THE FUNDAMENTAL CONCEPT OF FRAGILITY ANALYSIS FOR THE PERFORMANCE OF DAMS UNDER THE EFFECT OF EARTHQUAKES

Thulfiqar S. Hussein[1], Mariyana Aida Ab Kadir[2], Ayad Al-Yousuf [3], Mohammed Abbas Mousa [4], Lateef N. Assi *[5], and Mohd Zamri Ramli [6]

[1] Student, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia: Thulfiqar.hussein@qu.edu.iq
[2] Professor, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia: Mariyanaida@utm.my
[3] Professor, Department of Civil Techniques, Technical Institute of Basrah, Southern Technical University, Iraq, e-mail: Ayad.Alyousuf@st.edu.iq
[4] Student, School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Malaysia: Mohammed.mousa@qu.edu.iq
[5] Assoc Professor, Al Ayen University, Nasiriyah, Iraq: xx2@yy2.com
[6] Professor, Institute of Noise and Vibration, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia,81310, Bahru, Johor, Malaysia: mohdzamri@utm.my

***Corresponding Author**

ABSTRACT

According to the new motivation for probabilistic studies of concrete dams, the few past researchers seeking to remedy this timely subject, and the multiple methodologies utilized to collect data to generate fragility curves, a complete evaluation of the disparate prior work is required. Since seismic vulnerability analysis is fundamentally a probability analysis technique that contains uncertainties that affect the performance evaluation, like material properties (epistemic uncertainties) and the randomness of earthquake ground motions (aleatory uncertainties), these uncertainties reflect the degree of fuzziness in the analysis. Consequently, this research provides an exhaustive and comparative evaluation of significant (post-2015) works regarding seismic vulnerability analyses of concrete dams. Primarily, foundational topics are defined and explained to improve knowledge of the subsequent sections. Then, publications are evaluated individually, and their results are summarised to offer a standard basis for comparison. Next, the tables, summarise the numerous methodologies, provided, from which the authors derive the minimal criteria for seismic vulnerability curve development. Moreover, a flowchart depicts all the processes necessary to derive fragility curves relying on the performance-based engineering aspect of concrete dams.

Keywords: *Fragility Analysis, Earthquakes, Concrete Dams, Seismic Vulnerability Analysis*

1. INTRODUCTION

Dams are a vital resource for people in various parts of the globe. They may simultaneously serve many purposes, like water supply, flood control, recreation, and clean, renewable energy production via hydropower [1]. Thousands of dams throughout the globe have the potential to fall with catastrophic results. Dams are inherently risky constructions. According to the Association of State Dam Safety Officials [2], failure or improper operation may lead to the discharge of the reservoir's contents, including water, mining, and agricultural waste. There are roughly 16,500 dams with a high potential for danger in the United States as of 2021[3]. In addition to posing a threat to public safety, dam breaches may cost our economy millions of dollars in damages. In one recent year, dam breaches in 23 states resulted in downstream repair expenses totaling $54.3 million [4]. There are more than 2,330 defective dams with a high potential for danger. Without the necessary improvements and maintenance, these dams cannot be expected to resist the predicted floods and earthquakes.
However, dams must be repaired or upgraded because of degradation, changing technical requirements, and changes in downstream populations or land use [5]. The age of a dam is an indirect indication since older dams were not constructed to current standards. Some older dams are deemed in lousy condition only for this reason, whereas others may have been poorly maintained. The existing technique based on dams' Potential Failure Mode Analysis (PFMA) [6, 7] may not be enough and must be expanded. This critical issue in dams is, thankfully, amenable to various solutions. PBEE-Performance Based Earthquake Engineering is a novel probabilistic approach officially adopted by the Federal Emergency Management Agency (FEMA) and was primarily responsible for its development in the California construction and bridge industries[8]. The fragility curve is an essential indicator of the probabilistic safety evaluation that results from the combination of (PFMA) and (PBEE) suggested by Hariri-Ardebili [9]. The seismic fragility analysis contains uncertainties that influence the performance evaluation, such as material properties and the randomness of ground motions. The threshold between neighbouring Damage States (D.S.) should be uncertain since the development of (D.S.) for a structure is a progressively transitioning operation [10]. If the threshold's fuzziness is ignored, an erroneous estimate of (D.S.) may result. Until now, there has not been any review article about dams fragility analysis that focuses on the effect of fuzzy intervals for damage state thresholds and membership functions of damage indexes DIs belonging to a damaged state DS. The previous reviews only focused on the uncertainty resulting from the randomness of recorded earthquakes, material properties, and modelling. However, they did not cover this vital area, such as fuzzy intervals' effect on damage state thresholds, which makes this review critical. In summary, most research studies have been observed to rely on linear analyses using simple damage states. Few papers, furthermore, adopted a nonlinear strategy and explored the process of collapse and hybrid limit state (LS) concepts. Aside from this, the effect of the limit states threshold's fuzziness on the seismic vulnerability of concrete dams has not yet been investigated.
Therefore, the purpose of this research is to review the stated fragility analyses for concrete dams and to demonstrate the uncertainty considered in each study to identify the unresearched aspect and emphasize it in future research. Before that, the concept's essential foundations will be revealed to help understand the exhaustive and comparative investigation. Tables showing the summary of the various related articles will be presented.

2. THE NEXT-GENERATION OF PERFORMANCE-BASED EARTHQUAKE ENGINEERING (PBEE)

PBEE is the tools and procedures developed by the United States that represent a radical departure from standard seismic design practices and performance evaluation. Each step of the performance evaluation process will contain randomness and uncertainty [11, 12].
Four steps to evaluate the effectiveness of structures based on earthquake engineering are depicted in Figure 1 [13]. The Hazard Analysis is the first step. The position (relative to a fault), prerecorded earthquake magnitude, geotechnical conditions (shear wave velocity), rupture mechanism, rupture area size, rock properties, and crustal rock damping characteristics are all identified through probabilistic seismic hazard analysis (PSHA). The analysis gives the measurement for the seismic ground motion property known as (λ_{IM}) the rate of yearly exceedance of the earthquake motion size against intensity

measure (IM) and the (λ_{IM}) can be determined by Equation **Error! Reference source not found.**. Where (λ) is the opposite of the return period (T_R) at given earthquake intensity levels as defined by Poisson's probability and (P_E) is the likelihood that at least one event will occur during the lifetime (t).

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

The second step involves structural analysis. Seismic excitations were gathered, and dynamic analysis using aleatory (earthquake motion record to record variability) and epistemic (modelling and material) uncertainties could now be conducted. The obtained seismic excitation can be known as a structural reaction. Table 1 summarises this kind of investigation's different degrees of complexity [13]. The third step is Damage Analysis which must establish fragility curves. Loss Analysis is the final step in assessing the performance of dams, in which monetary damages associated with losses of life and damage must be evaluated depending on the results of the preceding step [13]. Multiple seismic excitations are necessary for fragility analysis, and four unique nonlinear approaches may provide this criterion.

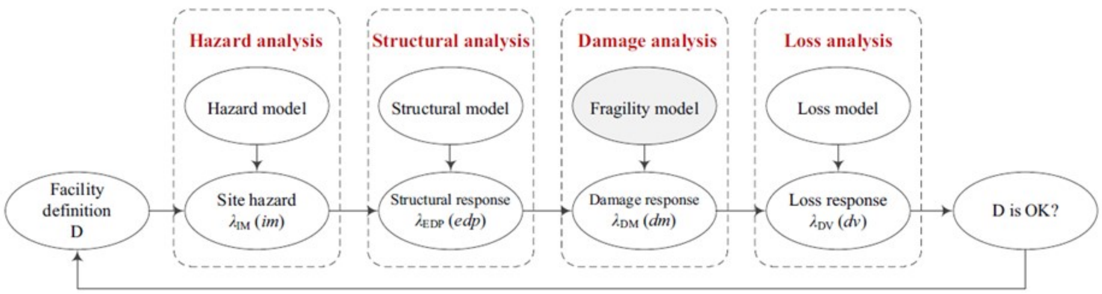

Figure 1 The overall Structure of PBEE-2 [14]

2.1 Multiple stripe analysis (MSA)

MSA is a nonlinear dynamic analysis that, as its name suggests, indicates a collection of (stripe) analyses conducted in several spectral acceleration levels, in which a stripe evaluation contains structural analyses for a set of earthquake motions, scaled to the popular spectral acceleration. Ideally, every stripe analysis's collection of ground motions must reflect the earthquake danger at the appropriate spectral acceleration [15]. MSA is generated by identifying seismic intensity levels (m) and then selecting and scaling earthquake ground motion (n) for each seismic intensity level. A stripe's specified earthquake ground movements may or may not be identical. However, the chosen ground motions are often distinct because of diverse reaction spectra in varying seismic intensity levels [16]. Typically, $(m \geq 3)$ correlates to multiple stripe analysis (MSA), whereas $(m = 1)$ & $(m = 2)$ that referred to as single & double stripe evaluation, separately. Stripe analysis results may be shown using discrete data points in an IM-EDP coordinate system (EDP meaning engineering demand parameter). The findings are expected to have a log-normal distribution inside every stripe.

2.2 IDA-Incremental Dynamic Analysis

IDA takes into account (n) distinct earthquake motions, each of which is scaled gradually (m) time till failure happens. Prior (m) is an unknown value, and any earthquake motion (n) will cause a structural failure at a particular seismic level of intensity [17]. The IDA curve links the derived (m) demand parameters for each of the (n) earthquake ground movements after the analysis. Each of these curves will asymptotically approach the respective failure. The associated probability distribution may be used to calculate the capturing of the whole responses by a single measurement quantity at a particular intensity measure IM $(IM = im_i)$.

2.3 Endurance Time Analysis (ETA)

The approach begins with a single artificial acceleration function with an amplitude that rises with time. That rising amplitude of a single earthquake ground motion is used in place of successive series of earthquake ground movements, which have constant amplitudes but grow in magnitude. Therefore, Endurance Time Analysis (ETA) might be considered an easy process. For every time interval, it is possible to construct a single artificial acceleration function that meets the following relations:

$$S_a(T.t) = \frac{t}{t_{trg}} S_a^{trg}(T) \qquad 2$$

$$PGA\ (T) = \frac{t}{t_{trg}} PGA^{trg} \qquad 1$$

$$S_d(T.t) = \frac{t}{t_{trg}} S_d^{trg}(T) \qquad 2$$

Where (PGA) is the peak ground acceleration, (t_{trg}) is the goal time, typically $(10\ s)$ [18], $S_d(T.t)$ is the spectral displacement at time (t) and period (T), and $S_a(T.t)$ is the spectral acceleration at time (t) and period (T). Take note that the term (trg) indicates the goal value of the quantity being evaluated.

2.4 Cloud Analysis (CLA)

CLA is a numerical process in which a dam is first exposed to a series of normal earthquake ground movements and then numerically assessed. If the earthquake motion recordings are gathered from a bin, they may depict a seismic case described by (M_{bin}, R_{bin}), where M_{bin} and R_{bin}, is the typical magnitude and distance for the bin [19]. Afterward, the so-called cloud reaction is computed by comparing $(EDP\ vs\ IM)$. Cloud Analysis (CLA) is frequently used in conjunction with probabilistic seismic demand analysis [20].

Table 1 Methodology for progressive study of concrete dams

Category	Popular	Method	Computational Effort	Overall Capability
Probability Deterministic Analysis Based Earthquake Engineering	Wide-Range Analyses	Multiple-Stripe Analysis	High	High
		Incremental Dynamic Analysis	Very High	Very High
		Endurance Time Analysis	Low	High
	Narrow-Range Analyses	Single-Stripe Analysis	Moderate	Very Good
		Double-Stripe Analysis	Moderate	Very Good
		Cloud Analysis	Moderate	Very Good
Nonlinear Static Analysis		Pushover Analysis (POA)	Moderate	Very Good
		Displacement Ductility Method	Moderate	Very Good
Deterministic Analysis		Nonlinear Time-History Analysis	Low	Very Good
		Linear Time-History Analysis	Low	Good
		Equivalent Lateral Force Method	Low	Moderate
		Response Spectrum Method	Low	Moderate
		Seismic Coefficient Method	Low	Low

3. FRAGILITY ANALYSIS

The goal of damage analysis is to determine vulnerability curves. Seismic fragility is often described as the likelihood that a particular boundary state (Limit States) will surpass a specified level of intensity measure of ground motion (IM). Light, moderate, severe damage, and collapse are examples of limit states. These are evaluated from either engineering demand parameters (EDP) or damage index (DI), and intensity measures are not restricted to peak ground acceleration (PGA) severity, as they may contain a spectral acceleration $S_a(T)$ or Arias intensity (I_A). Consequently, The fragility function calculates the conditional chance of surpassing specific damage states (d_i) at a given ground motion intensity, as explained in Equation 3.

$$\boldsymbol{P = P[D \geq d_i | IM = im]} \qquad (3)$$

Where P is the likelihood of surpassing damage (D) at a given ground motion $(IM = im)$. As stated in the preceding section, limit states (i) are specified here from slight to severe damage states. Typically, a log-normal cumulative distribution function describes the vulnerability function [21, 22].

$$\boldsymbol{P(\geq d_i) = \phi\left(\frac{\ln(X - \alpha)}{\beta}\right)} \qquad (4)$$

Where X is the ambiguous excitation, it is often expressed as an (IM), but in some cases, it may take the form of a safety factor. β and α are, respectively, the standard deviation and mean of $\ln X$, and Φ is the standard normal distribution. According to [23], Figure 2 (a) and (b) illustrate The fragility curves for PGA by taking into account the average values of the damage index for every limit state and the fragility curves for the crest displacements of a concrete dam, respectively. There are four common techniques to derive fragility curves, as mentioned in Table 2, which presents a comparative evaluation of techniques [13, 24].

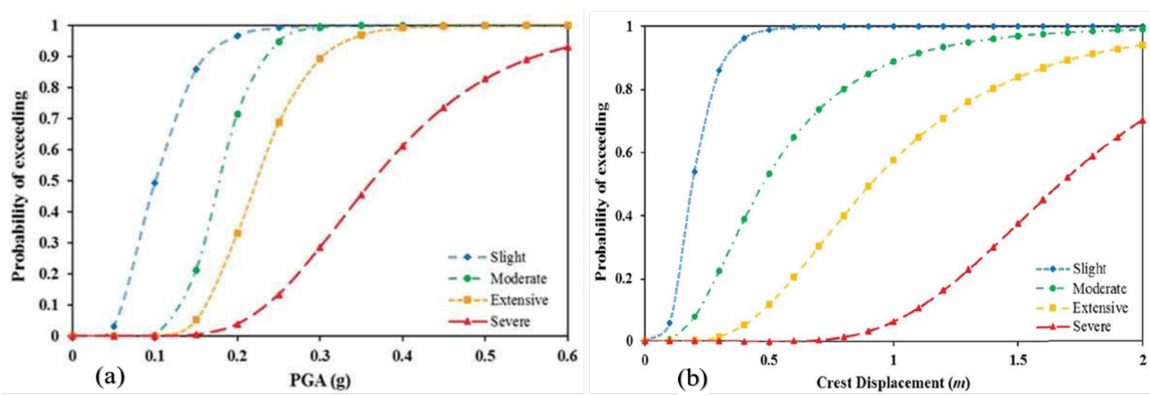

Figure 2 (a) Probability of exceeding against PGA. (b) Probability of exceeding against crest displacement.

3.1 Empirical Technique

This technique involves the site specifications based on the physical model results. It is based on post-earthquake surveys, which are often trustworthy, site-specific, and geotechnical sources; hence, it lacks generalizability [25-27]

3.2 Heuristic Technique

This strategy is based on the request for expert opinion when empirical evidence of damage is insufficient [13]. Since experimental findings offer a foundation for identifying multiple damage measures in analytical vulnerability curves, the applicability of experimental fragility curves is limited by the shortage of appropriate data points at all damage states and a low association among geometrical and structural properties [28]. There are instances of suggested expert points of view on infrastructure vulnerability curves in California [29].

3.3 Analytical Technique

Structural analysis, which is based on static and dynamic techniques, forms the basis for the analytical strategy. This procedure is more reliable than its predecessor [13, 30, 31].

3.4 Hybrid method

This strategy uses the abovementioned data to reduce computational effort [32-35].

Table 2 Comparison of techniques in developing vulnerability curves

Technique	Disadvantages	Advantages
Heuristic	Insufficient data. Its definitions of DSs are subjective. The relationship between geometry and structural characteristics is weak.	It Provides the real damage state.
Empirical	Insufficient data. Specific to a region and a structure. Inconsistency in the damage assessment.	Depict a true-to-life image. It demonstrates the real fragility.
Analytical	Cost of computation. Costly in time. Selection of an analysis method. DSs explanation. It must be choosing a probability distribution function.	Improved reliability. All kinds of uncertainty are considered. Less skewed.
Hybrid	Numerous data sources are needed. Damage data extrapolation. The model of demand has Significant variance.	It combines analytical and experimental observation. It Includes damage information from the post-quake survey. Less computational work.

4. THE REVIEW OF THE CURRENT APPLICATIONS

Numerous applications are now working on various projects; some of these applications, along with the research, are given in this part and categorized according to dam type as follows:

4.1 The Gravity Dams

A gravity dam is a structure designed to resist loads by its weight and by resisting sliding and toppling on its foundation. This style of the modern dam is often built of unreinforced concrete monoliths with sealed joints. Due to prior design methods, dams might be vulnerable to seismic occurrences in the future. It is crucial to identify their susceptibility as a result. By providing assertions of the conditional likelihood of reaching a limit state, seismic fragility curves enable a reasoned assessment of the safety and fragility of existing buildings under earthquake threats. Numerous scholarly studies have been conducted on the seismic vulnerability of gravity dams.

Bernier et al. [36] developed the fragility curves utilizing the nonlinear time history analysis for determining the limits of every damage state for a concrete gravity dam based on two failed modes (base sliding and neck sliding), and uncertainties in modelling parameters and earthquake motions are also incorporated and propagated using Latin Hypercube Sampling (LHS). The spatial variation of the angle of friction, which is frequently assumed to be constant in numerous studies, is incorporated into the analysis as a significant contribution of this paper. By including this information, the dam's susceptibility becomes more comprehensively understood, particularly in the context of catastrophic damage scenarios.The results indicated that spatial variation, specifically in the angle of friction, has a negligible effect on the dam's vulnerability but becomes critical at levels of severe damage. as illustrated in Figure 3.

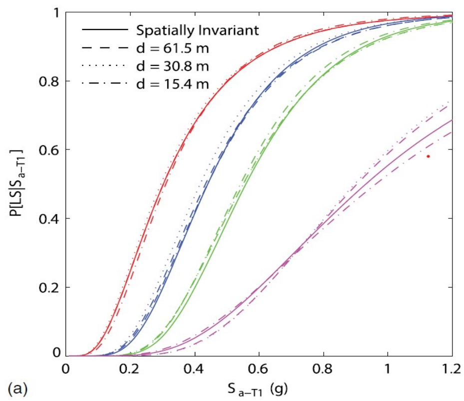

Figure 3 Spatial variation of the angle of friction in fragility curves for (a) base sliding and (b) neck sliding

Hariri-Ardebili & Saouma [37] classified information models (IMs) and provided guidelines for choosing the most optimal IM. However, they did not take into account epistemic difficulties. Subsequently, an examination was conducted on the Pine Flat concrete gravity dam to determine its damage states. This examination focused on engineering demand parameters (EDP) such as displacement, joint opening, and sliding. Cloud analysis (CLA) was employed to analyze the data. Additionally, a fragility curve was developed to represent the probability of EDP exceeding a certain threshold in relation to the intensity measure (IM) parameter. Figure 4 depicts the fragility curves based on joint opening and sliding extent.

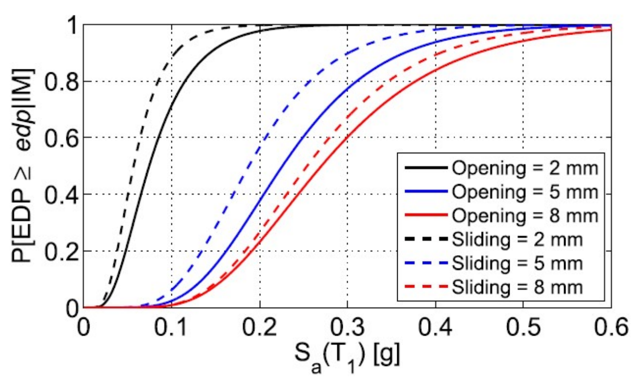

Figure 4 Comparing fragility curves using the intensity measure parameter.

Bernier et al. [38] Consider epistemic and aleatory uncertainties while proposing the usage of records selected with the Conditional Spectrum (CS) approach within a multiple stripes analysis (MSA) and incremental dynamic analysis (IDA) to establish the limits of each DS for a gravity dam based on two failed modes (base sliding and neck sliding). The paper utilizes the CS technique to select records in dam fragility analysis, demonstrating that it results in improved accuracy and reduced estimations of structural response and fragility. The process involves creating fragility curves for limit states of sliding at the base or within the dam using a multiple stripes analysis, as depicted in Figure 5. This approach minimizes the requirement for considerable screening and computational work, while highlighting the significance of accurately calculating modeling parameters.

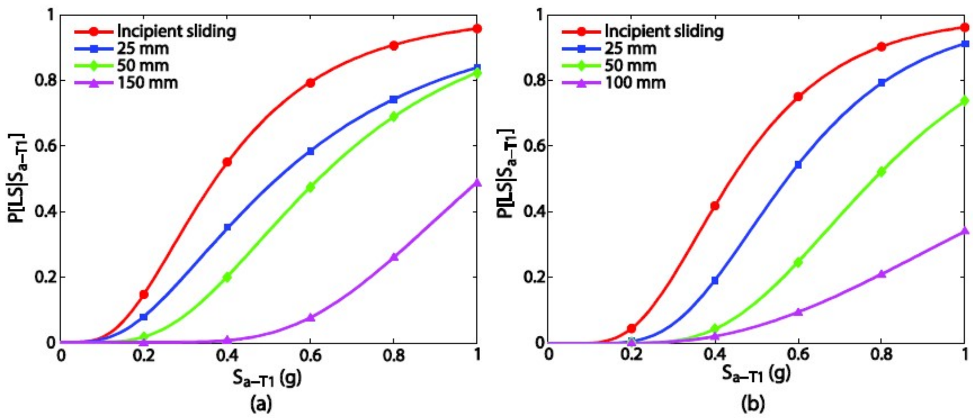

Figure 5 fragility curves for (a) base slipping and (b) neck slipping

Imteyaz Ansari and Pankaj Agarwal [23] presented novel interpretations of damage indices for identifying damage states based on the severity of cracking observed in a concrete gravity dam and the associated global instability conditions. Epistemic uncertainties were not considered in this analysis. Subsequently, fragility curves were constructed for various parameters of ground motion earthquakes, such as arias intensity, peak ground acceleration, destructiveness potential factor, and spectral acceleration, as depicted in Figure 6.

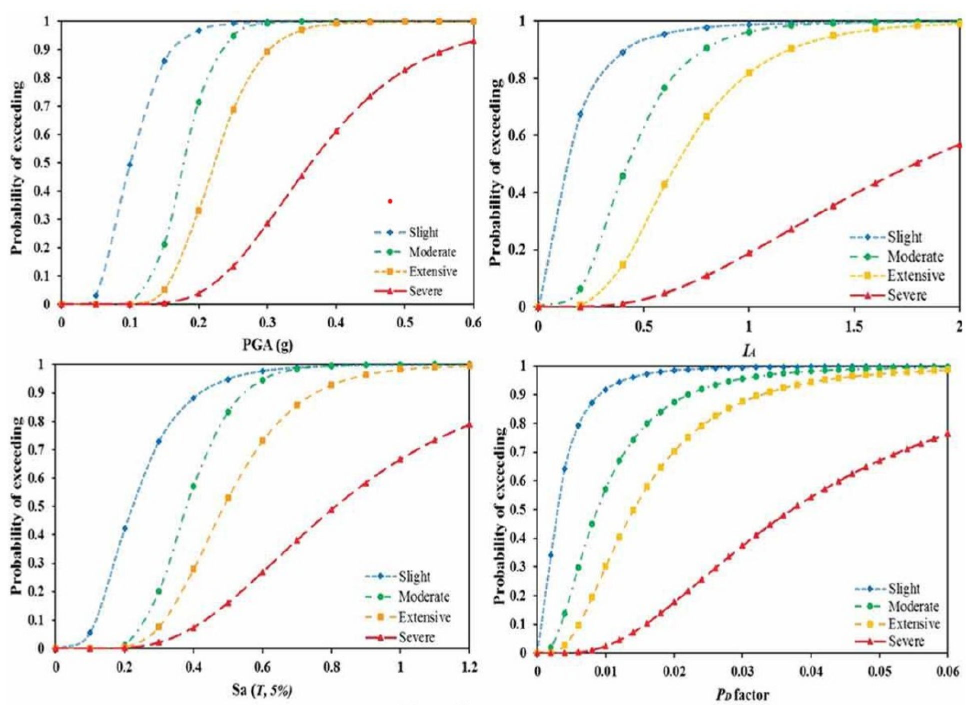

Figure 6 Fragility curves for arias intensity I_A, peak ground acceleration PGA, destructiveness potential factor P_D, and spectral acceleration Sa.

The research also examines the creation of a fragility function using crest displacement, which can work as a reliable health monitoring tool specifically designed for concrete gravity dams, as depicted in Figure 7.

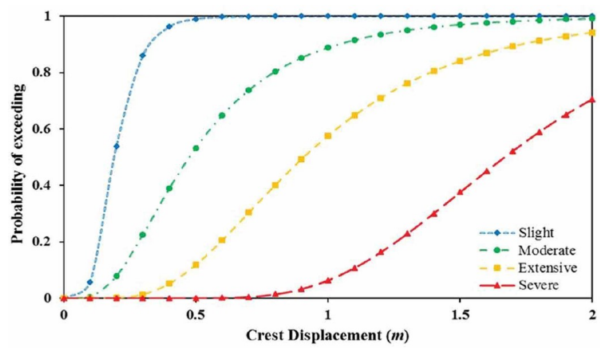

Figure 7 Fragility curve versus crest displacement as IM

Like that the impacts of re-entrant corners on the seismic performance of concrete gravity dams are explored, provided a potential remedy to the issue is also presented [39]. The findings suggest that re-entrant corners in the geometric Structure of dams can result in the accumulation of stress and the development of fractures in the dam body. This issue is of great importance to engineers and presents dangers to the stability of the dams during seismic occurrences.The work employs numerical modelling and simulations to investigate two distinct geometric configurations commonly found in high concrete gravity dams. Fragility curves and damage probability matrices are derived from empirical data on dam damages. The study also suggests a potential remedy to reduce the impact of re-entrant corners on the seismic behaviour of tall concrete gravity dams, as illustrated in Figure 8.

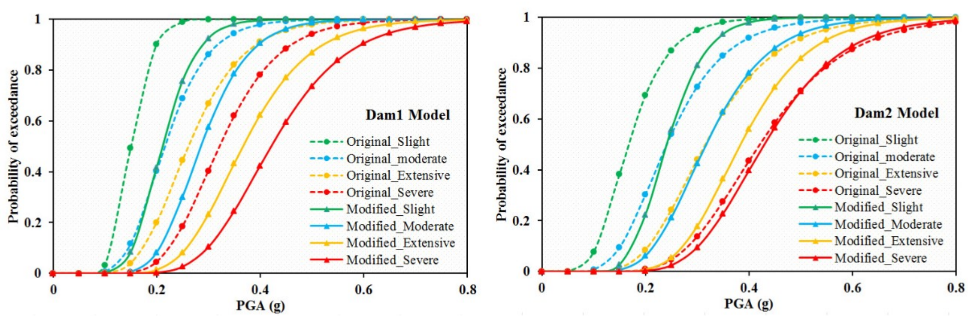

Figure 8 Fragility curve comparison between the original and modified dam models

According to Yazdani and Alembagheri [40], cloud analysis was used to generate the fragility curves (CLA), taking into account two kinds of near-field earthquake motions, comprising 60 non-pulse-like earthquake motions and 75 pulse-like earthquake motions, and creating IM-EDP relationships, an attempt is made to determine the optimal intensity measure that is most capable of predicting the limit states. The research emphasizes the significance of employing probabilistic seismic demand models (PSDMs) in conjunction with probabilistic seismic hazard analysis (PSHA) to evaluate seismic demands thoroughly. Prior research on vulnerability analysis of gravity dams has predominantly concentrated on seismic occurrences that occur at a distance, disregarding the inclusion of data from neighbouring fault lines. This work presents a novel method for evaluating the susceptibility of gravity dams located near fault zones, considering the ground vibrations occurring in the immediate vicinity. The researchers constructed a probabilistic seismic demand model (PSDM) by doing regression analysis on response data obtained from unscaled ground motions. The Structure undergoes nonlinear dynamic analysis utilizing a defined set of ground motions, resulting in the determination of engineering demand parameters (EDPs). Subsequently, fragility curves are generated to assess the seismic susceptibility of the dam, as depicted in Figure 9.

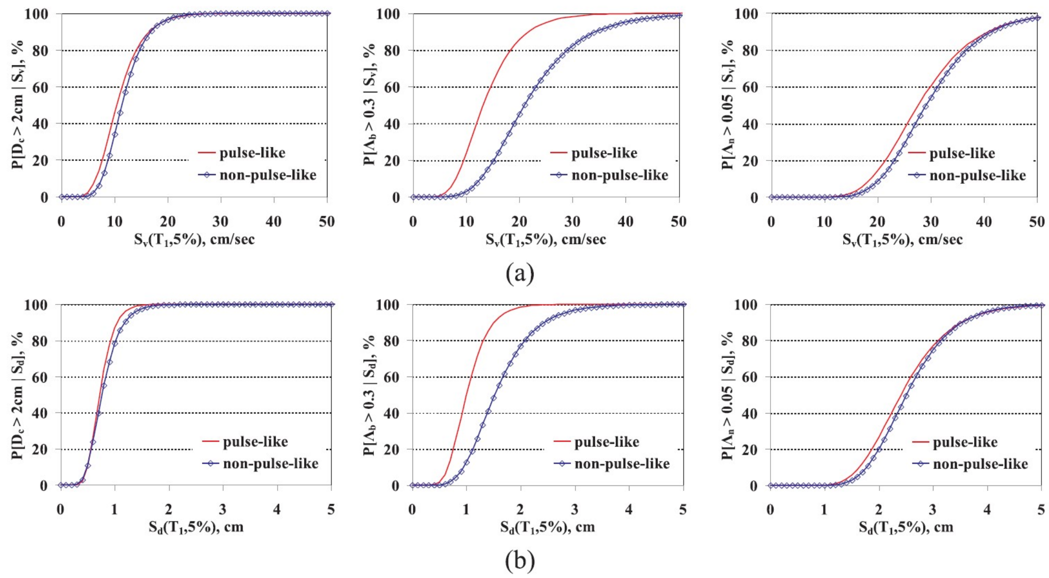

Figure 9 illustrates fragility curves with IM represented as (a) $S_v(T_1,5\%)$ and (b) $S_d(T_1,5\%)$. Records that are both pulse-like and non-pulse-like.

Sotoudeh et al. [41], this study aims to ascertain the Pine Flat dam's fragility curve by identifying particular Limit-States (LSs) associated with seismic performance. By integrating IDA and statistical analysis, a novel approach is utilized to ascertain the LS for each element using the Engineering Demand Parameter (EDP) values. As illustrated in Figure 10, the probabilistic performance of the dam is assessed through the construction of LS exceeding probability curves at various intensity measures utilizing three EDPs. The results illustrate the appropriateness of the specified LSs within a probabilistic framework, signifying a substantial progression in evaluating the seismic security of concrete gravity barriers.

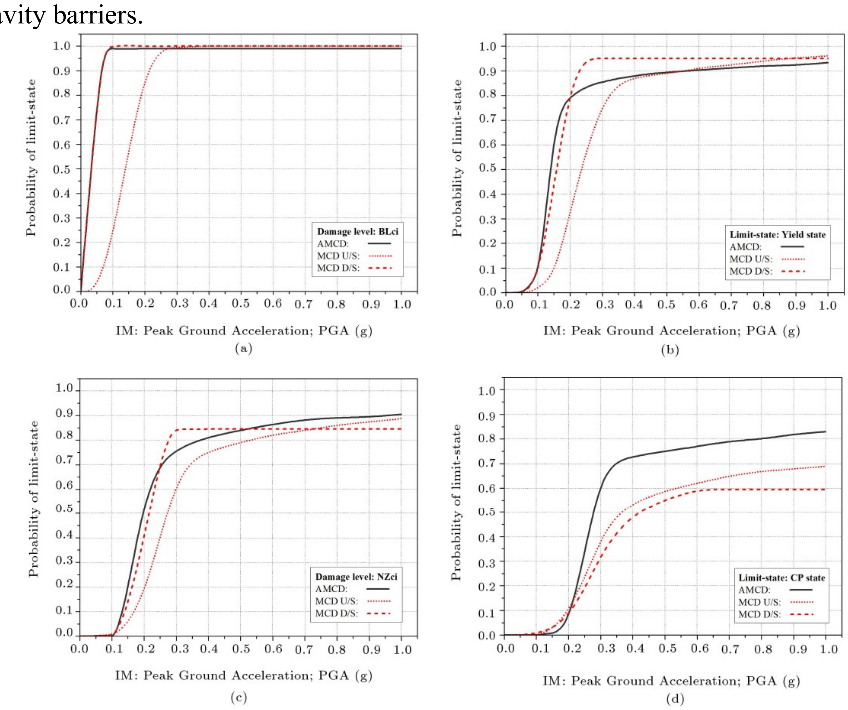

Figure 10 Fragility curves for LSs (a) LS1 is the limit state of BLci. (b) LS2 is the limit state of yielding. (c) LS3 is the limit state of NZci. (d) LS4 is the limit state of CP.

Segura et al. [42] present a methodology for precisely simulating and characterizing the uncertainties associated with determining the seismic risk of a dam-type structure. The article provides further details regarding the execution of fragility analysis. As illustrated in Figure 11, this entails the establishment of limit states, the execution of Incremental Dynamic Analysis (IDA) for a range of seismic intensity levels, and the generation of fragility curves utilizing a log-normal cumulative distribution function.

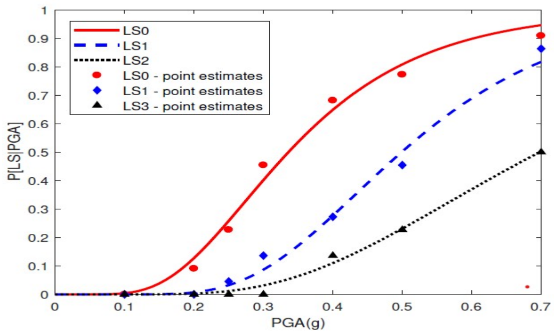

Figure 11 Fragility curves against intensity measure

Gavabar and Alembagheri [43], a novel damage index based on tensile cracking has been created, limit states have been specified, and fragility curves have been generated for three gravity dams with variable base width (L) and height (H), as shown in Figure 12. It was found that (L/H) ratio equals one and performs better under seismic excitation.

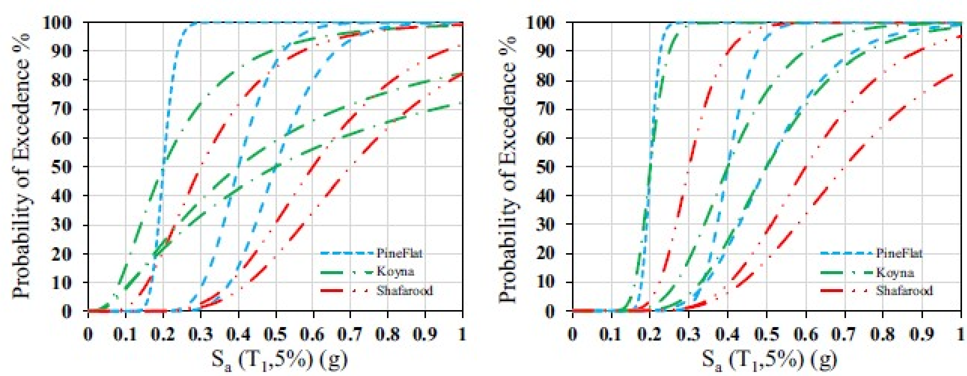

Figure 12 Fragility curves against intensity measure

Tidke and Adhikary [44] study evaluate the seismic sensitivity of the Koyna dam-reservoir-layered rock foundation system. It takes material nonlinearity models and foundation flexibility into account. Different intensities of ground motions are analyzed using Incremental Dynamic Analysis (IDA). Intensity metrics include Acceleration Spectrum Intensity (ASI), Peak Ground Acceleration (PGA), and Peak Ground Velocity (PGV). Fragility curves based on fracture length and dissipation energy are produced, and tensile crack failure in the dam is taken into consideration. The findings indicate that although dams with tougher rock layers are safer, those with more flexible rock layers are more vulnerable. PGV is not as good an indication of the seismic risk for gravity dams as PGA and ASI are for fragility analysis.

Li et al. [45], damage states threshold fuzziness is modelled mathematically. A fuzzy seismic vulnerability evaluation in the concrete dams, including spatial variability of material properties, is provided by combining nonlinear dynamic analysis of the dam-foundation-reservoir system, Hariri Ardebili's limit states [46], and a random field simulation approach, As illustrated in Figure 13.

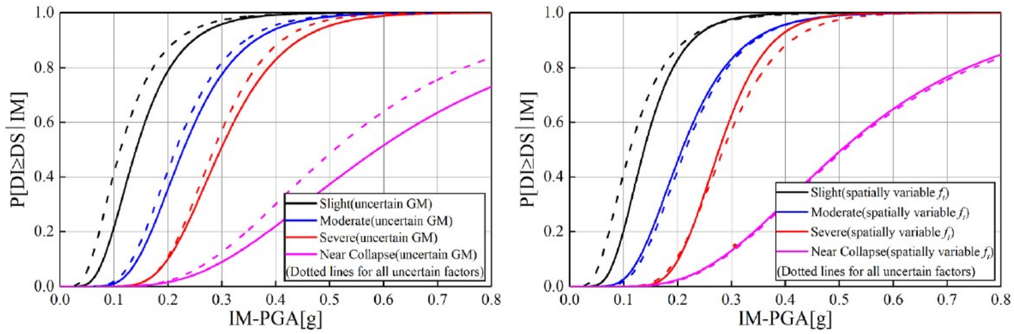

Figure 13 The gravity dam's fuzzy seismic fragility curves take into account the spatial variability of the tensile strength.

Sevieri et al. [47], This research proposes a strong Bayesian hierarchical frame for calibrating dynamic parameters of concrete dam mathematical models depending on the ambient vibrations, allowing an analyst to decrease epistemic uncertainty in seismic vulnerability derivation and analyze its effect on fragility curves. Li et al. [48], Checking the intensity measures and the replacement model for non-parametric vulnerability curves yields a computationally efficient method for many seismic waves. It incorporates the robust numerical method of earthquake damage to the dam-foundation-reservoir system, the exhaustive comparison of intensity measures, the replacement model for limit state categorization, and earthquake hazard analysis of gravity dam.

4.2 Arch Dam

Arch Dams have one curving concrete wall. They are arch-shaped with convexity upstream. Water pressure and other pressures are transferred to the abutments by the arch effect. Like a gravity dam, an arch dam's cross-section is triangular but thinner. Arch Dams work well in narrow, steep-sided valleys. Strong slope rock masses are needed to withstand arch activity [1]. If these structures fail to withstand loads, they unleash a tremendous amount of water, causing human and financial damage. Seismic assessment of such structures is difficult. Arch dam safety and practicality can be shown in numerous ways. Fragility curves are a modern method that demonstrates performance versus any random variable, such as dam water level or ground acceleration. Some studies have examined every dam's earthquake performance using fragility curves.

Kadkhodayan et al. [49], A thin, high-arched concrete dam is evaluated with the IDA approach. PGA, PGV, and Sa are intensity measures, whereas the overstressed area (OSA) is the engineering demand parameter. Then, using the IDA curves, three damage states are given to the investigated Structure, fragility curves are constructed, and it is proved that the PGA is a more appropriate parameter for IM. Hariri-Ardebili et al. [50] described a thorough approach for identifying and quantifying probable failure modes (PFM) of concrete dams subjected to seismic excitation. In the context of both linear and nonlinear investigations, a quantitative indicator of PFM is offered. As an illustration, a thin arch dam subjected to a series of ground vibrations at varying degrees of seismic energy is analyzed, and the related PFM is calculated. The probabilistic correlation among nonlinear and linear analyses and the discovery of the appropriate intensity measure parameter are outcomes of this investigation. Wang et al. [51] examined the seismic vulnerability of arched dams utilizing the dynamic damage evaluation model of dam-foundation-reservoir systems, which considers the opening of contraction joints, radiation damping of semi-unbounded foundation rock, and dam concrete damage cracking. 500 nonlinear damage analyses are done with epistemic and aleatory uncertainty using Monte Carlo simulation. Three limit states are presented depending on the computed joint opening and damage distribution, and seismic vulnerability curves are created using the IDA method. Liang et al. [52], A complete method described that considers the likely sliding rock mass of dam supports, the closing, and opening of contraction joints, the influence of foundation radiation damping, and the contact between the dam and its foundation. The Latin hypercube sampling approach creates uncertain and random parameters incorporating cohesions and friction coefficients. The estimated IDA is executed, and the sliding area ratios and slippage are selected as the engineer demand parameters. The sliding area ratio-based and slippage-based rules identify distinct damage levels depending on IDA curves. In addition, seismic vulnerability curves for the specified damage levels are created.

4.3 Concrete Face Rockfill Dams

A concrete face rock-fill dam (CFRD) is a kind of dam used for hydroelectric projects worldwide. Concrete slabs, supported and stabilized by the underlying rock-fill materials, are attached to the toe plinth through peripheral connections to create an impermeable framework. Numerous high rock-fill concrete face dams were constructed or designed. Such dams are widely scattered in regions with severe ground motions, like China, and thus must conduct seismic performance evaluations. Seismic vulnerability analysis is among the most efficient approaches for assessing seismic performance. Recent years have seen attempts by certain academics to analyze the seismic vulnerability of CFRDs; for example, Pang et al. [53] Extended a seismic vulnerability analysis technique depending on (IDA) to analyze the seismic behaviour of (CFRDs). After establishing a novel face-slab damage index, dam damage measures (DMs) are assumed to be permanent deformation and face-slab damage index utilizing a plastic-damage model for face-slabs and a modified general plasticity model for rockfills. Under different earthquake intensities, fragility curves and probability are determined for every DM. [54]; this study establishes seismic performance assessment methodologies and introduces fragility analysis to high CFRD safety assessment. As earthquake intensity measures, PGD, PGV, Sa(T1, 5%), and PGA are used (IMs). Dam damage measurements include dam crest relative settlement ratio, cumulative sliding displacement, and a novel face-slab destruction index (based on COD and DCR) (DMs). Each DM suggests failing grades for high CFRDs. Using IDA and MSA, earthquake fragility curves are produced for every DM. Congcong Jin and Shichun Chi [55], This study determines the vertical deformation by combining the three-dimensional F.E. programme DYNE3WAC with Biot dynamic consolidation theory and the Pastor–Zienkiewicz–Chan model. The relative seismic settlement rate is regarded as the DI to investigate the dam's fragility. Multiple stripe analysis (MSA) determines the high earth-rockfill dam's fragility curves. On the other hand, several similar research papers presented fragility analysis of concrete-faced rock-fill dams, such as [56-58].

4.4 Overflow Weir

A weir dam is a structure across the width of a river that adjusts the water flow characteristics and often alters the river's level. Weirs are also used to regulate water flow from lakes, ponds, and reservoirs' exits. Water often flows freely over the top of the weir crest before cascading to a lower level. In addition, the weir constructions can be subjected to many risks, such as earthquakes and flooding, resulting from major difficulties such as the discontinuity between the soil foundation and the weir, structural failure, and powerful impulse water waves induced by ground motions.
Based on Ju and Jung [59], This work was centered on probabilistic seismic hazard assessment of the weir structure utilizing the vulnerability approach depending on Monte Carlo simulation (MCS), focusing on the uncertainty of the earthquake motions in both near-field-induced pulse-like motions and distant field faults. The uncertainty was incorporated into the two-dimensions common linear elastic plain strain F.E. model with soil structural foundations utilizing the tie connection technique by Abaqus. Alam et al. [60], Probabilistic seismic hazard analysis (PSHA) is performed, and the seismic fragility that specifies the risk of structural collapse is evaluated using incremental dynamic analysis (IDA). Mass concrete tensile stress is more sensitive than other design criteria when combining seismic hazard and fragility data. Annual loss curves for two separate hazard source models are also extracted. On the other hand, several similar research papers presented fragility analysis of concrete-faced rock-fill dams, such as [61-64].

4.5 Summarisation

In order to build and improve the reliability of fragility curves, epistemic and aleatory uncertainty must be considered. Therefore, the researchers, as mentioned above, considered epistemic uncertainty, aleatory uncertainty, or both. Nonetheless, the threshold among neighbouring limit States (DS) is still unknown, as creating damage states in the Structure is a transitory procedure [10]. If the threshold's fuzziness is ignored, an erroneous estimate of (DS) may result. Using [23] as a reference, the (DI) Damage Index of 0.2 and 0.22 correspond to Damage States (Slight" and Moderate), respectively. The (DI) threshold among damage states (Moderate and Slight) is 0.21. When they are in a fuzzy gap, there might not be a functional difference between the (DS) connected to those two (DIs). Hence, when analyzing the seismic vulnerability of concrete dams, the fuzziness values of damage state thresholds must be considered. The fuzzy earthquake vulnerability of RC frame structures was examined by [65], which used a 2nd-order Bernstein polynomials equation to illustrate the fuzziness of the Damage States threshold. [66] Examining the bridge's seismic fragility fuzziness found that disregarding the fuzziness will underestimate the Structure's fragility. The effect of the limit states threshold's fuzziness on the seismic vulnerability of concrete dams not yet investigate.

5. FRAMEWORK OF CONTEXT

As stated in the introduction, fragility curves are crucial to engineered structures' contemporary probabilistic risk assessment. Therefore, the work context of the seismic vulnerability analysis of dams has been fully summarised below and shown in Figure 14:

Identify the Dam Location Seismicity Map, investigate the dam (using the Physical Model), decide on the Instrumentation, review the data from Long Term Field Monitoring, and, if necessary, carry out Forced Vibration Testing.

Depending on the previously collected data and the material properties, the Finite Element Model can establish the outstanding distinguishing characteristics in analyses and the constitutive models. In conclusion, choose the right Package for F.E. software.

The preliminary deterministic evaluation of the model, then a series of parametric analyses with initial $(N1)$ identified uncertain parameters that can be decreased to $(N2)$ by calibrating using long-term-field monitoring and forced vibration test.

Sensitivity Analysis After presuming that every one of the residual variables of $(N2)$ seems to have a maximum and minimum value, $(2 \times N2 + 1)$ is carried out of the performed to evaluate the sensitivity. In the first one, the mean values of all variables are established, after which, one at a time, the lowest and maximum values for each variable are determined. After that, the results are plotted in a chart known as the Tornado Diagram, wherein the highest sensitive (N3) random variables are chosen to be retained for use in subsequent research.

Perform Epistemic Uncertainties that refer to quantities that ought to be known but are difficult to measure, like materials property temporal uncertainty (for example, time-dependent material degradation) or spatial distribution uncertainty [67]. Each of those might contain two or more random variables (like compressive and tensile strengths) in addition to the variable correlation matrix.

Perform Aleatory Uncertainties which result from an insurmountable lack of information, such as the seismicity of a specific location and time. Before determining the hazard curves, the Probabilistic Seismic Hazard Analysis (PSHA) was performed. Next, appropriate earthquake motion records (GM) were chosen [68], and the optimal seismic intensity measure parameter like (Sa(T1)) and (PGA) was computed [69].

Ahead of fragility, last but not least, the results of epistemic and aleatory uncertainty are merged using Monte Carlo Structural Analyses. This is unquestionably the step with the highest computing cost. Data mining is then used to extract damage states and potential failure modes (PFM). Limit states (LS) include joint opening and sliding and crest displacements. Vulnerability curves and surfaces are constructed by the preceding step using a cumulative distribution function and a statistical interpretation provided by Equation 4.

6. CONCLUSION

This research aimed to comprehend and compare the numerous studies of the seismic vulnerability analysis of concrete dams. These findings are most effectively represented in Table 3, Table 4, and

Table 5. Despite the assessment of twenty-one studies, several features of this study field remain erroneous. Evaluation of the seismic vulnerability of concrete dams is extremely complex and uncertain. No such system probably exists to precisely and thoroughly assess all of these complexities and uncertainties. Every methodology has unique benefits and drawbacks. Individual approaches were developed depending on assumptions that emphasize certain aspects of the problem while downplaying or ignoring others.

Depending on a comprehensive assessment of these published studies, the review finds that future research should focus on and address the following characteristics:

Regarding epistemic uncertainty, the dam's age, the water level in the dam reservoir, mass density, Poisson's ratio, and dam height was not considered in concrete dams, excluding gravity dams.

Regarding Aleatory Uncertainties, the Optimal Intensity Measure parameter has not been well explored, nor has its effect on fragility curves been demonstrated, as it has only been addressed in a small number of studies and specific types of dams.

The fuzzy nature of (DS) thresholds must be considered.

Structural nonlinearity must account for failure mechanisms (Typically, a discrete joint crack is preferable).

Combined spatial and temporal uncertainty is still studied and must be investigated.

Fragility curves obtained by any approach should be viewed cautiously and not considered definitive.

Nonlinear analyses must be utilized in progressive failures and collapse seismic fragility curves.

Although vulnerability analysis has evolved as a viable approach for assessing the seismic performance of concrete dams, it has not yet been incorporated into any design rules or guidelines for estimating dams' seismic performance at various danger levels.

Combining joint nonlinearities and material must be required to account for the potential resurrection of the capacity curves.

Developing approaches for fragility analysis that may be implemented into the seismic design of concrete dams requires additional research in this area.

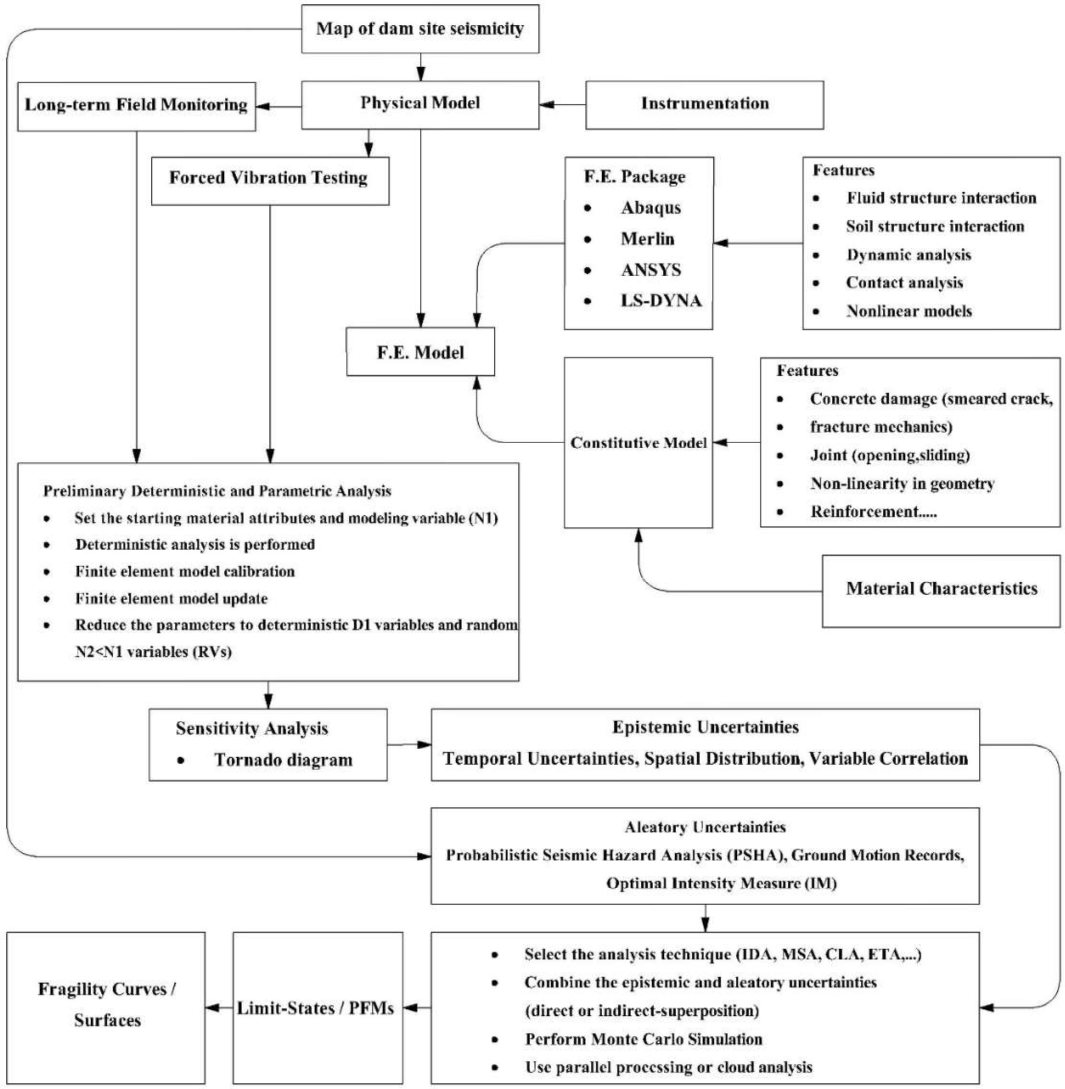

Figure 14 Flowchart shows the outline of the analysis of the vulnerability of concrete dams

Table 3 Overviews the concrete dam fragility analysis: Section I.

No.	Information				Modelling Features					Type of Analysis	
	Source	Year	Type of Dam	Kind of Software	Material NL	Joint NL	SSI	FSI	Uplift	LE or NL	Method
1	[49]	2015	Arch Dam	Ansys	No	Yes	Yes	Yes	No	NL	IDA
2	[59]	2015	Overflow Weir	Abaqus	No	No	Yes	Yes	Yes	NL	IDA
3	[36]	2016	Gravity	LS-Dyna	Yes	Yes	Yes	Yes	Yes	NL	Truncated IDA
4	[50]	2016	Arch Dam	Ansys	Yes	Yes	Yes	Yes	No	LE, NL	MSA
5	[37]	2016	Gravity	Merlin	No	Yes	Yes	Yes	Yes	NL	CLA
6	[38]	2016	Gravity	LS-Dyna	Yes	Yes	Yes	Yes	Yes	NL	MSA,IDA
7	[23]	2016	Gravity	Abaqus	Yes	No	Yes	Yes	Yes	NL	IDA
8	[39]	2017	Gravity	Abaqus	Yes	No	Yes	Yes	Yes	NL	IDA
9	[40]	2017	Gravity	Not Specified	Yes	No	No	Yes	No	NL	CLA
10	[51]	2018	Arch Dam	Abaqus	Yes	Yes	Yes	Yes	No	NL	IDA
11	[53]	2018	Concrete Face Rockfill Dam	LS-Dyna	Yes	No	Yes	Yes	No	LE, NL	IDA
12	[41]	2019	Gravity	NSAG-DRI	Smeared Crack	No	No	Yes	No	NL	IDA
13	[42]	2019	Gravity	LS-Dyna	Yes	No	Yes	Yes	Yes	NL	IDA
14		2019	Concrete Face Rockfill Dam	DYNE3WAC	Yes	No	Yes	Yes	No	NL	MSA
15	[54]	2019	Concrete Face Rockfill Dam	GEO-Dyna	Yes	No	Yes	Yes	No	NL	IDA, MSA
16	[52]	2020	Arch Dam	Abaqus	Yes	Yes	Yes	Yes	No	NL	IDA
17	[43]	2020	3 Gravity	Abaqus	Yes	No	No	Yes	No	NL	IDA
18	[44]	2021	Gravity	Abaqus	Yes	No	Yes	Yes	No	NL	IDA
19	[45]	2021	Gravity	Abaqus	Yes	No	Yes	Yes	No	NL	IDA
20	[47]	2021	Gravity	Abaqus	Yes	No		Yes	No	NL	MR-IDA
21	[48]	2022	Gravity	Not Specified		No	Yes	Yes	No	NL	IDA

Table 4 Overviews the concrete dam fragility analysis: Section II.

No.	The Aleatory Uncertainty				
	Number of Ground Motion	Number of Intensity Levels	Optimal (IM)	Structure response used	The post-processing on (EDP)
1	9	-	No	stresses	Overstressed Area
2	60	7	No	tensile and compressive	No
3	20 (Synthetic)	8	No	Base sliding, neck sliding	No
4	9	3	Yes	Displacement, strain, joint sliding, joint opening, stress, and crack area	DCR, CID, DSDR
5	100	-	Yes	displacement, joint opening, sliding	DI
6	20	7	No	Neck sliding, base sliding,	No
7	17	10	No	crest displacement, energy dissipation	Safety factor, DI
8	17	10	No	crest displacement, energy dissipation	Safety factor, DI
9	75(pulse-like), 60 (non-pulse-like)	-	Yes	maximum crest relative displacement, base local damage index, damage dissipated energy, and neck local damage index	DI
10	10	10	No	damage distribution, dynamic displacement, and joint opening	No
11	10 (recorded), 1(artificial)	18	No	permanent deformation, damage index	DCR
12	26	10	No	displacement upstream/downstream, absolute displacement (AMCD) and Dissipated Fracture Energy (DFE)	DI
13	22	7	No	sliding, Shear and Tensile Strength, maximum relative base displacement	No
14	60	-	No	the vertical deformation	DI
15	14 (recorded), 1(artificial)	10	No	Cumulative sliding displacement of dam slope stability, a new face-slab destroying index, relative settlement ratio of the dam crest	DCR
16	3(artificial)	10	No	slippage and sliding area ratio	_
17	30	10	No	displacement upstream/downstream, absolute displacement, tensile damage base/neck, total damage	DI
18	11	10	No	crest displacement, energy dissipation	No
19	20	8	No	crest displacement, energy dissipation	No
20	15	4	No	Qualitative damage states	No
21	65	8	Yes	The maximum relative displacement of the crest, Dissipated nonlinear energy	No

Table 5 Overviews the concrete dam fragility analysis: Section III.

No.	The Epistemic Uncertainties			The post-processing	
	Material uncertainties	Sampling Method	Random variables selected	Number of Analysis	Fragility Curve or Surface
1	No	No	No	80	Curve
2	No	No	No	420	Curve
3	Yes	LHS	The friction's angle (for C-to-R and C-to-C), tensile strength and cohesion	160	Curve
4	No	No	No	54	Curve
5	No	No	No	100	Curve, Surface
6	Yes	LHS	The friction's angle (for C-to-R and C-to-C), tensile strength and cohesion	140	Curve
7	No	No	No	170	Curve
8	No	No	No	170	Curve
9	No	No	No	135	Curve
10	Yes	LHS, MCS	The elastic modulus of foundation rock, the elastic modulus of concrete, the tensile strength of concrete, and the damping ratio of the system	500	Curve
11	No	No	No	198	Curve
12	No	No	No	520	Curve
13	Yes	LHS	Directionality factor, Concrete damping, Concrete–concrete cohesion, Concrete–rock cohesion, Concrete–the concrete angle of friction, Concrete–rock angle of friction, Concrete–concrete tensile strength, Concrete–rock tensile strength, Concrete elasticity modulus, Rock elasticity modulus, Drain efficiency	154	Curve
14	No	No	No	1000	Curve
15	No	No	No	600	Curve
16	Yes	LHS	friction coefficients and cohesion	500	Curve
17	No	No	No	900	Curve
18	No	No	No	330	Curve
19	Yes	Random field theory	tensile strength	640	Curve
20	Yes	MCS	concrete strength parameters	60	Curve
21	No	No	No	520	Curve

7. REFERENCES

[1] American Society of Civil Engineers. "Overview of Dams." ASCE. https://infrastructurereportcard.org/cat-item/dams-infrastructure/ (accessed 9 Feb 2022.

[2] Association of State Dam Safety Officials. "Dam Failures and Incidents." ASDSO. https://damsafety.org/dam-failures (accessed 5 Oct 2022.

[3] Association of State Dam Safety Officials. "The Increasing Hazard: Summary of US Dam Data." ASDSO. https://damsafety.org/Roadmap
(accessed 6 Oct 2022.

[4] Association of State Dam Safety Officials. "Risk of Failure: Failures and Incident Stats." ASDSO. https://damsafety.org/Roadmap (accessed 5 Oct 2022.

[5] R. Assaad and I. H. El-adaway, "Evaluation and prediction of the hazard potential level of dam infrastructures using computational artificial intelligence algorithms," Journal of Management in Engineering, vol. 36, no. 5, p. 04020051, 2020.

[6] B. Brand et al., "Selecting Analytic Tools for Concrete Dams to Address Key Events Along Potential Failure Mode Paths," FEMA P-1016, Federal Emergency Management Agency, 2014.

[7] U. USBR, "Dam Safety Risk Analysis Best Practices Training Manual," US Bureau of Reclamation and US Army Corps of Engineers, 2018.

[8] A. T. Council and N. E. H. R. Program, Seismic performance assessment of buildings. Federal Emergency Management Agency, 2012.

[9] M. A. Hariri-Ardebili, "Performance based earthquake engineering of concrete dams," University of Colorado at Boulder, 2015.

[10] X. Gu and Y. Lu, "A fuzzy–random analysis model for seismic performance of framed structures incorporating structural and non-structural damage," Earthquake engineering & structural dynamics, vol. 34, no. 10, pp. 1305-1321, 2005.

[11] L. Lin and J. Adams, "Seismic vulnerability and prioritization ranking of dams in Canada," in Proceedings of the 14th world conference on earthquake engineering, Beijing, China, 2008.

[12] A. Whittaker, Y. Huang, and R. Hamburger, "Next-generation performance based earthquake engineering," Electronic Journal of Structural Engineering, no. 2, pp. 49-57, 2007.

[13] M. A. Hariri-Ardebili and V. E. Saouma, "Seismic fragility analysis of concrete dams: A state-of-the-art review," Engineering structures, vol. 128, pp. 374-399, 2016.

[14] K. A. Porter, "An overview of PEER's performance-based earthquake engineering methodology," in Proceedings of ninth international conference on applications of statistics and probability in civil engineering, 2003, pp. 1-8.

[15] F. Scozzese, E. Tubaldi, and A. Dall'Asta, "Assessment of the effectiveness of Multiple-Stripe Analysis by using a stochastic earthquake input model," Bulletin of Earthquake Engineering, vol. 18, no. 7, pp. 3167-3203, 2020.

[16] A. Cornell and F. Jalayer, "Factored nonlinear displacement demand estimation methods for probability-based safety assessment," 2002.

[17] D. Vamvatsikos and C. A. Cornell, "Incremental dynamic analysis," Earthquake engineering & structural dynamics, vol. 31, no. 3, pp. 491-514, 2002.

[18] A. Nozari and H. Estekanchi, "Optimization of endurance time acceleration functions for seismic assessment of structures," دانشگاه علم و صنعت ایران, vol. 1, no. 2, pp. 257-277, 2011.

[19] F. Jalayer, Direct probabilistic seismic analysis: implementing nonlinear dynamic assessments. Stanford University, 2003.

[20] N. Shome, Probabilistic seismic demand analysis of nonlinear structures. Stanford University, 1999.

[21] K. R. Karim and F. Yamazaki, "A simplified method of constructing fragility curves for highway bridges," Earthquake engineering & structural dynamics, vol. 32, no. 10, pp. 1603-1626, 2003.

[22] P. B. Tekie and B. R. Ellingwood, "Seismic fragility assessment of concrete gravity dams," Earthquake engineering & structural dynamics, vol. 32, no. 14, pp. 2221-2240, 2003.

[23] M. I. Ansari and P. Agarwal, "Categorization of damage index of concrete gravity dam for the health monitoring after earthquake," Journal of Earthquake Engineering, vol. 20, no. 8, pp. 1222-1238, 2016.

[24] K. Pitilakis, H. Crowley, and A. M. Kaynia, "SYNER-G: typology definition and fragility functions for physical elements at seismic risk," Geotechnical, Geological and Earthquake Engineering, vol. 27, pp. 1-28, 2014.

[25] A. Rosti, M. Rota, and A. Penna, "Empirical fragility curves for Italian URM buildings," Bulletin of Earthquake Engineering, vol. 19, no. 8, pp. 3057-3076, 2021.

[26] A. Muntasir Billah and M. Shahria Alam, "Seismic fragility assessment of highway bridges: a state-of-the-art review," Structure and infrastructure engineering, vol. 11, no. 6, pp. 804-832, 2015.

[27] A. Miano, F. Jalayer, G. Forte, and A. Santo, "Empirical fragility assessment using conditional GMPE-based ground shaking fields: application to damage data for 2016 Amatrice Earthquake," Bulletin of Earthquake Engineering, vol. 18, no. 15, pp. 6629-6659, 2020.

[28] S. Lagomarsino, S. Cattari, and D. Ottonelli, "The heuristic vulnerability model: fragility curves for masonry buildings," Bulletin of Earthquake Engineering, vol. 19, no. 8, pp. 3129-3163, 2021.

[29] ATC-13, "Earthquake damage evaluation data for california," Applied Technology Council, 13, 1985.

[30] J. Kiani, C. Camp, and S. Pezeshk, "On the application of machine learning techniques to derive seismic fragility curves," Computers & Structures, vol. 218, pp. 108-122, 2019.

[31] S. Mangalathu and J. S. Jeon, "Stripe-based fragility analysis of multispan concrete bridge classes using machine learning techniques," Earthquake Engineering & Structural Dynamics, vol. 48, no. 11, pp. 1238-1255, 2019.

[32] A. J. Kappos, G. Panagopoulos, C. Panagiotopoulos, and G. Penelis, "A hybrid method for the vulnerability assessment of R/C and URM buildings," Bulletin of Earthquake Engineering, vol. 4, no. 4, pp. 391-413, 2006.

[33] A. Sandoli, G. P. Lignola, B. Calderoni, and A. Prota, "Fragility curves for Italian URM buildings based on a hybrid method," Bulletin of Earthquake Engineering, vol. 19, no. 12, pp. 4979-5013, 2021.

[34] K. Karimi-Moridani, P. Zarfam, and M. Ghafory-Ashtiany, "A novel and efficient hybrid method to develop the fragility curves of horizontally curved bridges," KSCE Journal of Civil Engineering, vol. 24, no. 2, pp. 508-524, 2020.

[35] V. Cardinali, M. Tanganelli, and R. Bento, "A hybrid approach for the seismic vulnerability assessment of the modern residential masonry buildings," International Journal of Disaster Risk Reduction, vol. 79, p. 103193, 2022.

[36] C. Bernier, J. E. Padgett, J. Proulx, and P. Paultre, "Seismic fragility of concrete gravity dams with spatial variation of angle of friction: case study," Journal of Structural Engineering, vol. 142, no. 5, p. 05015002, 2016.

[37] M. Hariri-Ardebili and V. Saouma, "Probabilistic seismic demand model and optimal intensity measure for concrete dams," Structural Safety, vol. 59, pp. 67-85, 2016.

[38] C. Bernier, R. Monteiro, and P. Paultre, "Using the conditional spectrum method for improved fragility assessment of concrete gravity dams in Eastern Canada," Earthquake Spectra, vol. 32, no. 3, pp. 1449-1468, 2016.

[39] M. I. Ansari and P. Agarwal, "Effects of re-entrant corner on seismic performance of high concrete gravity dams," Procedia engineering, vol. 173, pp. 1886-1893, 2017.

[40] Y. Yazdani and M. Alembagheri, "Seismic vulnerability of gravity dams in near-fault areas," Soil Dynamics and Earthquake Engineering, vol. 102, pp. 15-24, 2017.

[41] M. A. Sotoudeh, M. Ghaemian, and A. S. Moghadam, "Determination of limit-states for near-fault seismic fragility assessment of concrete gravity dams," Scientia Iranica. Transaction A, Civil Engineering, vol. 26, no. 3, pp. 1135-1155, 2019.

[42] R. L. Segura, C. Bernier, C. Durand, and P. Paultre, "Modelling and characterizing a concrete gravity dam for fragility analysis," Infrastructures, vol. 4, no. 4, p. 62, 2019.

[43] S. G. Gavabar and M. Alembagheri, "A study on seismic performance and fragility of gravity dams with various monolith shapes using nonlinear IDA," Geotechnical and Geological Engineering, vol. 38, no. 2, pp. 1133-1150, 2020.

[44] A. R. Tidke and S. Adhikary, "Seismic fragility analysis of the Koyna gravity dam with layered rock foundation considering tensile crack failure," Engineering Failure Analysis, vol. 125, p. 105361, 2021.
[45] Z. Li, Z. Wu, J. Chen, L. Pei, and X. Lu, "Fuzzy seismic fragility analysis of gravity dams considering spatial variability of material parameters," Soil Dynamics and Earthquake Engineering, vol. 140, p. 106439, 2021.
[46] M. Hariri-Ardebili and V. Saouma, "Quantitative failure metric for gravity dams," Earthquake Engineering & Structural Dynamics, vol. 44, no. 3, pp. 461-480, 2015.
[47] G. Sevieri, A. De Falco, M. Andreini, and H. G. Matthies, "Hierarchical Bayesian framework for uncertainty reduction in the seismic fragility analysis of concrete gravity dams," Engineering Structures, vol. 246, p. 113001, 2021.
[48] Z. Li et al., "Efficient seismic risk analysis of gravity dams via screening of intensity measures and simulated non-parametric fragility curves," Soil Dynamics and Earthquake Engineering, vol. 152, p. 107040, 2022.
[49] V. Kadkhodayan, S. M. Aghajanzadeh, and H. Mirzabozorg, "Seismic assessment of arch dams using fragility curves," Civil engineering journal, vol. 1, no. 2, pp. 14-20, 2015.
[50] M. A. Hariri-Ardebili, V. E. Saouma, and K. A. Porter, "Quantification of seismic potential failure modes in concrete dams," Earthquake Engineering & Structural Dynamics, vol. 45, no. 6, pp. 979-997, 2016.
[51] J.-T. Wang, M.-X. Zhang, A.-Y. Jin, and C.-H. Zhang, "Seismic fragility of arch dams based on damage analysis," Soil Dynamics and Earthquake Engineering, vol. 109, pp. 58-68, 2018.
[52] H. Liang, J. Tu, S. Guo, J. Liao, D. Li, and S. Peng, "Seismic fragility analysis of a High Arch Dam-Foundation System based on seismic instability failure mode," Soil Dynamics and Earthquake Engineering, vol. 130, p. 105981, 2020.
[53] R. Pang, B. Xu, X. Kong, and D. Zou, "Seismic fragility for high CFRDs based on deformation and damage index through incremental dynamic analysis," Soil Dynamics and Earthquake Engineering, vol. 104, pp. 432-436, 2018.
[54] R. Pang, B. Xu, D. Zou, and X. Kong, "Seismic performance assessment of high CFRDs based on fragility analysis," Science China Technological Sciences, vol. 62, no. 4, pp. 635-648, 2019.
[55] C. Jin and S. Chi, "Seismic fragility analysis of high earth-rockfill dams considering the number of ground motion records," Mathematical Problems in Engineering, vol. 2019, 2019.
[56] Y. Zhou, Y. Zhang, R. Pang, and B. Xu, "Seismic fragility analysis of high concrete faced rockfill dams based on plastic failure with support vector machine," Soil Dynamics and Earthquake Engineering, vol. 144, p. 106587, 2021.
[57] R. Pang, B. Xu, Y. Zhou, X. Zhang, and X. Wang, "Fragility analysis of high CFRDs subjected to mainshock-aftershock sequences based on plastic failure," Engineering Structures, vol. 206, p. 110152, 2020.
[58] B. Xu, X. Wang, R. Pang, and Y. Zhou, "Effect of Multi-Components Strong Motion Duration on Seismic Performance of High CFRDs Based on Fragility Analysis," Journal of Earthquake Engineering, pp. 1-19, 2022.
[59] B. S. Ju and W. Jung, "Evaluation of seismic fragility of weir structures in South Korea," Mathematical Problems in Engineering, vol. 2015, 2015.
[60] J. Alam, D. Kim, and B. Choi, "Seismic probabilistic risk assessment of weir structures considering the earthquake hazard in the Korean Peninsula," Earthq. Struct, vol. 13, no. 4, pp. 421-427, 2017.
[61] W. Jung, K. Kim, and B. Ju, "Seismic fragility of weir structures due to sliding effect," WIT Transactions on The Built Environment, vol. 168, pp. 1135-1141, 2015.
[62] W. Jung and B. Ju, "Seismic Fragility of Weir Structures with Infinite Foundations in Korea."
[63] M. Kwon, H. Seo, W. Jung, and J. Lim, "Safety Evaluation of Submerged Weir Based on Seismic Probabilistic Limit States," presented at the 16th World Conference on Earthquake, 16WCEE 2017, Santiago Chile,, 2017.
[64] S. S. Bodda, A. Gupta, B. S. Ju, and W. Jung, "Fragility of a Weir Structure due to Scouring," Computational Engineering and Physical Modeling, vol. 3, no. 1, pp. 1-15, 2020.

[65] F. Colangelo, "A simple model to include fuzziness in the seismic fragility curve and relevant effect compared with randomness," Earthquake engineering & structural dynamics, vol. 41, no. 5, pp. 969-986, 2012.
[66] L. Ren, S. He, H. Yuan, and Z. Zhu, "Seismic fragility analysis of bridge system based on fuzzy failure criteria," Advances in Civil Engineering, vol. 2019, 2019.
[67] A. M. Olsson and G. E. Sandberg, "Latin hypercube sampling for stochastic finite element analysis," Journal of Engineering Mechanics, vol. 128, no. 1, pp. 121-125, 2002.
[68] Pacific Earthquake Engineering Research Center. "PEER Ground Motion Database." PEER. https://ngawest2.berkeley.edu/site (accessed.
[69] J. E. Padgett, B. G. Nielson, and R. DesRoches, "Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios," Earthquake engineering & structural dynamics, vol. 37, no. 5, pp. 711-725, 2008.