	3.54	4.51	0.88

DFR model considered in this study and [1]Case A2 of the 15th ICOLD International Benchmark Workshop

6.4.2. Impact of aging on modal Parameters

Following the initial validation of the numerical model, the subsequent phase of the investigation focuses on examining the effects of material property degradation due to aging on the modal parameters of the structure. For this analysis, the study utilizes the mean values of material properties, as detailed in Table 20. An examination of the data presented in Table 23 reveals that with the progression of the structure's age, there is a noticeable increase in the structure's vibration period across all modes. This trend can be interpreted because of the diminished stiffness within the structure, which is a direct result of the degradation of material properties over time. Expanding on this observation, it becomes clear that the aging process impacts the dynamic behavior of the structure, with the increase in structural periods indicating a loss of rigidity and an associated increase in flexibility. This change in the dynamic properties of the structure could potentially affect its seismic response, making it more susceptible to seismic forces due to the decreased ability to resist dynamic loads. The findings underscore the importance of considering the aging factor in the seismic performance assessment of structures, as the progressive degradation of materials plays a crucial role in altering their natural frequencies and modes of vibration.

Table 23. Modal parameters with aging impact

Age (years)	Natural time period (s)			
modes	1st	2nd	3rd	4th
1	1.81	3.04	3.32	3.54
50	1.92	3.11	3.34	3.56
100	2.08	3.21	3.36	3.59

6.5. Seismic performance assessment

6.5.1. Fragility analysis

Fragility analysis serves as a pivotal tool to ascertain the likelihood of a structure's failure or damage when subjected to varying levels of seismic intensity. This probabilistic approach is integral to seismic risk assessments and informs the performance-based design of infrastructure. In the context of this study, the seismic performance assessment of a gravity dam is carried out, with a focus on the effects of material degradation due to aging, the variation in material properties resulting from construction practices, varying environmental exposure, and the impact of seismic ground motion across a spectrum of return periods. The methodology employed in this study involves the construction of fragility curves derived from specific damage indices, which include crest displacement and tensile stress at the heel and neck regions of the dam. By adopting this approach, the research offers a detailed and quantitative analysis of how the dam's performance fluctuates under seismic duress. It is through these curves that the study presents the variations in dam behavior, enabling a deeper understanding of how aging and heterogeneity in material properties influence structural integrity during seismic events.

6.5.2. Damage indices

Fragility analysis requires the use of damage indices, which are numerical indicators of the extent and severity of damage or deformation in a structure subjected to a specific loading condition. Damage indices are essential for generating fragility curves, which show the probability of a structure reaching or exceeding different levels of damage for a given intensity of loading, such as ground motion in seismic analysis. Some of the common damage indices in fragility analysis are crest displacement, stress-based damage indices, damage area ratio (DAR), joint opening and sliding, cumulative damage index, and relative seismic settlement rate. Crest displacement measures the maximum horizontal displacement of the crest or top of a structure during an event. Similarly, stress-based damage indices consider the distribution and magnitude of stress within a structure. Different stress components, such as tensile or compressive stress, may be assessed to gauge potential damage. Similarly, DAR based index quantifies the ratio of the damaged area to the total area of the structure. It provides a spatial measure of damage distribution and severity. Joint opening and sliding, measure the relative displacement and separation of the contraction joints in concrete dams. They indicate the loss of integrity and stability of the dam under seismic loading. The cumulative damage index is a scalar value that represents the accumulation of damage in the dam due to multiple earthquakes. It is based on the concept of damage mechanics and considers the effects of cyclic loading, fatigue, and degradation. Relative seismic settlement rate, this is the ratio of the seismic settlement to the initial height of the dam. It reflects the compaction and densification of the foundation materials under seismic loading. These damage indices help in classifying the damage into different levels, such as minor, moderate, or severe, and are instrumental in developing fragility curves. The fragility curves offer a probabilistic representation of the structural response under varying loading conditions, aiding in risk assessment and mitigation strategies.

6.5.3. Damage limit states

Seismic performance evaluation involves dynamic analysis, cumulative damage processes analysis, and consideration of various limit states. The goal is to ensure that the dam remains safe and functional during and after seismic events. The key parameters under investigation are crest displacement and stress at the neck and heel are vital indicators of the dam's structural integrity. The determination of displacement limit states can be established with careful consideration of their potential impacts on critical operational structures within the dam, such as gates and gantry cranes. The proper functioning of these components is essential for the dam's operation, and excessive displacement can lead to malfunction or failure. Thus, the displacement thresholds are required to be calibrated to ensure the ongoing integrity and operability of these essential elements. Similarly, the limit states for stress at the heel and neck of the dam are carefully set based on the tensile strength of the concrete. These stress thresholds are critical as they signal the onset of cracking, which can compromise the structural integrity of the dam. Exceeding these stress limits can result in the development of cracks, which, if not addressed, may lead to progressive damage and, in extreme cases, catastrophic failure of the dam structure.

Excessive crest displacement not only signifies potential damage to the dam itself but also raises concerns about the integrity of ancillary structures. Additionally, excessive movement can lead to sliding at the base or lift joints. It may also cause overturning. Similarly, Tensile stress can induce cracking in the dam body, exceedance of tensile stress combined with inelastic duration at the neck (σ_{tn}) and heel (σ_{th}) region shows material failure, propagation of crack path, and the risk to structural integrity. The neck of a gravity dam is a critical area where the structure is relatively thinner. Excessive tensile stresses here could be indicative of potential structural vulnerabilities. The heel of the dam is where the dam meets the foundation. Elevated tensile stresses at the heel could suggest issues related to the interaction between the dam and its foundation, potentially impacting stability, due to interface cracking and increased uplift pressure. Limit states for crest displacement, and stress at the neck and heel, when combined with ground motion return periods, facilitate the development of fragility curves. These curves serve as probabilistic representations of the likelihood of specific damage states occurring. In this study, limit states as a function of the crest displacement, and stress exceedance were defined. The crest displacement values were normalized with respect to the height of the dam. Normalized crest displacement (NCD) was calculated using Equation 33.

$$NCD = \frac{crest\ displacemnt(m)}{height\ of\ the\ dam(m)} \qquad 34$$

The three considered limit states (LS_0, LS_1, and LS_2) represent progressively increasing levels of damage to the concrete gravity dam, each indicative of different degrees of structural impairment as per the performance-based earthquake engineering (PBEE) guidelines. LS_0, or Minor damage, corresponds to the lowest performance level, signifying the presence of superficial or minor issues that do not significantly compromise the dam's overall integrity. This might include hairline cracks, surface abrasions, or localized imperfections that, while necessitating attention, do not pose an immediate threat to the structure. Moving up the performance levels, LS_1, or Moderate damage, signifies a more pronounced level of impairment. In this state, structural elements experience notable distress, with cracks and deformations surpassing superficial characteristics. While the dam remains stable, restorative actions become imperative to prevent further deterioration. Finally, LS_2, or Severe damage, represents the highest performance level on the scale and a critical condition where the structural integrity of the dam is significantly compromised. This involves extensive cracking, deformations, and potential instability. Immediate and comprehensive remediation is essential to avert catastrophic failure. These limit states provide a systematic framework for assessing and addressing the evolving condition of the dam, allowing for timely interventions at different stages of structural distress, thereby enhancing the dam's overall seismic resilience. The considered damage limit states in this analysis are provided in Table 24.

Table 24. Damage limit states

Limit State			
LS_0- Minor damage	NCD > 0.02%	σ_{tn} > 2.27,1.94,1.31 MPa	σ_{th} > 2.27,1.94,1.31 MPa
LS_1- Moderate damage	NCD > 0.08%	σ_{tn} > 3.04,2.59,1.77 MPa	σ_{th} > 3.04,2.59,1.77 MPa
LS_2- Severe damage	NCD > 0.11%	σ_{tn} > 3.80,3.24,2.22 MPa	σ_{th} > 3.80,3.24,2.22 MPa

Normalized crest displacement (NCD), Tensile stress at the neck and the heel (σ_{tn}, σ_{th})

6.5.4. Fragility framework

In the literature on post-earthquake structural analysis, numerous studies have investigated the various failure criteria applicable to diverse structures. Commonly, these studies focus on specific failure mechanisms within the structure, such as deformation of the dam body, neck cracking, and material failure due to compression or tension forces. These failures can manifest in different parts of the dam structure, including the foundation, the concrete at the toe, or at the interface between the dam and the surrounding soil, as detailed by Tekie and Ellingwood [230]. Observations by Lupoi and Callari [294] suggest that the failure behavior of concrete gravity dams can be distinguished based on certain critical zones within the structure. Among these zones, the interface region between the dam and the foundation, the main body of the dam, and the area above the neck region are considered to be of particular importance. The dam-foundation interface and the area above the neck region are generally regarded as the most common areas where failure can occur. In light of these zones, this study has chosen to focus on a tensile stress-based failure mode at the neck and heel, as well as on crest displacement as key indicators of structural integrity under seismic loading.

Fragility analysis is a crucial technique in assessing the vulnerability of engineered systems to specific events, often used in seismic engineering and other fields where structural integrity is paramount [230]. The fragility function, $P_f(y)$, as shown in Equation 35 indicates the likelihood of structural failure given a specific ground motion intensity measure IM level. In this context, y represents the demand variable measured in the same units as the IM. D is the probability of exceeding a failure threshold. d_i refers to different damage states, such as minor, moderate, and severe IM represents the Intensity measure parameters.

$$P_f(y) = P[D > d_i | IM = y] \quad 36$$

In the context of a gravity dam, the fundamental failure modes encompass sliding, overturning, tensile cracking, and compressive crushing. In this study, the structural limit states considered are tensile crack failure and normalized crest displacement, as proposed in the previous section. To construct fragility curves, the log-normal cumulative distribution function (CDF) is employed. The failure probability P_f can be calculated using the Equation 37.

$$P_f = \Phi\left[\frac{\ln(y) - \alpha}{\beta}\right] \quad 38$$

In this equation, Φ represents the standard normal distribution function, and α and β are the mean and the standard deviation of the lognormal CDF, respectively.

6.5.5. Fragility function

The fragility curves generated for the five intensity levels correspond to five return periods, considering material variation and degradation in years 1, 50, and 100. In each of the 22 nonlinear dynamic analyses conducted for each return period, combined H_1V or H_2V ground motion records were utilized. This resulted in a total of 990 analyses considering all variations in material properties and aging effect. For each simulation, NCD, and stress at neck, and heel were computed. The limit states were considered based on tensile stress, and NCD as detailed in section 6.5.3. The results, representing the five fragility point estimates, were used to develop fragility curves for the three considered limit states.

6.5.6. Fragility Curves

The fragility curves of aging dams are impacted by the time-dependent changes in the material properties and the structural response. Fragility curves represent the probability of exceeding a certain limit state (such as overstressing, sliding, or overturning) as a function of an intensity measure (such as peak ground acceleration, spectral acceleration, or cumulative absolute velocity). The fragility curves for normalized crest displacement (NCD), tensile stress at the neck (σ_n), and tensile stress at the heel (σ_h) across three limit states (LS_0 for minor damage, LS_1 for moderate damage, and LS_2 for severe damage) as shown in Figure 45, 46 and 47, illustrate the probability of damage occurrence under various seismic return periods, taking into account the aging of the dam and variability in material properties due to construction heterogeneity.

The fragility curves of aging dams show in general a shift to the left, indicating higher vulnerability, or changing their shape, indicating higher uncertainty, due to the aging effects. The fragility curves for the dam at year 1 show lower probabilities of exceedance for all limit states compared to the dam at years 50 and 100. This indicates that a newer dam is less likely to experience damage under the same seismic conditions. As the dam ages to 50 and then to 100 years, the curves shift upwards, suggesting an increased probability of damage. This is particularly noticeable for LS_2, where the dam at 100 years shows a much higher probability of severe damage even at longer return periods. The curves corresponding to mean+1σ and mean-1σ show the sensitivity of the dam to variations in material strength. Higher strength properties (mean+1σ) result in lower probabilities of damage, indicating better performance under seismic loading. Conversely, when material properties are weaker (mean-1σ), the probability of damage increases, suggesting that variability in material properties can significantly impact the dam's seismic resilience.

6.5.7. Comparative assessment of fragility curves

In the comparative analysis of fragility curves based on NCD, stress at the neck σ_n, and stress at the heel σ_h for the Pine Flat Dam, several patterns emerge across the three limit states of minor (LS_0), moderate (LS_1), and severe damage (LS_2). For all three indicators (NCD, σ_n, and σ_h), as the dam ages from 1 year to 100 years, the probability of exceedance for each limit state increases. This indicates a clear trend: as the dam's material properties degrade over time, the dam becomes more susceptible to damage under seismic events. The increase in the probability of exceedance is more pronounced in the transition from 50 to 100 years, which could be attributed to an accelerated degradation process as the dam approaches the latter stages of its design life.

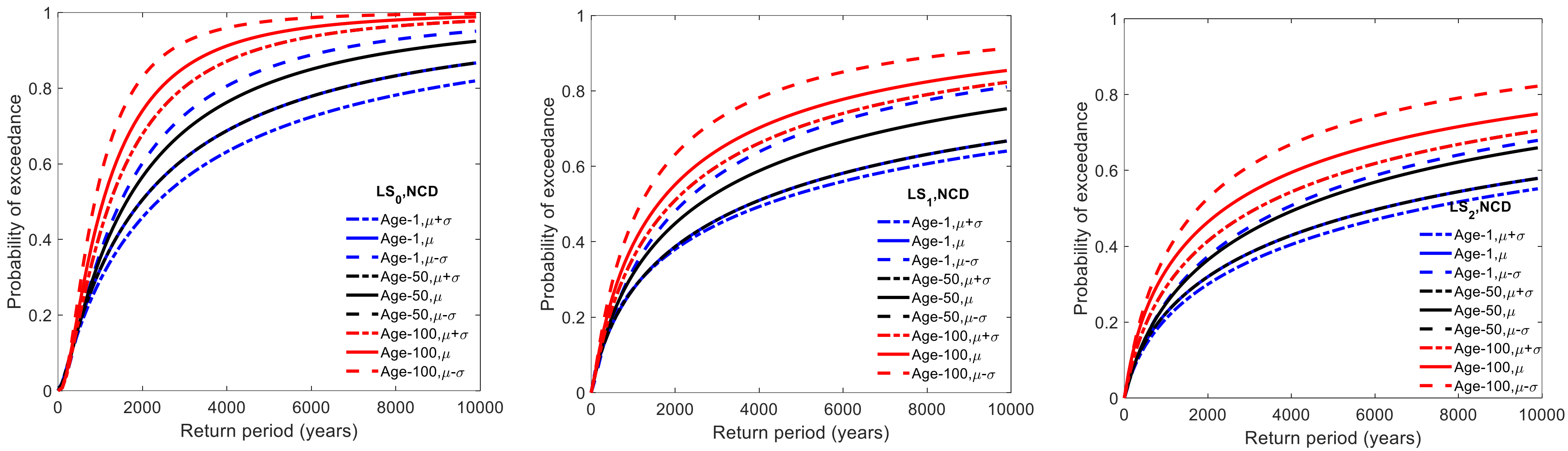
The fragility curves for mean+1σ and mean-1σ material properties suggest that higher strength material properties (mean+1σ) result in a lower probability of exceedance for all limit states, reflecting better performance under seismic loading.

Conversely, lower-strength material properties (mean-1σ) exhibit a higher probability of exceedance, indicating an increased risk of damage. This variation highlights the importance of material quality and the necessity to account for potential deviations from mean property values in design and assessment. Across the limit states, the transition from LS_0 to LS_2 shows an increasing gradient in the probability of exceedance, with severe damage (LS_2) being more sensitive to the aging of the dam and variations in material properties. The neck region σ_n, shows a higher sensitivity to seismic excitation compared to the

NCD and stress at the heel σ_h. This implies that for a given seismic event, the neck region is more likely to reach or exceed the defined limit states. This higher sensitivity could be due to the neck region being a critical stress concentration point, where tensile stresses are maximized during seismic events. While the probability of limit state exceedance for the heel region σ_h, is generally lower than that for the neck region, it's important to note that failures initiated at the heel can have more significant consequences. This is because the heel is crucial for the overall stability of the dam, and failures here can lead to more extensive structural damage or even potential dam failure.

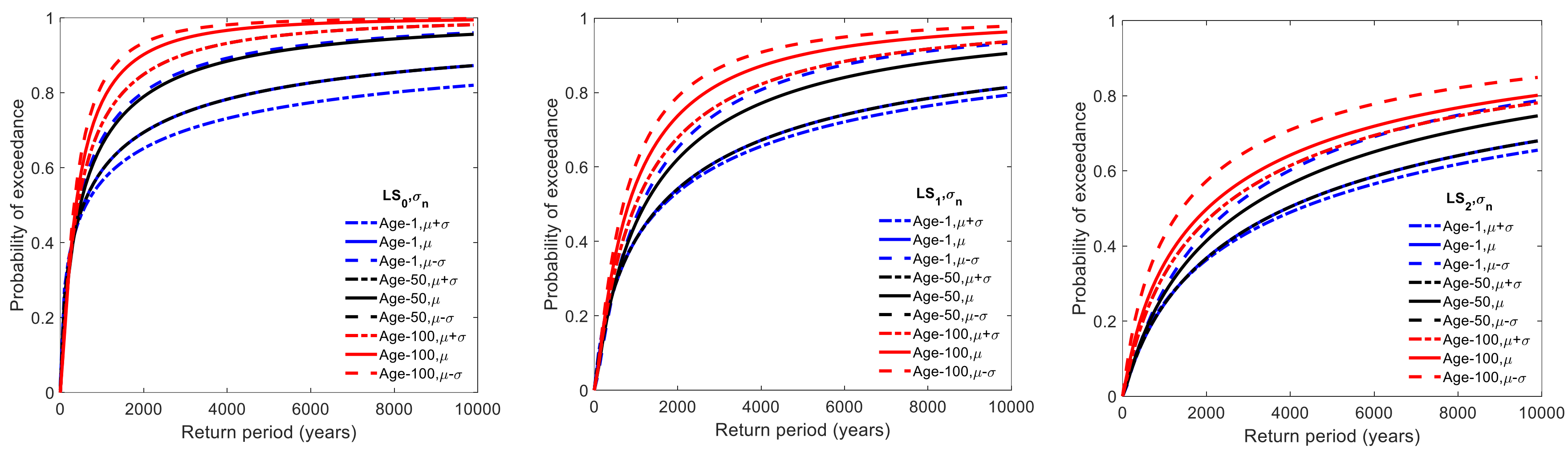
As the dam ages, the fragility curves for all three indicators shift towards higher probabilities of exceedance, indicating that older dams are more vulnerable to seismic-induced damage. This shift is more pronounced in the σ_n curves, reinforcing the notion that the neck region's vulnerability increases with age. The variation in material properties due to construction heterogeneity affects the spread of the fragility curves. Higher material strength (mean+1σ) results in a lower probability of exceedance across all limit states, suggesting that regions of the dam with better-than-average material properties will perform better seismically. Conversely, areas with lower material strength (mean-1σ) show higher probabilities of exceedance, which may require targeted retrofitting or enhanced monitoring. Shorter return periods (e.g., 1 in 475 years) indicate a higher frequency of seismic events and are associated with higher probabilities of exceedance for minor and moderate damage (LS_0 and LS_1). However, for severe damage (LS_2), the probability of exceedance increases significantly with longer return periods (e.g., 1 in 10,000 years), particularly for the NCD and σ_n indicators. This suggests that while frequent, less intense seismic events can cause minor to moderate damage, rarer, more intense events pose a significant risk of causing severe damage.

In summary, the fragility analysis based on NCD, σ_n, and σ_h provides a multifaceted view of the seismic vulnerability of the dam, with the neck region identified as a critical area for seismic resilience, especially as the dam ages. Understanding these comparative vulnerabilities can guide targeted interventions to enhance dam safety, prioritize retrofitting efforts, and inform emergency preparedness plans. These fragility curves are crucial for understanding the seismic vulnerability of concrete gravity dams over their operational lifespan. Aging significantly increases the risk of damage, especially for severe damage states, and construction heterogeneity further influences this risk. The return period of seismic events is also a critical factor; dams are more vulnerable to frequent seismic events, a vulnerability that becomes more pronounced as the dam ages. This information is vital for risk assessment and management, indicating that older dams may require more intensive monitoring, maintenance, or retrofitting to mitigate the increased risk of damage due to aging and the inherent variability in material properties.



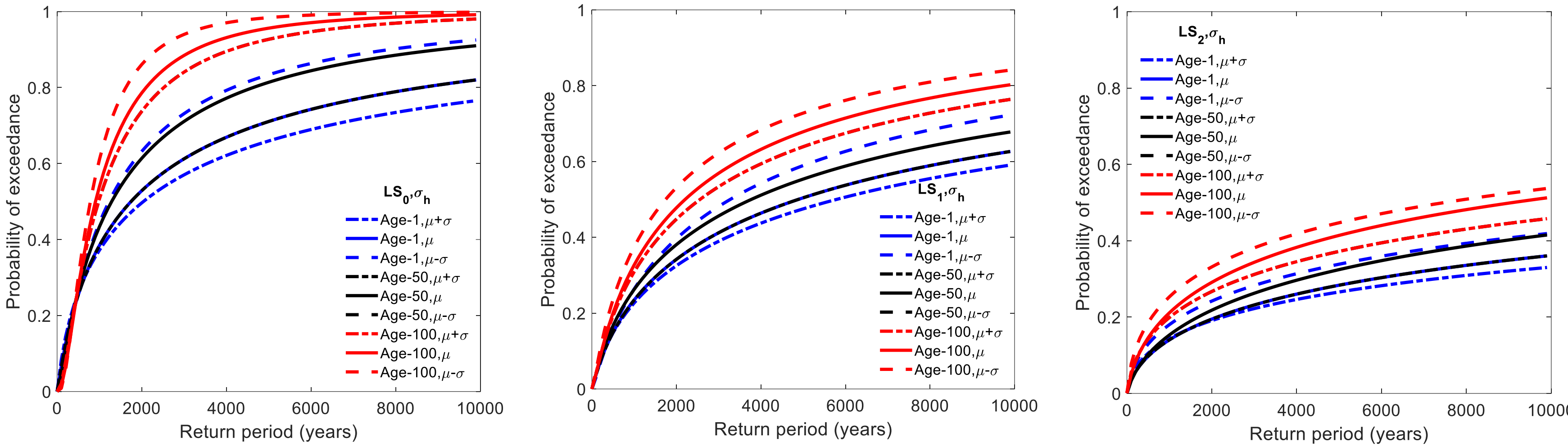
(a) (b) (c)

Figure 45. Fragility curves based on NCD for limit states (a) LS_0 (b)LS_1(c)LS_2



(a) (b) (c)

Figure 46. Fragility curves based on tensile stress at the neck for limit states (a) LS_0 (b)LS_1(c)LS_2



(a) (b) (c)

Figure 47. Fragility curves based on tensile stress at heel for limit states (a) LS_0 (b)LS_1(c)LS_2

6.6. Concluding remarks

The comprehensive seismic vulnerability assessment of the Pine Flat DFR system, explored in this study, thoroughly accounting the material degradation due to aging and heterogeneity. This analysis employed a range of ground motions corresponding to five distinct return periods, carefully selected using the CMS method. The study was carried out with a suite of 990 numerical simulations, to ensure accuracy and reliability in the findings. Based on these analyses, fragility curves were developed, providing a probabilistic representation of the dam's susceptibility to seismic events. In defining the limit states for the development of these fragility curves, two critical failure modes were considered, i.e., tensile crack failure and crest displacement within the dam. These limit states are particularly relevant as they directly relate to the structural integrity and safety of the dam under seismic loading. The resulting fragility curves, plotted against the return periods of the seismic events, offer valuable insights into the dam's performance under varying seismic intensities. These curves serve as a tool for understanding the likelihood and extent of damage under different seismic conditions, considering both the inherent variability of the materials used in the dam's construction and the progressive degradation of these materials over time. This approach not only enhances our understanding of the seismic resilience of the Pine Flat dam but also sets a precedent for similar assessments of other large-scale dam structures, where material heterogeneity and degradation play significant roles in determining seismic vulnerability. Below are the important conclusions based on this study.

1. The modal analysis indicates that aging markedly affects the dynamic characteristics of the dam. As the dam ages, an increase in the natural periods of vibration for the first four modes is observed, which can be attributed to the reduction in material stiffness due to aging processes such as creep, shrinkage, and environmental degradation.
2. The increase in natural periods due to aging suggests a less stiff dam system that may perform differently under seismic loads compared to a newer structure. This change in dynamic response must be accounted for in long-term seismic risk assessments.
3. These findings highlight the importance of incorporating aging effects into maintenance and retrofitting plans. Understanding how the modal parameters and dynamic characteristics of the dam change over time is crucial for designing interventions that address the specific vulnerabilities of aging structures.
4. The study demonstrates that aging significantly affects the seismic vulnerability of dams. As the dam progresses from 1 to 100 years, there is an evident increase in the probability of exceeding various damage limit states due to the reduction in material stiffness over time.
5. Variability in material properties due to construction heterogeneity has a pronounced impact on the fragility curves. Material properties above the mean result in a lower probability of damage, while properties below the mean increase the risk of exceeding limit states, underscoring the importance of quality control during construction.
6. Shorter return periods (1 in 475 years) are associated with higher probabilities of damage across all limit states and ages, reflecting a greater expected frequency of seismic events. In contrast, longer return periods (1 in 10,000 years) show lower probabilities of damage, indicating rarer but more severe seismic events.
7. The fragility curves based on normalized crest displacement (NCD), stress at the neck (σ_n), and stress at the heel (σ_h) reveal different sensitivities to damage. The neck region shows a higher sensitivity to exceeding limit states compared to the heel and NCD, suggesting that it may be a critical point of monitoring and reinforcement in dam safety protocols.

8. The study shows that the neck region remains particularly sensitive to the exceedance of limit states compared to other indicators for a given seismic excitation. This increased sensitivity could be due to its position and function within the dam structure, potentially accumulating more stress over time.
9. While the probability of limit state exceedance at the heel region is lower, the magnitude of potential damage from such failures could be more devastating, implying that failures in this region, although less likely, may have more severe consequences.
10. The study's conclusions regarding the impact of aging on dynamic characteristics should be integrated into dam safety protocols and guidelines, ensuring that the seismic assessments reflect the most accurate and current understanding of the dam's behavior.
11. Engineers and researchers should consider the effects of aging on dynamic characteristics in the design of new dams and the assessment of existing ones. Design standards may need to be adjusted to account for long-term changes in modal parameters due to aging.
12. A comprehensive risk assessment should include the impact of aging on the dam's modal parameters and overall dynamic characteristics, alongside material property heterogeneity and seismic excitation, to provide a full picture of the structure's seismic resilience.
13. By incorporating the effects of aging on the dam's dynamic characteristics, this study enriches the understanding of seismic fragility for concrete gravity dams and underscores the need for age-informed risk assessments and intervention strategies.

The seismic performance evaluation, incorporating the effects of aging and heterogeneity in material properties, has led to a better understanding of the dam's behavior under seismic loading. This knowledge is crucial for designing retrofitting measures and emergency preparedness strategies. Suggested future research directions include a more detailed examination of the effects of other factors such as uplift pressure and silt accumulation, as well as the application of these findings to a broader range of dam types and seismic environments.

Chapter 7

Conclusions and Future works

7.1. Summary

From the case studies and discussions conclusive remarks are mentioned in this chapter. Also, the future scope of the work could be done as an extension of this thesis. The primary aim of the present research has been to develop a comprehensive framework for assessing the seismic risk associated with the safety of existing concrete gravity dams. Central to this analysis is the careful selection of a consistent numerical model that forms the basis of any probabilistic evaluation. This proposed framework adopts a holistic strategy that includes a step-by-step numerical simulation that is in line with the overall objectives of the study. It incorporates contemporary techniques for selecting ground motion, and detailed numerical modeling, and accounts for the variability in material properties due to aging and the inherent heterogeneity from the construction process. This approach addresses various uncertainties i.e., both aleatory and epistemic, and evaluates their influence on fragility and risk assessment outcomes. Aimed at providing an exhaustive probabilistic analysis of seismic risks, this framework leverages the latest advancements in fragility analysis and risk quantification. By covering the complex aspects of dam safety, it aspires to significantly bolster the seismic resilience of concrete gravity dams, ensuring their continued safe and dependable function amidst earthquake threats. The goal of the present work has been to serve as a benchmark for dam safety professionals and researchers alike.

7.2. Conclusions

The following are the key conclusions of this thesis.

1. Understanding safety practices: Recognizing the strengths and limitations of existing safety practices is fundamental for evaluating the seismic performance of dams. This understanding forms the basis for all subsequent analyses and improvements.
2. Impact of model variability: As highlighted in Chapter 4, variations in the modeling approach and underlying modeling assumptions can significantly influence both the system's response to seismic events and the resulting fragility assessments. This underscores the need for careful model selection and validation. The key takeaways from the research work presented in Chapter 4 are as follows.
    a. Modeling consistency and discrepancies: This study confirms that simpler dam models yield consistent modal parameters and crest displacement histories across different software systems based on varying solution procedures, highlighting reliable performance in less complex simulations. However, discrepancies in crest displacement values emerge when comparing simplified methods, like the added mass approach, to more accurate acoustic element modeling, underlining the critical need for precise fluid-structure interaction representation.

    b. Impact of modeling choices on results: The selection of reservoir modeling techniques significantly affects outcomes, with acoustic elements offering a closer approximation of fluid-structure interactions than the added mass method. Variations in results, even with standardized material properties and boundary conditions, point to the substantial influence of software-specific implementations of soil-structure interactions and the necessity of employing progressive simulation to grasp system behavior fully.

   c. Recommendations for dam safety assessments: For preliminary assessments, simpler 2D models are recommended, while high-risk dams require more complex analysis for compliance and detailed safety evaluations, advocating the use of tools like Abaqus for in-depth studies. Recognizing methodological variations is essential for devising effective remedial actions and emergency response strategies and avoiding the shortcomings of oversimplification. Further research should delve into factors like joint dynamics, base sliding, and variable foundation properties to enhance modeling accuracy and our understanding of dam behavior under diverse conditions.

3. Merit of progressive analysis: To effectively manage computational resources and align with safety assessment goals, the adoption of progressive simulation techniques is recommended. These methods enable a more nuanced exploration of potential seismic impacts and structural responses.
4. Influence of ground motion selection: The present research shows how different ground motion selection methods and record-to-record (RTR) variability can alter the system's response, subsequently affecting the risk assessment outcomes. This emphasizes the importance of methodical ground motion selection. The key takeaways from the case study as presented in Chapter 5 are as follows.
   a. Importance of ground motion selection: The selection of suites of ground motions, using methods such as ASCE 7-16 and CMS, is crucial in seismic fragility assessments. Proper selection enhances the understanding of variations in dam response to various seismic scenarios and influences predicted failure probabilities. By incorporating a comprehensive suite of ground motions across different return periods aligned with the performance objectives of the structure, the evaluation of critical failure modes becomes more robust, thereby improving the reliability of risk assessments.

   b. Comprehensive evaluation through return periods and damage indices: Incorporating a range of return periods and multiple damage indices, such as Normalized Crest Displacement (NCD), Damage Area Ratio (DAR), and stress levels at critical locations (e.g., neck and heel), provides detailed insights into the dam's performance under different seismic hazards. This holistic approach aids in understanding structural vulnerability, supporting long-term safety and resilience planning.

   c. Strategic implications for dam safety and resilience: The study's findings emphasize a nuanced approach to seismic risk assessment, focusing on targeted investigations, especially in vulnerable areas like the neck region. The choice of ground motion selection method significantly impacts risk evaluations and informs decisions on dam safety measures. A comprehensive, adaptable strategy that considers the complex interplay of factors affecting dam behavior under seismic forces is essential for effective risk management.
   d. Comparison of Traditional Standard-Based and Risk-Based Approaches: The investigation compares traditional standard-based approaches with risk-based approaches, highlighting the latter's advantage in providing a holistic view of stress and displacement-based failure modes. Risk-based approaches offer a common currency for comparing different risks, facilitating more informed decision-making.

e. Empirical Approaches and Refined Models for Consequence Estimation: The current investigation uses empirical approaches for estimating the failure discharge and consequences of selected failure modes. Adopting refined models for failure discharge estimation associated with any failure mode enhances the accuracy of consequence estimations, thereby improving overall risk assessments.

f. Recommendations on ground motion selection and its impact on seismic performance assessment: Ground motion selection is a critical component of seismic performance assessment, significantly influencing system response variation and subsequent fragility and risk evaluations. It is essential to understand the theoretical framework and expected variations associated with each method. Ground motion selection should be methodical, utilizing diverse and representative records across return periods while considering site geology, source characteristics, near and far-field effects, and appropriate ground motion prediction equations (GMPEs). This study employs CMS and ASCE 7-16 methods, using PGA as the intensity measure parameter. To enhance system response comprehension, it is recommended to extend ground motion selection methods to include GCIM and multiple intensity measure parameters. The focus on stress and displacement-based damage indices should be expanded to incorporate energy-based damage indices and others, capturing a comprehensive range of structural responses and vulnerabilities. The study also compares the advantages and limitations of traditional standard-based approaches with risk-based approaches, advocating for the integration of both in safety evaluations. This holistic view of potential failure modes improves the reliability of risk assessments. While the current study uses empirical approaches for estimating failure discharge and consequences, adopting refined models for these estimations will further improve the accuracy of risk assessments.

5. Effects of variability in material degradation and construction**:** The present study shows how aging, construction heterogeneity, and record-to-record (RTR) variability can impact system response and fragility assessments. Acknowledging these factors is crucial for accurate risk analysis. The key takeaways from the case study as presented in Chapter 6 are as follows.
    a. Aging's impact on dynamic characteristics: Aging significantly alters the seismic vulnerability of dams, evidenced by an increase in the natural periods of vibration due to processes like creep, shrinkage, and environmental degradation. This suggests a less stiff dam system over time, necessitating adjustments in seismic risk assessments to accommodate the changing dynamic response.

    b. Variability and damage sensitivity: Construction heterogeneity affects fragility curves, where material properties deviating from the mean influence the probability of damage. The study highlights critical areas like the neck region for monitoring due to its higher sensitivity to stress and potential damage, emphasizing the importance of incorporating variability and specific structural sensitivities into maintenance and retrofitting strategies.

    c. Implications for dam safety and design: The findings underscore the necessity of integrating the effects of aging and material variability into dam safety protocols, risk assessments, and design standards. By understanding how dynamic characteristics evolve, engineers can design interventions that address aging dams' vulnerabilities, ensuring resilience against seismic events and informing new dam designs for enhanced long-term stability.

6. Understanding the uncertainties: A detailed grasp of the uncertainties involved in every step of the assessment process, including the adopted solution procedure, model complexity, ground motion selection, and variations in material properties, is essential. This comprehensive understanding is key to reliably estimating system risk.
7. Strategic planning for controlling uncertainty: Identifying and addressing uncertainties enables more effective planning for risk mitigation, rehabilitation, and informed decision-making. This strategic focus is critical for enhancing the seismic resilience of dam structures.

In summary, this thesis advocates for a holistic approach to seismic risk assessment of dams, emphasizing the importance of understanding existing safety practices, adopting progressive simulation techniques, and meticulously addressing uncertainties at every step of the assessment process. Such an approach is pivotal for improving the reliability of dam safety evaluations and ensuring the resilience of these critical infrastructures.

7.3. Scope for future research

Looking ahead, the scope for future work within this thesis is vast and presents numerous avenues for deepening and broadening the seismic risk assessment framework. Areas of potential exploration include:

1. Foundation heterogeneity: Investigate the impact of varying foundation properties on the seismic response of dams, which can significantly influence the accuracy of risk assessments.
2. Additional failure modes: Explore other potential failure modes, such as sliding at the dam foundation interface, and lift joints, which could critically affect dam stability during seismic events.
3. Use of meta-models: Implementation of meta-models to reduce computational demands. These simplified models can efficiently approximate complex numerical simulations, facilitating quicker assessments without compromising on accuracy.
4. Three-dimensional model: The current study uses only two-dimensional models, however, to capture realistic behaviors of the DFR model, with joint opening/closing, and relative block movement, a three-dimensional model will be useful.
5. Advanced ground motion selection techniques: Evaluate the application of generalized conditional intensity measure (GCIM) and other sophisticated ground motion selection methods to enhance the representativeness of seismic hazard scenarios.
6. Deconvolution of ground motion: In the current study the ground motions are applied at the dam-foundation interface, as an alternative the ground motion can be deconvoluted and applied at the foundation base.
7. Variation in loading conditions: Consider the effects of variable loading conditions, including changes in reservoir water levels, uplift pressure, silt pressure, and thermal loading, on the structural integrity and seismic performance of dams.
8. Different damage Indices: Employ a broader range of damage indices to capture the multifaceted nature of dam responses under seismic loading, offering a more nuanced understanding of potential vulnerabilities.
9. Development of fragility surfaces: Expand fragility analysis to include surfaces that relate multiple Intensity Measures (IMs) to exceedance probabilities, providing a more comprehensive risk assessment framework.
10. Extension to other types of dams: Applying the proposed framework to other dam types, such as embankment and arch dams, to validate its applicability and effectiveness across different structural designs.

11. Application of BMRA alongside RBA: Integrating Bayesian Model Risk Assessment (BMRA) with Risk-Based Analysis (RBA) for a more robust assessment of uncertainties and risks.
12. Other applicable areas: Future studies could integrate real-time monitoring data and consider black swan events, which are unpredictable yet impactful occurrences. Retrofitting strategies for existing dams should be explored to enhance their resilience. Additionally, examining the implications of climate change on seismic risk assessments is crucial. Proper planning for hazard categorization, securing rehabilitation finance, and establishing catastrophe insurance for downstream infrastructures are also key areas for advancing the field of seismic risk management for dams.

By addressing these areas, future research based on this thesis can enhance the robustness and applicability of the proposed framework, paving the way for innovative solutions that ensure the long-term safety and resilience of dam infrastructures against seismic threats.

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Research Publications from the present research

Peer-reviewed journal articles

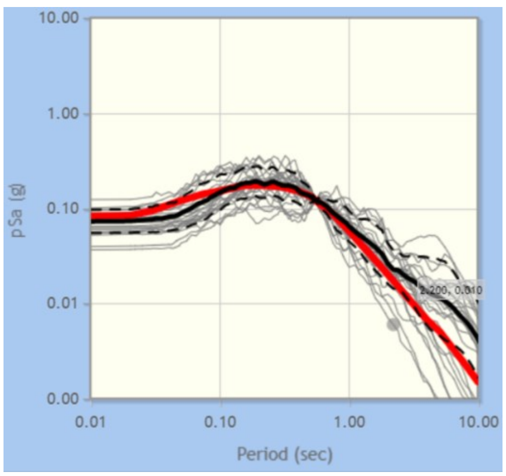
- Bikram K Patra, Rocio L. Segura, A. Bagchi. (2024). Modeling variability in seismic analysis of concrete gravity dams: A parametric analysis of Koyna and Pine Flat Dams, Infrastructures, volume 9, ISBN: 2412-3811.
- Bikram K Patra, A. Bagchi (2024). Impact of material degradation due to aging on fragility assessment of concrete gravity dams. (In review).
- Bikram K Patra, Rocio L. Segura, A. Bagchi. (2024). Impact of uncertainty associated with ground motion selection methods on fragility assessment of dams. (In review).

Conference publications

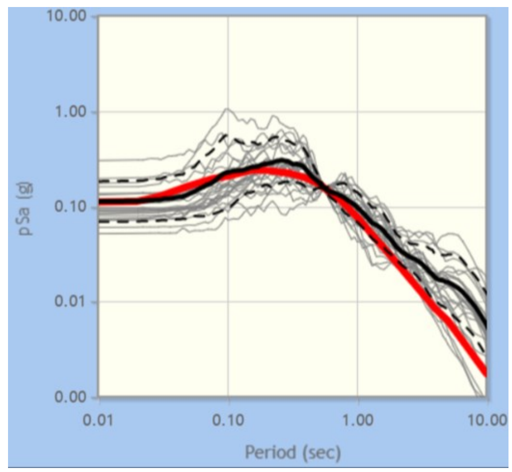
- Avirup Sarkar, Bikram Patra, and Ashutosh Bagchi (2024). A simplified thermal stress analysis to model the effect of Alkali-Aggregate Reaction (AAR) on concrete gravity dams. Canadian Society for Civil Engineering (CSCE)'s annual conference, June 5 - 7, 2024, at Niagara Falls, Ontario.
- Bikram K Patra, Pramod Narayan, A. Bagchi (2024). Assessment of seismic resilience of aging concrete gravity dams, Symposium "Dams for People, Water and Environment and Development" 92nd ICOLD Annual Meeting, September 29 to October 03, 2024, at New Delhi, India.
- Bikram K Patra, Rocio L. Segura, A. Bagchi. (2024). Impact of uncertainty associated with ground motion selection on fragility assessment of dams, 18th World Conference on Earthquake Engineering (WCEE2024), June 30 to July 5, 2024, at Milan, Italy.
- Avirup Sarkar, Bikram Patra, Sharad Ghodke and Ashutosh Bagchi (2023). Monitoring the deformation pattern of an instrumented concrete arch dam. 14th International Workshop on Structural Health Monitoring (IWSHM), September 12-14, 2023, at Stanford University, CA, USA.
- Bikram K Patra, A. Bagchi. (2022). Displacement monitoring of an Instrumented Arch dam and related data Interpretation. SHMII-11: 11th International Conference on Structural Health Monitoring of Intelligent Infrastructure, August 8-12, 2022, at Concordia University, Montreal, QC, Canada.
- Gabriella Fiorino, Chadi Mitri, Ahmad Rajab, and Bikram K Patra (2022). Structural health monitoring of dams. SHMII-11: 11th International Conference on Structural Health Monitoring of Intelligent Infrastructure, August 8-12, 2022, at Concordia University, Montreal, QC, Canada.
- Bikram K Patra, Saikat Bagchi and A. Bagchi (2019). Seismic Safety and Performance Evaluation of Existing Concrete Gravity Dam. 7th International Congress on Computational Mechanics and Simulation, December 11-13, 2019, at IIT Mandi, Mandi, India.

Appendix-A Ground motions selection based on CMS

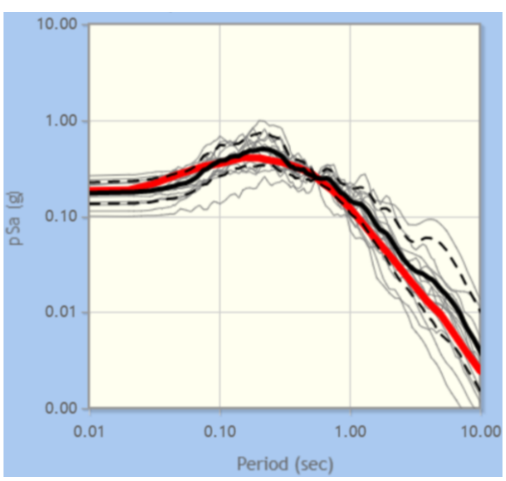
The ground motions for the Pine Flat Dam location were selected using the CMS method. A total of fifty-five ground motions were chosen, with eleven ground motions corresponding to each of five return periods: 1 in 10000 years, 1 in 5000 years, 1 in 2475 years, 1 in 975 years, and 1 in 475 years. The response spectra plots, including the target spectrum, suite mean, and spectra of individual ground motions for the selected ground motions across the return periods, are shown in Figures A.1. Similarly, Tables A.1 to A.5 provide the details of these ground motions, following the standard notations of the PEER database [253]. Section 5.3 of Chapter 5 outlines the procedure adopted for selecting these ground motions. Each ground motion includes two horizontal components (H_1, H_2) and one vertical component (V). The peak ground acceleration (PGA) for each horizontal component is denoted as PGA_{H1} and PGA_{H2}, and the vertical component as PGA_V, in the units of (g). The ground motions were selected to represent eleven unique seismic events, covering a range of magnitudes and durations, to capture the record-to-record (RTR) variability for the location in consideration. The selection process also accounts for the effects of both near-field and far-field events. This comprehensive selection ensures that the ground motions adequately represent the seismic hazard at the Pine Flat Dam location.



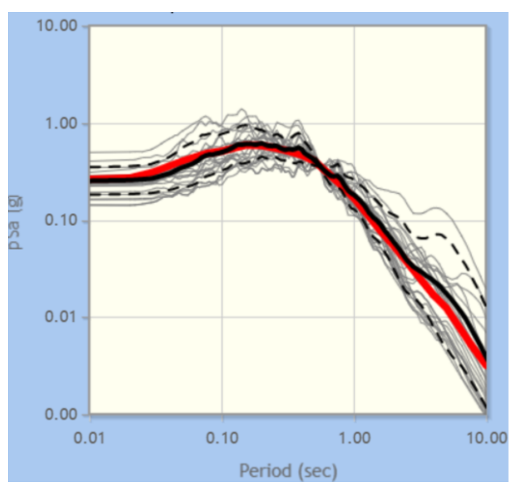
(a) 1 in 475 years



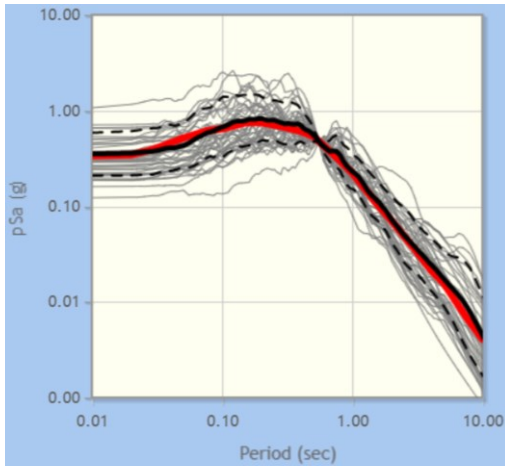
(b) 1 in 975 years



(c) 1 in 2475 years



(d) 1 in 5000 years



(e) 1 in 10000 years

Figure A.1 Spectra of suites of GMs based on CMS

Table A.1 Ground motion details for 1 in 10000 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
164	Imperial Valley 06	1979	Cerro Prieto	6.5	15.19	471.53	63.80	0.21	0.20	0.26
265	Victoria Mexico	1980	Cerro Prieto	6.3	13.80	471.53	25.57	0.43	0.42	0.19
448	Morgan Hill	1984	Anderson Dam (downstream)	6.1	3.22	488.77	41.48	0.26	0.20	0.10
881	Landers	1992	Morongo Valley Fire Station	7.2	17.36	396.41	53.48	0.36	0.35	0.38
1111	Kobe Japan	1995	Nishi-Akashi	6.9	7.08	609.00	45.29	0.16	0.20	0.09
1618	Duzce Turkey	1999	Lamont 531	7.1	8.03	638.39	31.90	0.17	0.16	0.15
1633	Manjil Iran	1990	Abbar	7.3	12.55	723.95	299.78	0.22	0.39	0.23
1787	Hector Mine	1999	Hector	7.1	10.35	726.00	149.98	0.20	0.19	0.13
2734	Chi-Chi Taiwan-04	1999	CHY074	6.2	6.02	553.43	28.35	0.29	0.20	0.14
3943	Tottori Japan	2000	SMN015	6.6	9.10	616.55	56.06	0.14	0.11	0.11
4068	Parkfield-02 CA	2004	Parkfield - Hog Canyon	6.0	0.73	363.69	40.94	0.20	0.19	0.16

Table A.2 Ground motion details for 1 in 5000 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
1	Helena Montana 01	1935	Carroll College	6.0	2.07	593.35	51.04	0.50	0.48	0.31
164	Imperial Valley 06	1979	Cerro Prieto	6.5	15.19	471.53	63.80	0.16	0.15	0.20
265	Victoria Mexico	1980	Cerro Prieto	6.3	13.80	471.53	25.57	0.32	0.32	0.15
548	Chalfant Valley 02	1986	Benton	6.1	21.55	370.94	41.48	0.19	0.15	0.08
1618	Duzce Turkey	1999	Lamont 531	7.1	8.03	638.39	25.52	0.04	0.08	0.27
1787	Hector Mine	1999	Hector	7.1	10.35	726.00	299.78	0.16	0.30	0.17
3852	Chi-Chi Taiwan 04	1999	CHY006	6.2	24.58	438.19	149.98	0.15	0.14	0.10
3943	Tottori Japan	2000	SMN015	6.6	9.10	616.55	28.51	0.26	0.27	0.15
4068	Parkfield-02 CA	2004	Parkfield - Hog Canyon	6.0	0.73	363.69	55.00	0.20	0.19	0.15
6878	Joshua Tree CA	1992	North Palm Springs Fire Sta #36	6.1	21.4	367.84	139.99	0.27	0.23	0.17
8164	Duzce Turkey	1999	IRIGM 487	7.1	2.65	690.00	45.29	0.12	0.15	0.07

Table A.3 Ground motion details for 1 in 2475 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
164	Imperial Valley-06	1979	Cerro Prieto	6.5	15.19	471.53	63.80	0.11	0.10	0.14
548	Chalfant Valley-02	1986	Benton	6.1	21.55	370.94	31.90	0.19	0.16	0.12
1614	Duzce Turkey	1999	Lamont 1061	7.1	11.46	481.00	45.29	0.09	0.11	0.05
1787	Hector Mine	1999	Hector	7.1	10.35	726.00	31.90	0.15	0.15	0.10
3757	Landers	1992	North Palm Springs Fire Sta #36	7.2	26.95	367.84	25.52	0.05	0.03	0.19
3852	Chi-Chi Taiwan-04	1999	CHY006	6.2	24.58	438.19	21.20	0.19	0.14	0.06
4129	Parkfield-02 CA	2004	Parkfield - Temblor	6.0	12.29	524.69	15.57	0.22	0.19	0.12
4284	Basso Tirreno-Italy	1978	Naso	6.0	17.15	620.56	28.47	0.23	0.33	0.16
6057	Big Bear-01	1992	Highland Fire Station	6.4	26.18	362.39	28.83	0.22	0.11	0.17
6875	Joshua Tree-CA	1992	Morongo Valley Fire Station	6.1	21.73	396.41	31.90	0.09	0.09	0.06
6971	Darfield-New Zealand	2010	SPFS	7.0	29.86	389.54	42.31	0.18	0.24	0.10

Table A.4 Ground motion details for 1 in 975 years

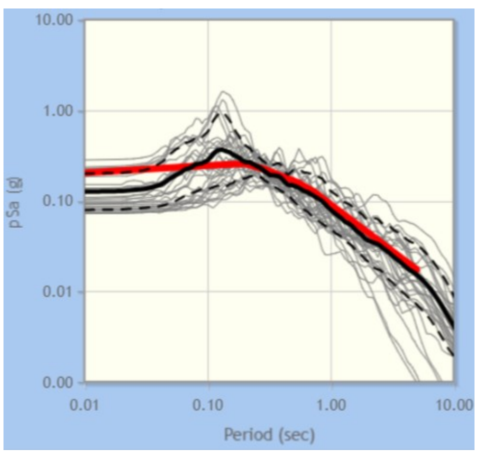
RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
471	Morgan Hill	1984	San Justo Dam (L Abut)	6.19	31.88	543.63	28.36	0.10	0.08	0.04
838	Landers	1992	Barstow	7.28	34.86	370.08	39.96	0.09	0.09	0.04
910	Big Bear-01	1992	Joshua Tree	6.46	40.99	379.32	59.96	0.10	0.09	0.07
1102	Kobe-Japan	1995	Chihaya	6.90	49.91	609.00	53.98	0.15	0.18	0.12
1619	Duzce-Turkey	1999	Mudurnu	7.14	34.30	535.24	28.82	0.17	0.09	0.09
1836	Hector Mine	1999	Twentynine Palms	7.13	42.06	635.01	59.96	0.11	0.12	0.07
2712	Chi-Chi-Taiwan-04	1999	CHY042	6.20	34.10	665.20	299.78	0.05	0.05	0.02
3870	Tottori-Japan	2000	HRS001	6.61	48.72	361.60	74.99	0.14	0.08	0.08
4054	Bam-Iran	2003	Mohammad Abad-e-Madkoon	6.60	46.20	574.88	139.99	0.05	0.07	0.04
6891	Darfield-New Zealand	2010	CSHS	7.00	43.60	638.39	199.99	0.09	0.11	0.07
8597	El Mayor-Cucapah-Mexico	2010	Sam W. Stewart	7.20	31.79	503.00	299.78	0.88	0.85	0.52

Table A.5 Ground motion details for 1 in 475 years

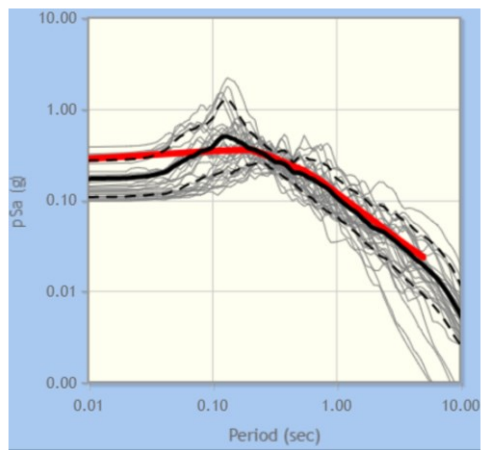
RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
891	Landers	1992	Silent Valley – Poppet Flat	7.2	50.85	659.09	54.96	0.10	0.08	0.08
910	Big Bear-01	1992	Joshua Tree	6.4	40.99	379.32	59.96	0.07	0.07	0.05
1785	Hector Mine	1999	Fun Valley	7.1	54.68	388.63	46.09	0.03	0.03	0.03
2714	Chi-Chi-Taiwan-04	1999	CHY046	6.2	38.11	442.15	109.99	0.06	0.06	0.02
4054	Bam-Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	74.99	0.11	0.06	0.06
4086	Parkfield-02-CA	2004	Templeton – hospital grounds	6.0	43.18	410.66	130.03	0.03	0.04	0.02
5830	El Mayor-Cucapah-Mexico	2010	Rancho San Luis	7.2	43.64	523.99	299.78	0.11	0.09	0.06
6948	Darfield-New Zealand	2010	OXZ	7.0	30.63	481.62	149.96	0.05	0.05	0.04
471	Morgan Hill	1984	San Justo Dam (L Abut)	6.1	31.88	543.63	139.99	0.07	0.06	0.02
557	Chalfant Valley-02	1986	Tinemaha Res. Free Field	6.1	50.92	467.62	199.99	0.03	0.04	0.02
1102	Kobe-Japan	1995	Chihaya	6.9	49.91	609	53.98	0.11	0.13	0.09

Appendix-B Ground motions selection based on ASCE 7-16

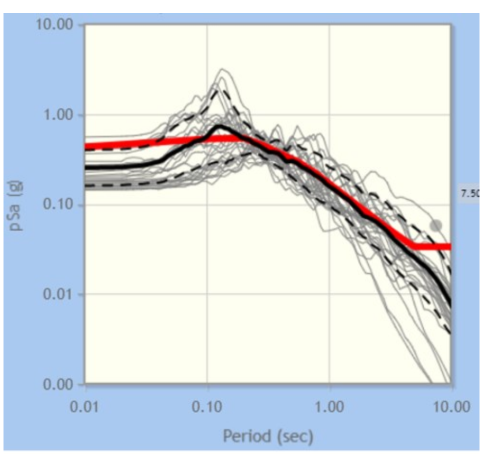
The ground motions for the Pine Flat Dam location were selected using the ASCE 7-16 method. Fifty-five ground motions were chosen, with eleven ground motions corresponding to each of five return periods: 1 in 10000 years, 1 in 5000 years, 1 in 2475 years, 1 in 975 years, and 1 in 475 years. The response spectra plots, including the target spectrum, suite mean, and spectra of individual ground motions for the selected ground motions across the return periods, are shown in Figures B.1. Similarly, Tables B.1 to B.5 provide the details of these ground motions, following the standard notations of the PEER database [253]. Section 5.3 of Chapter 5 outlines the procedure for selecting these ground motions. Each ground motion includes two horizontal components (H_1, H_2) and one vertical component (V). The peak ground acceleration (PGA) for each horizontal component is denoted as PGA_{H1} and PGA_{H2}, and the vertical component as PGA_V, in the units of (g). The ground motions were selected to represent eleven unique seismic events, covering a range of magnitudes and durations, to capture the record-to-record (RTR) variability for the location in consideration. The selection process also accounts for the effects of near- and far-field events. This comprehensive selection ensures that the ground motions adequately represent the seismic hazard at the Pine Flat Dam location.



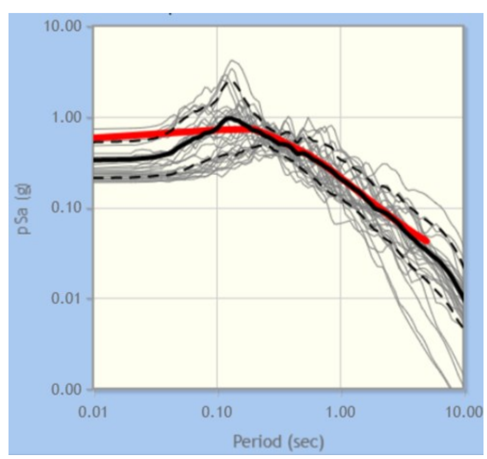
(a) 1 in 475 years



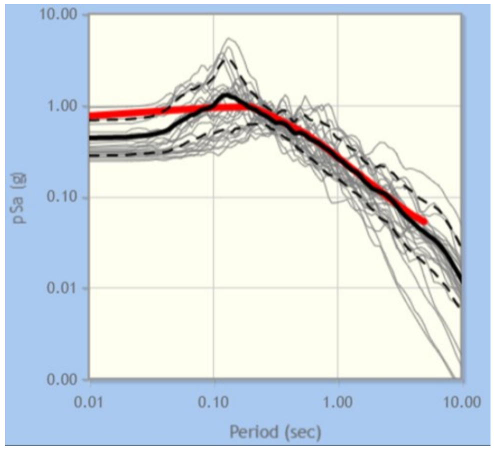
(b) 1 in 975 years



(c) 1 in 2475 years



(d) 1 in 5000 years



(e) 1 in 10000 years

Figure B.1 Spectra of suites of GMs based on ASCE 7-16

Table B.1 Ground motion details for 1 in 10000 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
454	Morgan Hill	1984	Gilroy - Gavilan Coll.	6.19	14.83	729.65	29.98	0.74	0.61	0.70
550	Chalfant Valley-02	1986	Bishop - Paradise Lodge	6.19	14.97	585.12	39.98	0.67	0.65	0.53
897	Landers	1992	Twentynine Palms	7.28	41.43	635.01	49.96	0.53	0.40	0.26
934	Big Bear-01	1992	Silent Valley - Poppet Flat	6.46	34.43	659.09	39.98	0.44	0.51	0.35
1102	Kobe-Japan	1995	Chihaya	6.9	49.91	609	53.98	0.35	0.42	0.28
1633	Manjil-Iran	1990	Abbar	7.37	12.55	723.9	53.48	0.29	0.28	0.30
1787	Hector Mine	1999	Hector	7.13	10.35	726	45.29	0.25	0.31	0.14
2709	Chi-Chi-Taiwan-04	1999	CHY035	6.2	25.01	573.04	89.99	0.22	0.26	0.09
3923	Tottori-Japan	2000	OKYH05	6.61	46.75	610.22	260.99	0.63	0.88	0.48
4054	Bam-Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	74.99	0.38	0.22	0.22
6891	Darfield-New Zealand	2010	CSHS	7	43.6	638.39	139.99	0.20	0.27	0.16

Table B.2 Ground motion details for 1 in 5000 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
454	Morgan Hill	1984	Gilroy - Gavilan Coll.	6.1	14.83	729.65	29.985	0.57	0.47	0.54
550	Chalfant Valley-02	1986	Bishop - Paradise Lodge	6.1	14.97	585.12	39.985	0.52	0.50	0.41
897	Landers	1992	Twentynine Palms	7.2	41.43	635.01	49.96	0.41	0.31	0.20
934	Big Bear-01	1992	Silent Valley - Poppet Flat	6.4	34.43	659.09	39.98	0.34	0.40	0.27
1102	Kobe_ Japan	1995	Chihaya	6.9	49.91	609.00	53.98	0.27	0.32	0.22
1787	Hector Mine	1999	Hector	7.1	10.35	726.00	45.29	0.19	0.24	0.11
2709	Chi-Chi_ Taiwan-04	1999	CHY035	6.2	25.01	573.04	89.99	0.17	0.20	0.07
3923	Tottori_ Japan	2000	OKYH05	6.6	46.75	610.22	260.99	0.48	0.67	0.37
4054	Bam_ Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	74.99	0.29	0.17	0.17
4284	Basso Tirreno_ Italy	1978	Naso	6.0	17.15	620.56	139.99	0.27	0.24	0.15
6891	Darfield_ New Zealand	2010	CSHS	7.0	43.6	638.39	139.99	0.16	0.20	0.12

Table B.3 Ground motion details for 1 in 2475 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
454	Morgan Hill	1984	Gilroy - Gavilan Coll.	6.1	14.83	729.65	29.98	0.43	0.35	0.41
550	Chalfant Valley-02	1986	Bishop - Paradise Lodge	6.1	14.97	585.12	39.98	0.39	0.38	0.31
897	Landers	1992	Twentynine Palms	7.2	41.43	635.01	49.96	0.31	0.23	0.15
934	Big Bear-01	1992	Silent Valley - Poppet Flat	6.4	34.43	659.09	39.98	0.26	0.30	0.20
1102	Kobe_ Japan	1995	Chihaya	6.9	49.91	609.00	53.98	0.20	0.24	0.17
1787	Hector Mine	1999	Hector	7.1	10.35	726.00	45.29	0.14	0.18	0.08
2709	Chi-Chi_ Taiwan-04	1999	CHY035	6.2	25.01	573.04	89.99	0.13	0.15	0.05
3923	Tottori_ Japan	2000	OKYH05	6.6	46.75	610.22	260.99	0.37	0.51	0.28
4054	Bam_ Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	74.99	0.22	0.13	0.13
4284	Basso Tirreno_ Italy	1978	Naso	6.0	17.15	620.56	139.99	0.21	0.18	0.11
6891	Darfield_ New Zealand	2010	CSHS	7.0	43.60	638.39	139.99	0.12	0.15	0.09

Table B.4 Ground motion details for 1 in 975 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
454	Morgan Hill	1984	Gilroy - Gavilan Coll.	6.1	14.83	729.65	29.98	0.29	0.24	0.28
550	Chalfant Valley-02	1986	Bishop - Paradise Lodge	6.1	14.97	585.12	39.98	0.27	0.26	0.21
897	Landers	1992	Twentynine Palms	7.2	41.43	635.01	49.96	0.21	0.16	0.10
934	Big Bear-01	1992	Silent Valley - Poppet Flat	6.4	34.43	659.09	39.98	0.18	0.20	0.14
1102	Kobe_ Japan	1995	Chihaya	6.9	49.91	609.00	53.98	0.14	0.17	0.11
1836	Hector Mine	1999	Twentynine Palms	7.1	42.06	635.01	59.96	0.13	0.13	0.08
2709	Chi-Chi_ Taiwan-04	1999	CHY035	6.2	25.01	573.04	89.99	0.09	0.10	0.03
3923	Tottori_ Japan	2000	OKYH05	6.6	46.75	610.22	260.99	0.25	0.35	0.19
4054	Bam_ Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	139.99	0.15	0.09	0.08
4284	Basso Tirreno_ Italy	1978	Naso	6.0	17.15	620.56	28.97	0.14	0.12	0.07
6891	Darfield_ New Zealand	2010	CSHS	7.0	43.60	638.39	139.99	0.08	0.10	0.06

Table B.5 Ground motion details for 1 in 475 years

RSN	Earthquake Name	Year	Station Name	M	R_{jb} (km)	V_{s30}(m/s)	$Duration(s)$	PGA_{H1}	PGA_{H2}	PGA_V
454	Morgan Hill	1984	Gilroy - Gavilan Coll.	6.1	14.83	729.65	29.98	0.22	0.18	0.21
550	Chalfant Valley-02	1986	Bishop - Paradise Lodge	6.1	14.97	585.12	39.98	0.20	0.19	0.15
897	Landers	1992	Twentynine Palms	7.2	41.43	635.01	49.96	0.15	0.11	0.07
934	Big Bear-01	1992	Silent Valley - Poppet Flat	6.4	34.43	659.09	39.98	0.13	0.15	0.10
1102	Kobe_ Japan	1995	Chihaya	6.9	49.91	609.00	53.98	0.10	0.12	0.08
1836	Hector Mine	1999	Twentynine Palms	7.1	42.06	635.01	59.96	0.10	0.10	0.06
2709	Chi-Chi_ Taiwan-04	1999	CHY035	6.2	25.01	573.04	89.99	0.06	0.07	0.02
3923	Tottori_ Japan	2000	OKYH05	6.6	46.75	610.22	260.99	0.18	0.26	0.14
4054	Bam_ Iran	2003	Mohammad Abad-e-Madkoon	6.6	46.2	574.88	139.99	0.11	0.06	0.06
4284	Basso Tirreno_ Italy	1978	Naso	6.0	17.15	620.56	28.97	0.10	0.09	0.05
6891	Darfield_ New Zealand	2010	CSHS	7.0	43.60	638.39	139.99	0.06	0.08	0.04

Appendix-C Tensile damage plots

Figures C.1 and C.2 illustrate the tensile damage plots derived from a total of 220 simulations, i.e., 110 simulations for each ground motion selection method, CMS, and ASCE 7-16. Each figure displays 110 tensile damage plots across five return periods. Within each return period, the plots are organized into two rows, with 22 simulations per return period, and are labeled accordingly. The plots show the extent of damage within the dam body resulting from the exceedance of the tensile strength of concrete during the seismic event. These plots provide the area of damaged elements for estimating the Damage Area Ratio (DAR), as discussed in Section 5.6.2 of Chapter 5. One key observation is that ground motions associated with longer return periods, such as those occurring every 5000 or 10000 years, tend to induce more substantial damage. This pattern holds for both ground motion selection methods, ASCE 7-16 and CMS. Interestingly, when comparing these methods, it becomes evident that CMS, in particular, leads to comparatively greater damage across the different return periods. What adds an intriguing dimension to this assessment is the finding that, even in the case of shorter return periods, such as 975 and 2475 years, there are instances of significant damage. This underscores the critical importance of conducting performance evaluations across a spectrum of return periods and employing a diverse set of ground motions. Such an approach enables us to capture the nuanced variations in seismic hazard levels both within and between different return periods. Moreover, this investigation serves as a reminder of the pivotal role played by the careful selection of ground motion methods. The choice between ASCE 7-16 and CMS can yield notably distinct results in terms of the damage incurred by the dam. Therefore, this decision should be made judiciously, considering the specific objectives and safety considerations of the dam's design and maintenance.

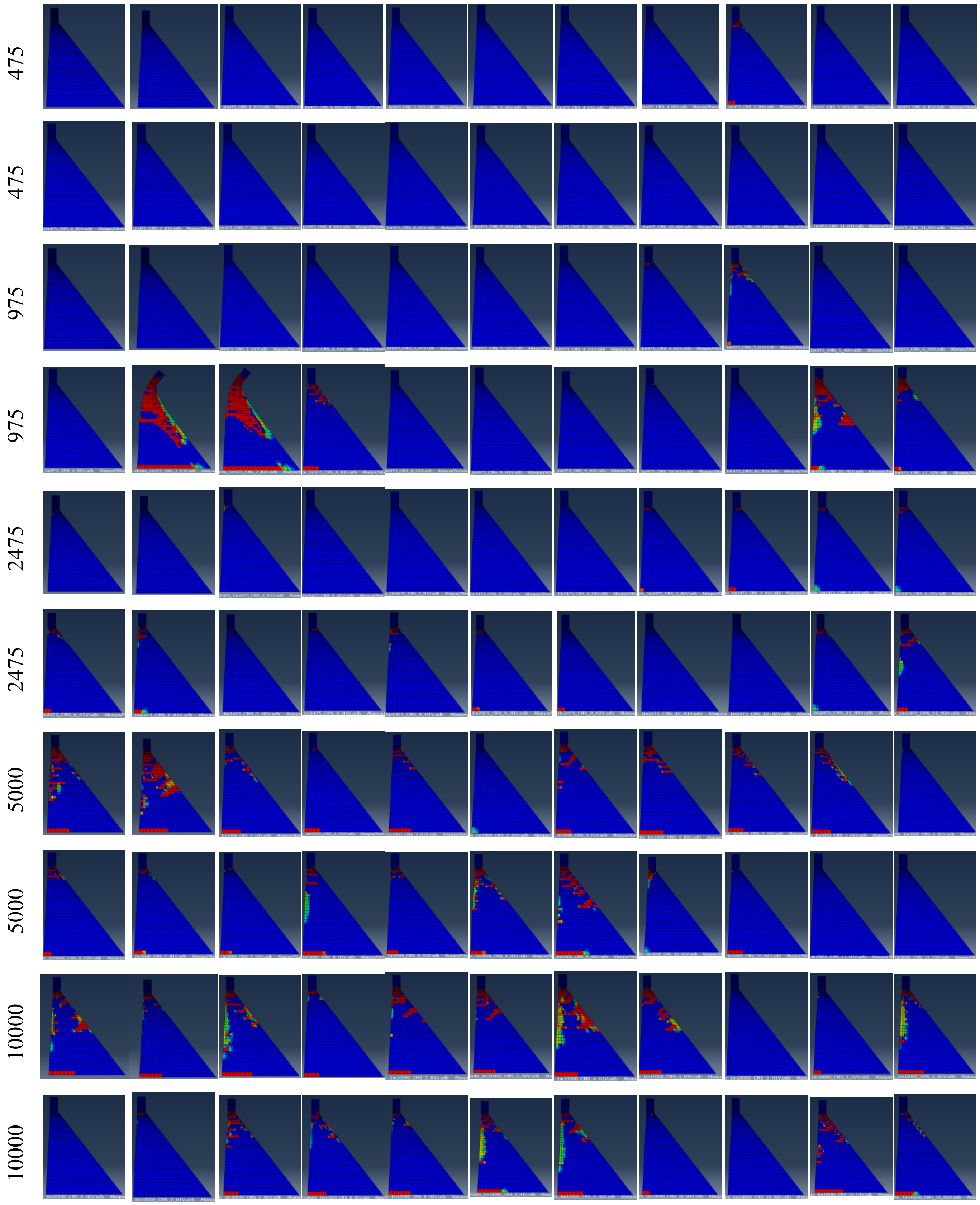


Figure C.1 Tensile damage plots of the dam subjected to CMS-based ground motion

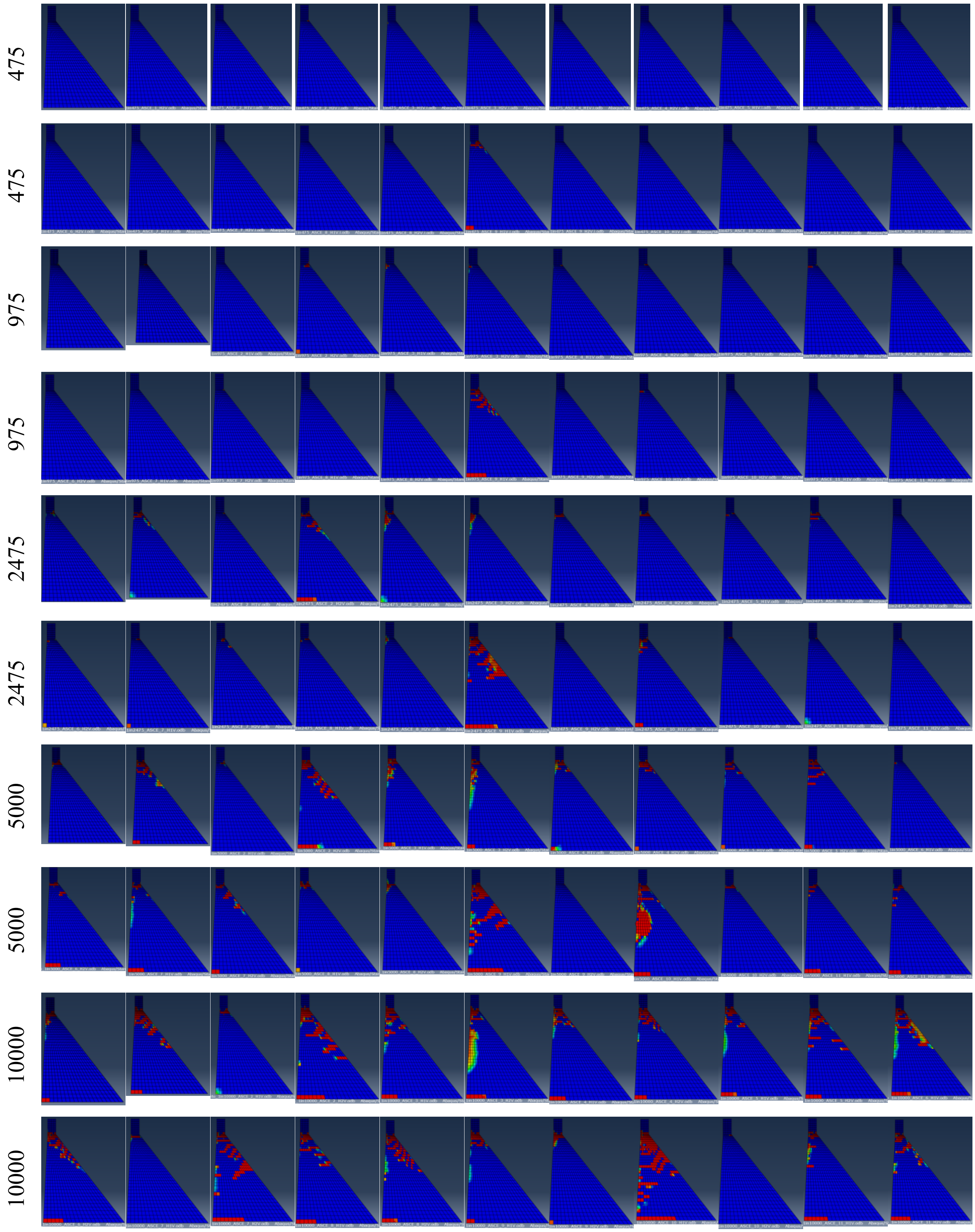


Figure C.2 Tensile damage plots of the dam subjected to ASCE 7-16 based ground motion