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Article

Seismic Performance Evaluation of Concrete Dams: Methods, Advances, and the Role of Strain-Rate-Dependent Tensile Strength in Demand–Capacity Analysis

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Abstract

The seismic performance evaluation of concrete dams is a critical task in dam safety engineering, given the catastrophic consequences that dam failure can produce. Over the past two decades, the demand–capacity ratio (DCR) and cumulative inelastic duration (CID) framework, codified in USACE EM 1110-2-6051 and proposed by Ghanaat, has become the standard methodology for linear-elastic performance assessment. However, this framework intentionally uses static tensile strength as the capacity measure, introducing conservatism by neglecting the well-documented strain-rate enhancement of concrete tensile strength under seismic loading. This paper presents a comprehensive review of the current state of knowledge on seismic performance evaluation of concrete dams, synthesizing findings from gravity, arch, and buttress dam studies. It covers the DCR/CID framework, near-fault versus far-fault ground motion effects, dam–reservoir–foundation interaction modeling, nonlinear analysis methods, and emerging capacity-based approaches such as incremental dynamic analysis (IDA) and endurance time analysis (ETA). The paper then proposes an enhanced DCR formulation that incorporates strain-rate-dependent dynamic tensile strength using the CEB-FIP and Malvar–Ross dynamic increase factor (DIF) models. This rate-dependent DCR provides a more physically accurate capacity estimate for seismic strain rates (10^{-4} to 10^{-1} s^{-1}), potentially reducing unnecessary conservatism while maintaining safety. The implications for performance level classification and the triggering of nonlinear analysis are discussed.

Keywords: concrete dams; seismic performance; demand–capacity ratio; strain-rate-dependent tensile strength; dynamic increase factor; near-fault ground motions; incremental dynamic analysis; dam–reservoir–foundation interaction

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1. Introduction

Concrete dams are critical infrastructure whose failure during earthquakes can cause catastrophic downstream consequences. Although no concrete dam has experienced complete catastrophic failure solely due to earthquake loading, several notable cases—including the Koyna Dam (India, 1967), the Hsinfengkiang Dam (China, 1962), and the Sefid-Rud Dam (Iran, 1990)—have demonstrated that significant cracking and structural distress can occur under strong ground shaking [1–3].

Traditional seismic evaluation of dams relied on simple stress checks: compressive stresses were required to remain below the compressive strength divided by a safety factor, and tensile stresses were not to exceed the tensile strength of concrete [4,5]. While practical, this approach offers no systematic framework for assessing the severity of stress excursions, the spatial extent of damage, or the time-varying characteristics of seismic demand. In response, Ghanaat [6,7] proposed a performance-based methodology using demand–capacity ratios (DCR), cumulative inelastic durations (CID), and failure mode identification, which was subsequently codified in the USACE Engineer Manual EM 1110-2-6051 [8].

Since its introduction, this methodology has been widely applied to gravity and arch dams worldwide [2,3,9–11]. However, a fundamental assumption embedded in the standard DCR formulation is the use of *static* tensile strength as the capacity measure. This choice was intentional, providing "some degree of conservatism in the qualitative estimation of damage" [8]. Yet, extensive experimental evidence demonstrates that concrete tensile strength increases significantly under dynamic loading due to strain-rate effects. The dynamic increase factor (DIF) for tensile strength ranges from approximately 1.1 at low seismic strain rates ($\sim 10^{-4}\ \mathrm{s}^{-1}$) to values exceeding 1.5 at moderate seismic rates ($\sim 10^{-1}\ \mathrm{s}^{-1}$) [12–14].

A recent comprehensive review by Mohorović et al. [14] has provided the first synthesis explicitly focused on large-aggregate dam concrete behavior across the seismic strain rate range, identifying significant gaps between current design guidelines and state-of-the-art experimental evidence. Furthermore, Hariri-Ardebili [15] has proposed a risk-informed performance-based (RIPB) framework for seismic design of concrete dams that moves beyond deterministic two-level seismic hazard philosophies.

This paper makes two contributions: (1) it provides a comprehensive literature review synthesizing the current methods for seismic performance evaluation of concrete dams, including DCR/CID analysis, near-fault effects, nonlinear methods, and emerging capacity-based approaches; and (2) it proposes an enhanced DCR formulation incorporating strain-rate-dependent dynamic tensile strength, and discusses its implications for performance assessment practice.

2. Performance Evaluation Framework

2.1. Demand–Capacity Ratio (DCR)

The demand–capacity ratio is the cornerstone of modern performance-based evaluation of concrete dams. As defined by Ghanaat [6,7] and codified in USACE EM 1110-2-6051 [8], the DCR for gravity dams is:

$$\mathrm{DCR} = \frac{\sigma_{\max}}{f_t} \tag{1}$$

where $\sigma_{\max}$ is the computed maximum principal tensile stress and f_t is the static tensile strength of concrete. For arch dams, the DCR may also refer to the ratio of calculated arch or cantilever stresses to tensile strength [7].

The static tensile strength (or capacity) can be obtained from uniaxial splitting tension tests or from the empirical relation proposed by Raphael [16]:

$$f_t = 1.7\, f_c'^{2/3} \tag{2}$$

where f_c' is the compressive strength of concrete. The maximum permitted DCR for linear analysis is 2.0, which corresponds to the "apparent dynamic" tensile strength $f_{t,dyn} = 3.4\, f_c'^{2/3}$ proposed by Raphael [16], as illustrated in Figure 1.

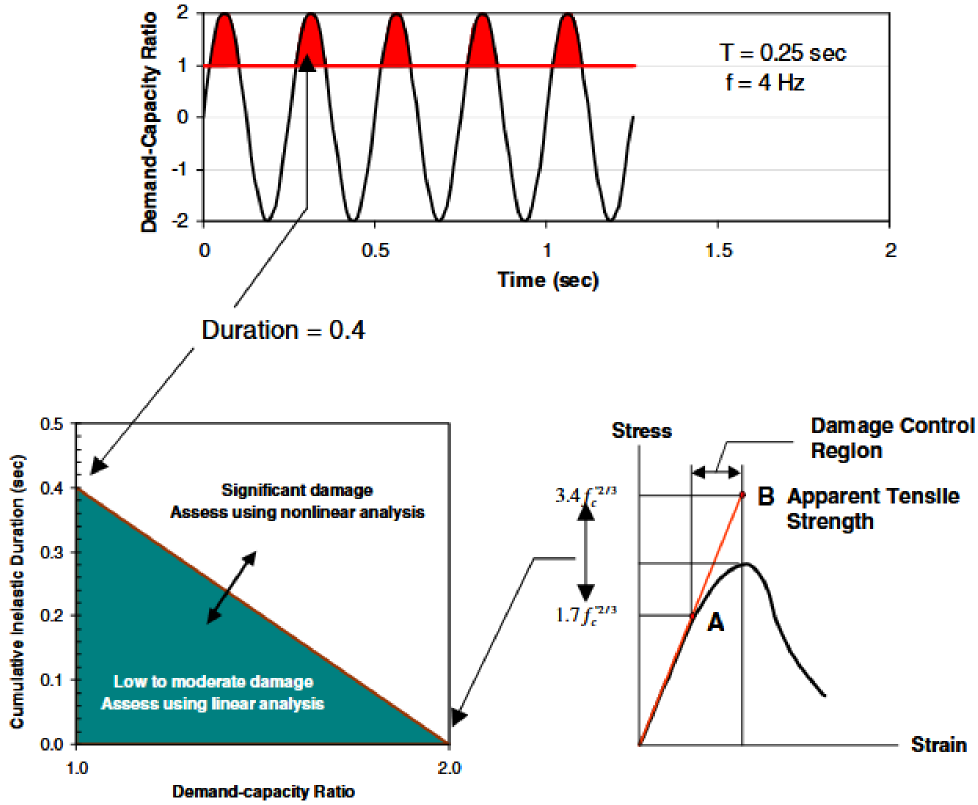


Figure 1. Illustration of seismic performance and damage criteria showing the stress–strain relationship, DCR thresholds, performance curve for cumulative inelastic duration, and the three performance levels (adapted from Ghanaat [7]).

2.2. Cumulative Inelastic Duration (CID)

The cumulative inelastic duration is the total duration of stress excursions above a stress level associated with a given DCR ≥ 1. For gravity dams, the performance curve specifies a maximum cumulative duration of 0.3 s at DCR $= 1$, decreasing linearly to zero at DCR $= 2$. For arch dams, a higher allowable cumulative duration of 0.4 s at DCR $= 1$ is used, reflecting the additional resistance provided by arch action [7]. This temporal measure provides a physically meaningful quantification of the severity of inelastic demand over the entire earthquake duration [17].

2.3. Performance Levels

Three performance levels are established [7,8]:

- **Minor or no damage** (DCR ≤ 1): The response remains within the linear elastic range.
- **Acceptable level of damage** ($1 <$ DCR < 2): Nonlinear response in the form of cracking is expected but is considered acceptable provided that overstressed regions are limited to 15% (gravity) or 20% (arch) of the dam cross-section surface area, and the cumulative inelastic duration falls below the performance curve.
- **Severe damage** (DCR > 2 or performance curve exceeded): Nonlinear time-history analysis is required to determine the actual extent of damage.

3. Case Studies and Applications

3.1. Gravity Dams

Several studies have applied the DCR/CID framework to specific gravity dams, providing validation and insights into the methodology.

Esmaili et al. [3] evaluated the Pine Flat Dam in California at three seismic hazard levels using the EAGD computer code. At the Operating Basis Earthquake level (0.18g), no damage was predicted.

At the Maximum Design Earthquake (0.27g) and Maximum Credible Earthquake (0.45g) levels, some tensile cracking occurred but remained within acceptable limits, as shown in Figure 2. The performance criteria did not require nonlinear analysis, confirming the adequacy of the dam's design.

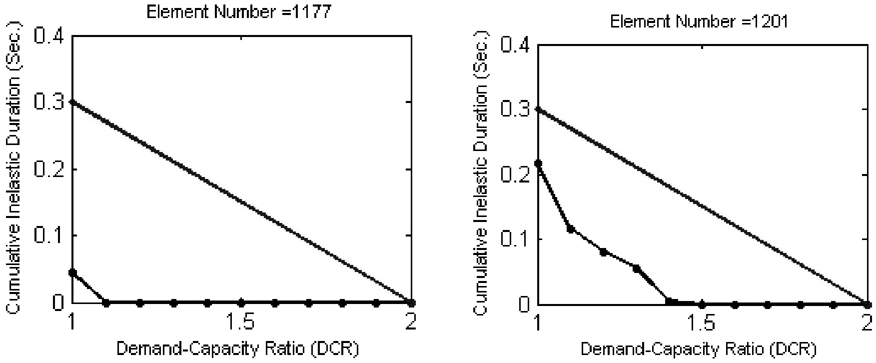
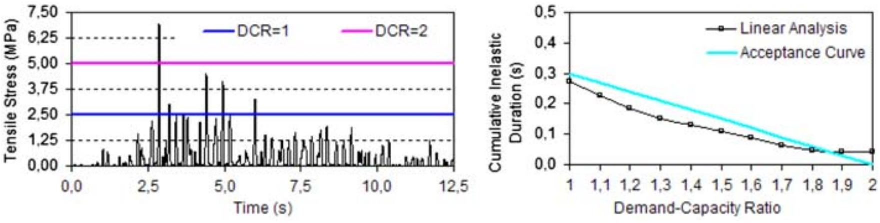
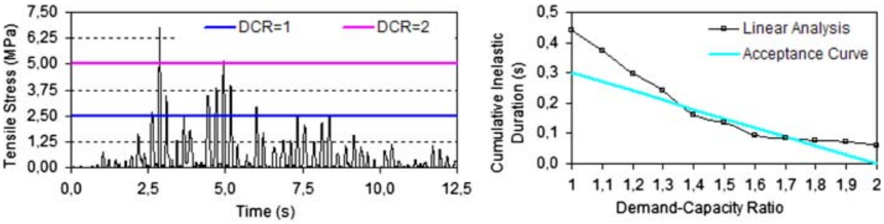


Figure 2. Performance curves of the overstressed elements at the heel of Pine Flat Dam due to MDE ground motion level (adapted from Esmaili et al. [3]).

Bayraktar et al. [9] investigated the effect of reservoir length on the Folsom Dam, varying it from H to $4H$. They found that tensile stresses increase with reservoir length and that a reservoir length of $3H$ is adequate for modeling gravity dams. Notably, the performance curve for the $3H$ reservoir length model under near-fault ground motion exceeded the acceptance curve (Figure 3), triggering the need for nonlinear analysis.



(a) Dam with H reservoir length



(b) Dam with 4H reservoir length

Figure 3. Time histories of maximum principal tensile stresses and corresponding performance curves for near-fault ground motion at different reservoir lengths (adapted from Bayraktar et al. [9]).

Wang et al. [2] evaluated the Koyna Dam subjected to both near-fault and far-fault ground motions using the concrete damaged plasticity (CDP) model. The near-fault ground motions produced substantially different stress patterns (Figure 4) compared to far-fault motions (Figure 5).

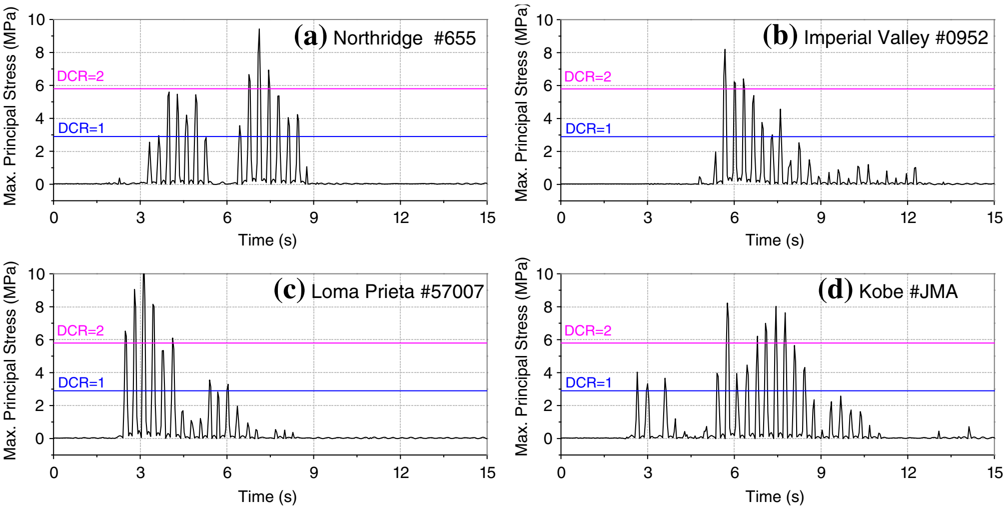


Figure 4. Time histories of maximum principal tensile stresses for near-fault ground motions with a PGA of 0.30 g (adapted from Wang et al. [2]).

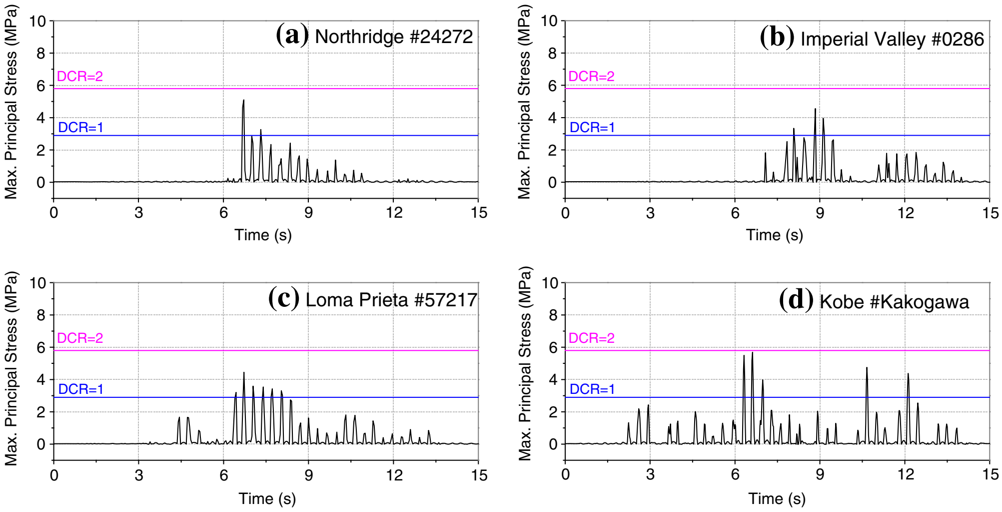


Figure 5. Time histories of maximum principal tensile stresses for far-fault ground motions with a PGA of 0.30 g (adapted from Wang et al. [2]).

Yamaguchi et al. [17] used shake table test data from a 1/20-scale Koyna Dam model to evaluate the USACE guidelines. They confirmed that linear time-history analysis can provide qualitative damage estimates (Figure 6), while emphasizing that different ground motions producing similar peak stresses can have very different damage potentials.

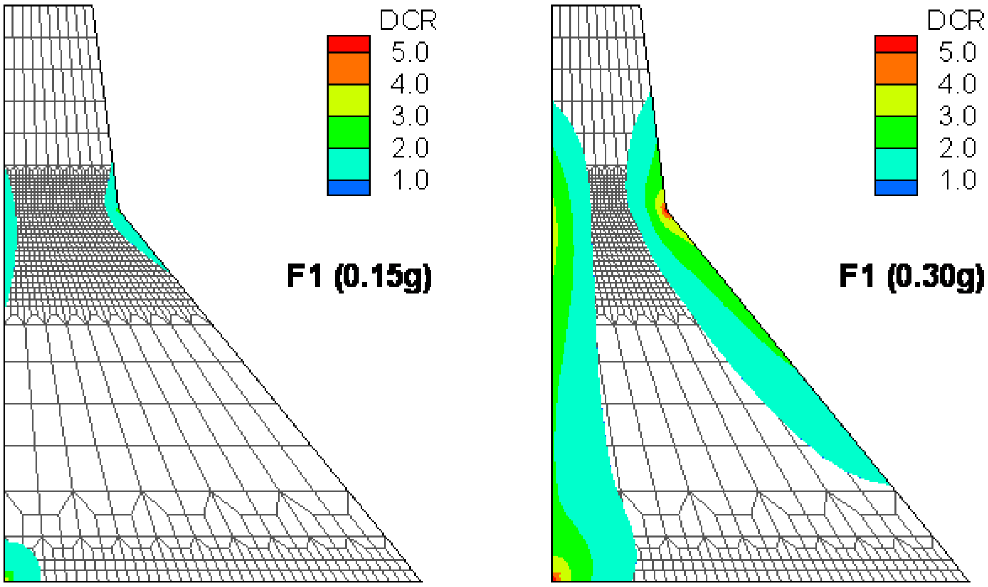
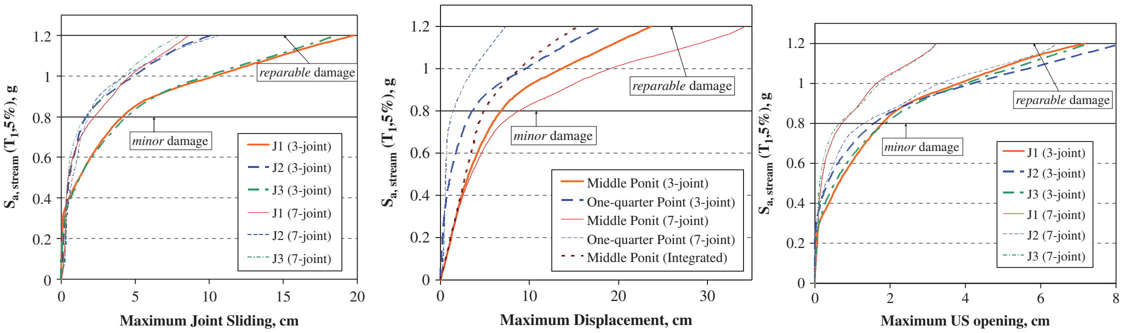


Figure 6. DCR values for two scaling levels of the input motion showing the spatial distribution of overstressed regions (adapted from Yamaguchi et al. [17]).

3.2. Arch Dams

Alembagheri and Ghaemian [11] investigated the Morrow Point arch dam through nonlinear incremental dynamic analysis (IDA) with three and seven contraction joints. They found that increasing the number of contraction joints generally reduces joint opening and sliding displacements, and that the primary failure mode of jointed arch dams is in compression (Figure 7).



(a) (b) (c)

Figure 7. Mean IDA curves: (a) maximum sliding of crown and quarter-span joints, (b) maximum radial crest displacements, and (c) maximum opening of crown and quarter-span joints (adapted from Alembagheri and Ghaemian [11]).

Pan et al. [18] applied IDA to the Dagangshan arch dam in China. They proposed three damage measures for identifying performance levels specific to arch dams: maximum joint opening, cracking depth on the dam–foundation interface, and extent of cracking in the upper portion. The IDA curves for joint opening are shown in Figure 8.

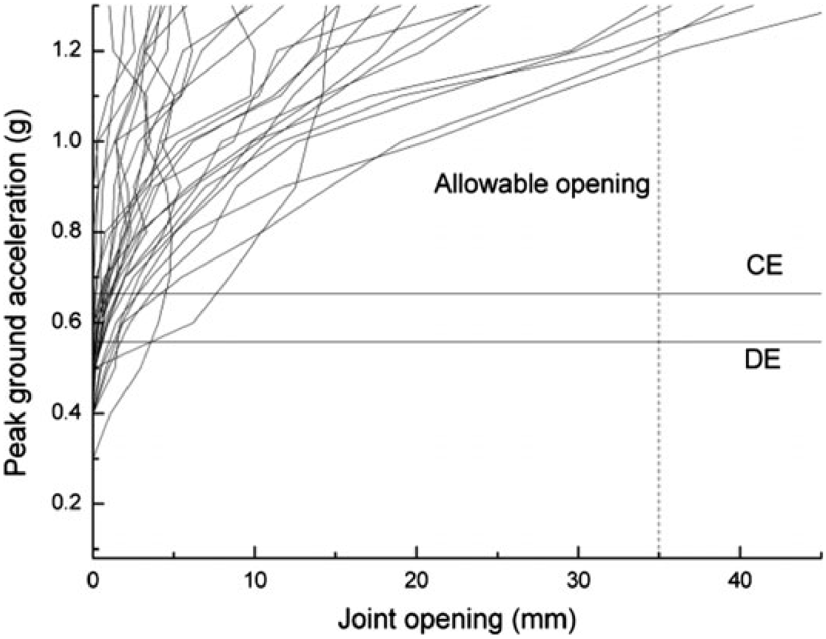
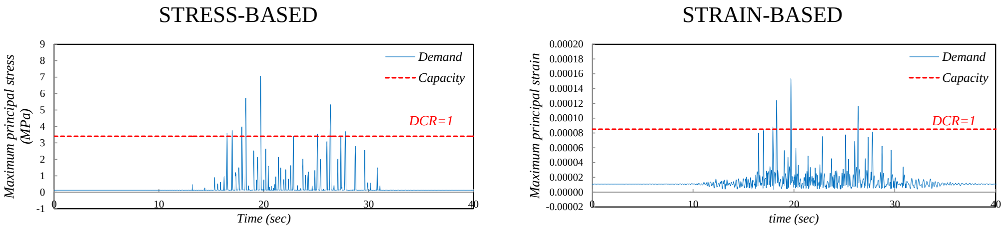


Figure 8. IDA curves for maximum openings of 28 contraction joints of the Dagangshan arch dam (adapted from Pan et al. [18]).

Heshmati et al. [19] compared stress-based and strain-based performance criteria for the Dez Dam (Figure 9). They found that strain-based criteria yield considerably different interpretations, suggesting that the stress-based approach currently used in guidelines may not fully capture the behavior of mass concrete, whose response is fundamentally governed by strain.


STRESS-BASED

STRAIN-BASED

Figure 9. Time-history of first principal stress (left) and strain (right) for the most critical node in Dez Dam, illustrating the difference between stress-based and strain-based DCR = 1 thresholds (adapted from Heshmati et al. [19]).

4. Near-Fault Versus Far-Fault Ground Motion Effects

Ground motions recorded near active faults exhibit forward directivity effects and fling-step displacements that produce long-period velocity pulses absent from far-fault records. Multiple studies have demonstrated that these characteristics cause substantially greater damage to dams than far-fault motions at equivalent peak ground accelerations.

Bayraktar et al. [9] showed that near-fault motions produce stress concentration in the upper part of the dam, while far-fault motions cause stress concentration near the base. Wang et al. [2] demonstrated that near-fault motions produce residual displacements of approximately 1.98 cm, compared to negligible residual deformation under far-fault motions, with plastic deformations being considerably larger under near-fault excitation.

Ardebili and Mirzabozorg [20] investigated the Karaj arch dam and found that near-fault ground motions increase displacement in the stream direction and that far-fault ground motions can actually produce more critical cumulative damage indices (Figure 10).

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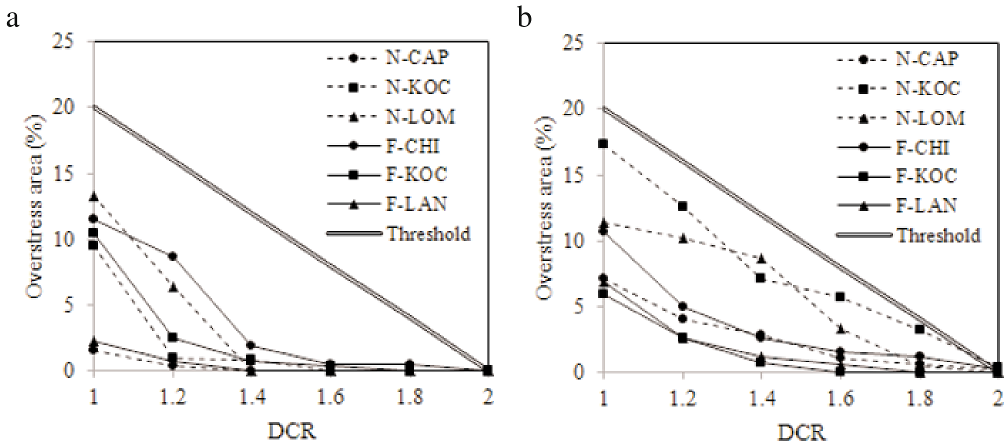

Figure 10. Percentage of overstressed area in the upstream face of the Karaj arch dam body based on (a) massless foundation, and (b) rigid foundation (adapted from Ardebili and Mirzabozorg [20]).

These findings underscore that peak ground acceleration alone is an insufficient intensity measure for characterizing seismic demand on dams. The selection of ground motion type is one of the most critical decisions in seismic performance assessment.

5. Strain-Rate-Dependent Tensile Strength and Enhanced DCR

5.1. The Case for Rate-Dependent Capacity

The standard DCR formulation uses static tensile strength, intentionally neglecting the well-documented strain-rate enhancement of concrete. This conservatism can lead to premature triggering of costly nonlinear analyses for dams that may actually be performing within acceptable limits. A recent review by Mohorović et al. [14] has provided the first comprehensive synthesis focused specifically on large-aggregate dam concrete across the seismic strain rate range (10^{-4} to 10^{-2} s^{-1}), highlighting that the DIF for dam concrete in this range is typically between 1.1 and 1.5.

Experimental studies have confirmed that both the splitting tensile strength and compressive strength of dam concrete increase with strain rate [21,22]. Wang et al. [22] showed that when strain-rate effects are included in the analysis of Koyna Dam, the principal tensile stresses are higher and more consistent with actual observed damage patterns.

5.2. Dynamic Increase Factor Models

The dynamic increase factor (DIF) quantifies the ratio of dynamic to static tensile strength:

$$\mathrm{DIF} = \frac{f_{t,dyn}}{f_{t,s}} \tag{3}$$

Several well-established DIF formulations exist:

CEB-FIP Model Code 1990/2010 [13]: For strain rates $\dot{\varepsilon} \leq 30\ \mathrm{s}^{-1}$:

$$\mathrm{DIF} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} \tag{4}$$

where $\dot{\varepsilon}_s = 3 \times 10^{-6}\ \mathrm{s}^{-1}$ is the quasi-static reference strain rate, and $\delta = 1/(1 + 8 f_{cm}/f_{cm0})$ with $f_{cm0} = 10$ MPa.

Malvar and Ross (1998) [12]: A modified CEB formulation that better fits experimental data:

$$\mathrm{DIF} = \begin{cases} \left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} & \text{for } \dot{\varepsilon} \leq 1\ \mathrm{s}^{-1} \\ \beta\left(\dfrac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} & \text{for } \dot{\varepsilon} > 1\ \mathrm{s}^{-1} \end{cases} \tag{5}$$

where $\delta = 1/(1 + 8f'_c/f_{c0})$, $f_{c0} = 10$ MPa, and $\log \beta = 6\delta - 2$.

Raphael's approximation [16]: A fixed factor of 2.0 (apparent dynamic strength = 2× static strength), which is the basis for the current DCR = 2 upper limit. This is a coarse approximation that does not vary with actual strain rate.

For typical seismic loading conditions ($\dot{\varepsilon} \sim 10^{-3}$ to 10^{-1} s^{-1}), the CEB-FIP and Malvar–Ross models predict DIF values in the range of 1.2 to 1.8, which is generally below Raphael's factor of 2.0.

5.3. Proposed Rate-Dependent DCR Formulation

We propose replacing the fixed static capacity in the standard DCR with a time-varying, strain-rate-dependent capacity:

$$\mathrm{DCR}^{dyn}(t) = \frac{\sigma_1(t)}{f_t \cdot \mathrm{DIF}(\dot{\varepsilon}(t))} \tag{6}$$

where $\sigma_1(t)$ is the maximum principal tensile stress at time t, f_t is the static tensile strength, and $\mathrm{DIF}(\dot{\varepsilon}(t))$ is the dynamic increase factor evaluated at the current strain rate.

The implementation requires the following steps:

1. Perform a linear time-history analysis of the dam–reservoir–foundation system.
2. Extract principal stress time histories $\sigma_1(t)$ and principal strain time histories $\varepsilon_1(t)$ at each critical element.
3. Compute the strain rate at each time step using central finite differences: $\dot{\varepsilon}(t_i) = [\varepsilon_1(t_{i+1}) - \varepsilon_1(t_{i-1})]/(2\Delta t)$.
4. Evaluate the DIF at each time step using the CEB-FIP or Malvar–Ross formulation.
5. Compute $\mathrm{DCR}^{dyn}(t)$ according to Equation (6).
6. Evaluate performance using the standard three-level framework with DCR^{dyn}.

5.4. Implications for Performance Assessment

The rate-dependent DCR has several important implications:

- **Reduced conservatism**: Elements that exceed DCR = 1 under static capacity may fall within acceptable limits when the dynamic strength enhancement is considered, potentially avoiding unnecessary nonlinear analyses.
- **Spatial variation in capacity**: Different parts of the dam experience different strain rates during the same earthquake. The rate-dependent DCR captures this spatial variation, providing a more nuanced damage assessment.
- **Ground motion sensitivity**: Near-fault ground motions with impulsive velocity pulses produce higher strain rates than far-fault motions, resulting in different DIF distributions across the dam. The rate-dependent DCR naturally accounts for this.
- **Consistency with the DCR = 2 limit**: Since typical seismic DIF values (1.2–1.8) are below Raphael's factor of 2.0, the rate-dependent formulation is consistent with the existing DCR = 2 upper bound while providing finer resolution for intermediate performance levels.

It is important to note that the standard formulation's conservatism was intentional, and adopting a rate-dependent capacity should be done with appropriate engineering judgment and additional safety considerations.

6. Emerging Assessment Methods

6.1. Incremental Dynamic Analysis (IDA)

IDA involves scaling a suite of ground motions to progressively increasing intensity levels and performing nonlinear analysis at each level [11,18]. It provides continuous capacity curves that enable direct identification of performance limits. Pan et al. [18] proposed an approximate single-record IDA method that yields reliable median IDA curves with significant computational savings.

6.2. Endurance Time Analysis (ETA)

Furgani et al. [23] advocated for the adoption of dynamic capacity functions using endurance time analysis, which employs specially designed intensifying acceleration functions. The ETA method allows the full capacity curve to be obtained from a single time-history analysis, offering the most favorable balance between computational cost and information yield.

6.3. Risk-Informed Performance-Based (RIPB) Framework

Hariri-Ardebili [15] has recently proposed a risk-informed performance-based framework that moves beyond the traditional two-level seismic design philosophy (OBE and SEE/MDE). This approach recognizes that the seismic response of dams is nonlinear and non-proportional, and that moderate-to-high intensity shaking can produce significant nonlinear effects. The RIPB framework integrates probabilistic seismic hazard analysis with continuous performance characterization through methods like IDA.

7. Conclusions

This paper has presented a comprehensive review of seismic performance evaluation methods for concrete dams and proposed an enhanced DCR formulation incorporating strain-rate-dependent tensile strength. The principal conclusions are:

1. The DCR/CID framework provides a systematic methodology for seismic performance assessment that overcomes shortcomings of traditional stress-check approaches. It has been widely validated across gravity and arch dam case studies.
2. Near-fault ground motions produce substantially greater damage than far-fault records at equivalent PGA levels due to forward directivity and fling-step effects. The selection of appropriate ground motion records is critical.
3. Dam–reservoir–foundation interaction must be properly modeled. A reservoir length of $3H$ is adequate for gravity dam models, and the deconvolved earthquake input mechanism provides the most rational seismic input representation.
4. Strain-based performance criteria may be more appropriate than stress-based criteria for arch dams, where the three-dimensional stress state is complex.
5. The proposed rate-dependent DCR formulation (Equation 6) provides a more physically accurate capacity estimate by incorporating the DIF at seismic strain rates. For typical seismic conditions ($\dot{\varepsilon} \sim 10^{-3}$ to 10^{-1} s^{-1}), the DIF ranges from 1.2 to 1.8, potentially reducing unnecessary conservatism in the performance assessment.
6. Emerging methods including IDA, ETA, and risk-informed performance-based frameworks offer promising advances for standardizing seismic assessment across dam portfolios.
7. Further research is needed to: (a) validate the rate-dependent DCR against nonlinear analysis results and experimental data for specific dam configurations; (b) develop standardized procedures for extracting strain rate histories from linear analyses; and (c) establish appropriate safety factors to compensate for the reduced conservatism when using dynamic tensile strength.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DCR	Demand–Capacity Ratio
CID	Cumulative Inelastic Duration
DIF	Dynamic Increase Factor
IDA	Incremental Dynamic Analysis
ETA	Endurance Time Analysis
CDP	Concrete Damaged Plasticity
MDE	Maximum Design Earthquake
MCE	Maximum Credible Earthquake
OBE	Operating Basis Earthquake
PGA	Peak Ground Acceleration
USACE	U.S. Army Corps of Engineers
RIPB	Risk-Informed Performance-Based

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