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Bayesian–Deterministic Seismic-Demand Scenarios for Baish Dam, Southwestern Saudi Arabia: An Engineering Hazard-Screening Assessment

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Abstract

Dam-safety assessment requires physically traceable earthquake scenarios with explicit treatment of epistemic uncertainty. This study develops a deterministic Bayesian point-source stochastic framework for seismic-demand screening at Baish Dam, southwestern Saudi Arabia, using the 23 January 2014 Jazan earthquake source. Nine scenarios (Mw 4.0–8.0) are simulated at fixed source-site geometry (35.6 km epicentral; 37.0 km hypocentral distance). The Mw 8.0 case is retained only as an upper engineering-screening bound because its estimated ~230 km strike-slip rupture length exceeds mapped local fault dimensions. The preferred focal mechanism (strike 259°, dip 87°, rake -171°) enters the double-couple radiation term. Site conditions are represented by VS30 = 760 m/s (NEHRP B/C) and 560 m/s (NEHRP C), with regional coda-Q attenuation. For Mw 8.0, median PGA/SAm_{ax} values are 0.202/0.448 g for NEHRP B/C and 0.321/0.719 g for NEHRP C. From 500 posterior realizations, SAm_{ax} medians and 5th–95th percentile credible bounds are 0.444 g (0.228–0.759 g) and 0.704 g (0.380–1.134 g), respectively. An independent regional PGA benchmark gives a mean absolute logarithmic residual of 0.23 (factor ~1.25) up to Mw 5.5, increasing to ~2.7 times at Mw 8.0. Stress drop and regional attenuation dominate uncertainty. Rupture-length screening indicates that Mw ≥ 6.5 scenarios require increasing caution and Mw ≥ 7.0 should be evaluated with finite-fault simulations before design-basis use. The results provide conditional demand envelopes for preliminary dam-safety screening and investigation planning.

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27 spectra; dam-safety screening; Baish Dam

28 **1 Introduction**

29 Earthquake engineering increasingly requires hazard assessments that extend beyond the characterization of
30 regional seismicity and provide scenario-based seismic-demand estimates that can be used to support structural
31 demand evaluation, retrofit screening, emergency planning, and infrastructure risk mitigation. For dams and
32 other critical facilities, particular emphasis is placed on evaluating the ground-motion demands associated with
33 credible earthquake scenarios generated by nearby or controlling seismic sources. Although probabilistic
34 seismic hazard analysis (PSHA) remains the standard framework for code-based design maps and risk-
35 consistent engineering design, deterministic seismic hazard assessment (DSHA) provides an essential
36 complementary approach for critical facilities. DSHA evaluates the ground-motion consequences of physically
37 credible controlling earthquake scenarios directly, thereby providing a clear basis for assessing safety-critical
38 demands that may not be adequately represented by a single annual-exceedance probability. Accordingly,
39 international guidance for the seismic safety assessment of large dams recognizes scenario-based seismic
40 hazard evaluation as an important component of the assessment and design of facilities where the consequences
41 of failure could be severe.

42 It is important to clarify how the present study relates to the classical deterministic seismic hazard
43 assessment (DSHA) framework. In its conventional form, DSHA involves four principal stages: (1)
44 identification and characterization of the earthquake sources capable of affecting the site; (2) selection of a
45 controlling earthquake, commonly represented by the maximum credible earthquake (MCE) or another
46 specified controlling scenario, together with an appropriate source-to-site geometry; (3) estimation of the
47 corresponding ground motion for the selected magnitude–distance combination; and (4) representation of the
48 resulting hazard by a deterministic ground-motion level or response spectrum. The present study adopts the
49 source-characterization component of this framework directly, using the well-characterized 2014 Jazan
50 earthquake source and its published focal mechanism. However, it deliberately departs from the conventional
51 single-controlling-earthquake formulation in the subsequent stages. Rather than selecting a single governing
52 magnitude, the analysis considers nine deterministic scenario magnitudes (M_w 4.0–8.0) at the fixed epicentral
53 location of the 2014 Jazan earthquake, thereby maintaining a constant source-to-site geometry without
54 imposing a closest-approach rupture configuration or invoking an independently established fault-specific
55 maximum credible earthquake (MCE). Rather than representing the hazard by a single deterministic response
56 spectrum, the analysis produces a family of magnitude-dependent seismic-demand spectra, with epistemic
57 uncertainty quantified through Bayesian credible intervals for each scenario. Accordingly, the methodology is

best regarded as a scenario-based engineering extension of DSHA for seismic-demand screening, rather than a strict application of the conventional single-controlling-earthquake procedure. The resulting ground-motion estimates are therefore intended to characterize magnitude sensitivity and site-specific seismic demand and to support engineering hazard screening, rather than to define a fault-specific MCE or serve as a formal design-basis seismic hazard assessment.

The southwestern Arabian margin is a relevant setting for this kind of assessment because infrastructure growth, coastal urbanization, and water-resource facilities sit close to a tectonically active Red Sea rift system. The 23 January 2014 Jazan earthquake sequence is especially relevant to Baish Dam because its epicentral area lies only about 36 km from the dam, and its focal mechanism indicates dextral strike-slip motion on a high-angle, ENE-WSW-striking plane, consistent with reactivation of inherited Precambrian structures in the regional stress field of the Red Sea margin. Previous regional studies provide important building blocks for engineering hazard analysis in this area. Seismotectonic assessments have described the Red Sea and Arabian Shield source framework, and local ground-motion studies have addressed recurrence, attenuation, microzonation, and source-zone hazard for Jazan and the southern Red Sea. The Jazan microzonation literature is particularly relevant because it documents strong lateral variability in near-surface velocity and amplification in coastal deposits, with site V_{s30} spanning roughly 200 to 590 m/s and surface PGA exceeding bedrock PGA at several borehole sites. A regional ground-motion prediction equation for western Saudi Arabia is also available: it was developed by adjusting a global next-generation attenuation model to more than 2700 local strong-motion recordings, including records from the 2014 Jazan sequence itself, and it shows that the regional path term implies weaker anelastic attenuation than the global reference model. A separate regional DSHA study has mapped areal-source hazard for southwestern Saudi Arabia using maximum historical magnitudes; that work establishes regional envelope motions but does not resolve source-specific, focal-mechanism-explicit demand at an individual critical facility.

The contribution of this study is not the development of a new regional seismicity catalogue, areal-source hazard model, or regional ground-motion model, for which suitable published information is already available. Instead, the study reorganizes and integrates existing seismological and empirical constraints into a source-specific, facility-focused deterministic seismic-demand framework for Baish Dam, with epistemic uncertainty explicitly quantified and propagated into the predicted ground-motion response spectra. Three aspects distinguish the present approach from previous regional studies. First, the strike, dip, and rake of the 2014 Jazan focal mechanism are explicitly incorporated into the double-couple radiation term along the source-to-Baish-Dam propagation path. This provides a mechanism-specific representation of seismic radiation that is not directly available from the categorical faulting-style classifications commonly used in empirical ground-motion models. Second, site condition is treated as an explicit engineering parameter through two

representative NEHRP site classes, NEHRP B/C and NEHRP C, corresponding to V_{s30} values of 760 and 560 m/s, respectively. This formulation allows the sensitivity of predicted seismic demand to foundation/site conditions to be evaluated independently. Third, epistemic uncertainty associated with the principal source, path, and site parameters is propagated through a Bayesian framework into the resulting engineering response spectra, providing uncertainty bounds that are directly applicable to screening-level dam-safety assessment. A further practical consideration concerns the magnitude range of the analysis. The available regional ground-motion model is empirically constrained primarily to earthquakes up to approximately M_w 5.4–5.5, with a cautious smoothed extrapolation extending toward approximately M_w 7. Consequently, it provides a useful independent benchmark for the lower portion of the scenario range but does not, by itself, provide a sufficiently constrained basis for the complete engineering magnitude sweep adopted here. The present analysis therefore evaluates scenarios from M_w 4.0 to 8.0 while explicitly treating M_w 8.0 as a conservative upper engineering-screening bound, rather than as a demonstrated fault-specific maximum magnitude. For each scenario, the ground-motion calculations are conditioned on the specified earthquake magnitude, source-to-site distance, focal mechanism, propagation path, and site condition. Accordingly, the objectives of this study are to: (i) quantify deterministic spectral seismic demand at Baish Dam for scenario earthquakes with M_w 4.0–8.0 associated with the 2014 Jazan source; (ii) evaluate the sensitivity of predicted demand to NEHRP B/C and NEHRP C site conditions using V_{s30} values of 760 and 560 m/s, respectively; (iii) propagate Bayesian epistemic uncertainty in the governing source, path, and site parameters into the predicted ground-motion spectra; (iv) benchmark the resulting PGA levels against an independent regional ground-motion model; (v) identify and rank the principal contributors to epistemic uncertainty; (vi) assess the applicability of the point-source approximation by comparing the assumed source dimensions with physically plausible rupture dimensions; and (vii) interpret the resulting magnitude-dependent seismic-demand scenarios in the context of screening-level dam-safety assessment and risk-mitigation decision making.

2 Surface Geology, Tectonic Setting and Engineering Site Conditions

Baish Dam is treated as the engineering target because it is a critical water-resource asset in southwestern Saudi Arabia, close enough to the Jazan seismic source for near-source spectral demand to matter for safety evaluation. The dam is located at 17.6675° N, 42.6606° E. The source point is the 2014 Jazan mainshock location, at 17.3493° N, 42.6977° E and 10 km focal depth. The resulting epicentral and hypocentral distances are 35.6 and 37.0 km, respectively, and are held fixed throughout the magnitude sweep to isolate the effect of increasing moment magnitude from variations in source-to-site geometry. Applying the same fixed 2014 epicentral location to all scenarios is a deliberate engineering simplification: it represents a magnitude-sensitivity scenario analysis in which the characterized 2014 Jazan source is assumed to generate progressively

123 larger earthquakes, rather than a search for the closest rupture position along an extended fault. The
124 implications and limitations of this fixed-geometry assumption, particularly for the largest scenario
125 magnitudes, are evaluated through the adopted maximum-magnitude scope and the subsequent rupture-length
126 screening.

127 The Baish–Jazan area lies within the transition zone between the Precambrian crystalline rocks of the
128 southern Arabian Shield and the sedimentary and volcanic succession of the Red Sea coastal plain. Inland and
129 elevated areas are dominated by Precambrian metamorphic, metavolcanic, and plutonic rocks, whereas the
130 coastal plain comprises Tertiary–Quaternary sedimentary and volcanic sequences and extensive
131 unconsolidated surficial deposits. This geological configuration reflects the tectonic evolution of the western
132 Arabian Shield and the development of the Red Sea rift, including uplift of the Red Sea escarpment and
133 subsequent erosion and sediment accumulation toward the coastal plain (Brown, 1970; Schmidt et al., 1983;
134 Brown et al., 1989). Within the Baish catchment, Precambrian basement rocks constitute the principal
135 geological units and include tonalitic–dioritic, granodioritic–dioritic, monzogranitic, amphibolitic, gabbroic–
136 dioritic, and syenitic rocks, together with metasedimentary and metavolcanic units. Younger volcanic and
137 intrusive rocks occur locally, while Quaternary alluvial, terrace, eolian, and reworked deposits are concentrated
138 along the wadi systems and in the western part of the catchment toward the coastal plain. These deposits reflect
139 erosion of the elevated crystalline terrain and subsequent transport and deposition within the drainage network
140 (Blank & Gettings, 1985; Brown et al., 1989). A network of mapped faults crosses the catchment, with
141 predominant NW–SE and NE–SW trends. These structures are associated with the inherited tectonic fabric of
142 the Arabian Shield and its subsequent modification during deformation related to Red Sea rifting and uplift of
143 the escarpment (Brown, 1970; Brown et al., 1989). The lithological and structural heterogeneity is relevant to
144 deterministic seismic-demand assessment because variations in near-surface geological conditions can modify
145 the propagation, attenuation, and local amplification of earthquake ground motions. In particular, the
146 impedance contrast between competent crystalline basement and relatively unconsolidated alluvial materials
147 may lead to substantially different site responses, particularly at short to intermediate periods. These
148 differences provide a physical basis for evaluating the sensitivity of the predicted seismic demand at Baish
149 Dam to alternative engineering site conditions. Baish Dam is situated near the western margin of the catchment,
150 where Precambrian basement occurs close to Quaternary surficial deposits. This geological setting provides a
151 suitable basis for evaluating alternative site conditions in the seismic-demand analysis. Accordingly, the
152 present study considers both competent-rock and stiff-soil conditions represented by the selected NEHRP site
153 classes. Figure 1 presents the regional and local geological context of the study area, showing the source–site
154 geometry, the location of Baish Dam, the distribution of the principal geological units, and the major mapped
155 fault systems.

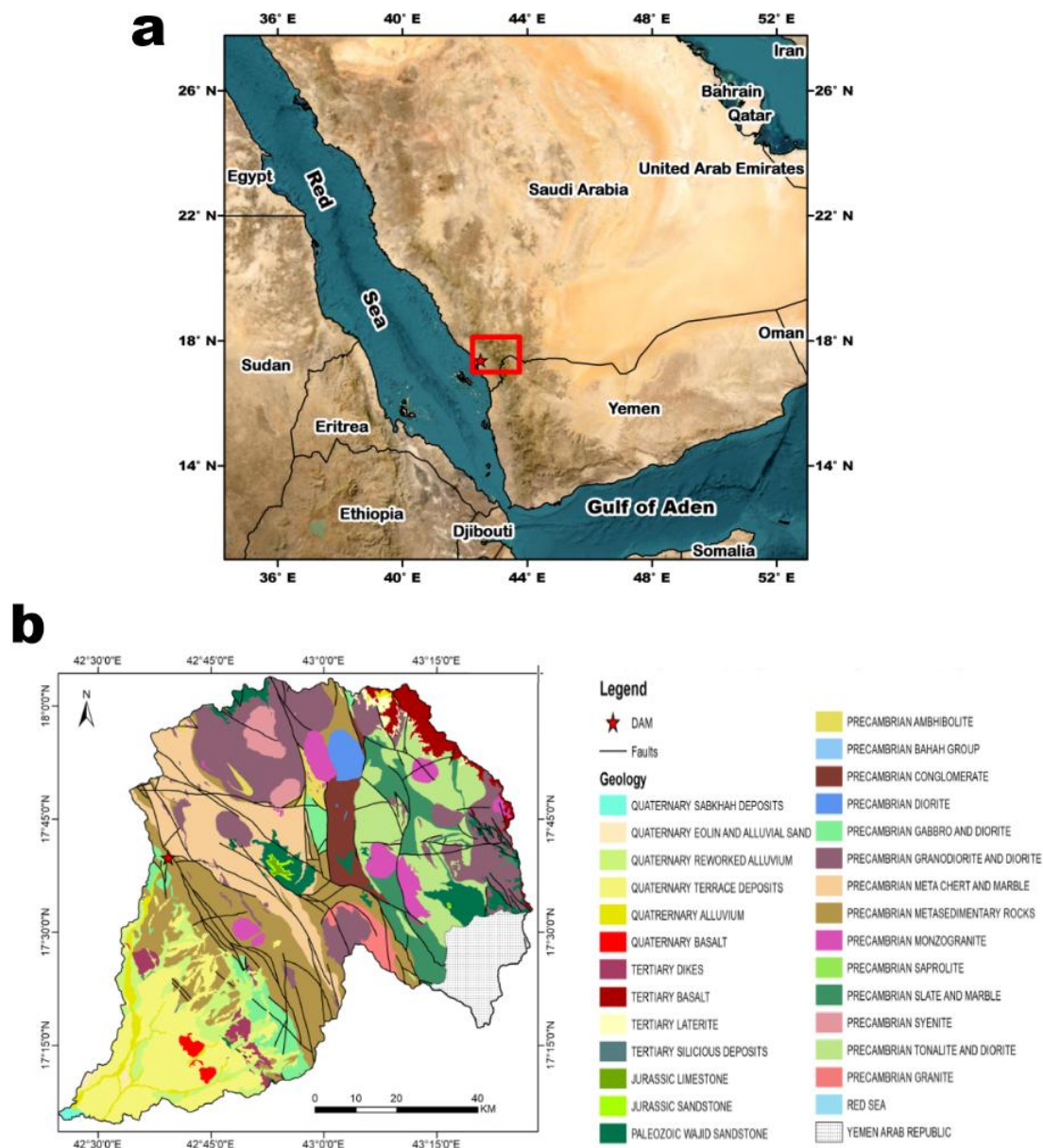
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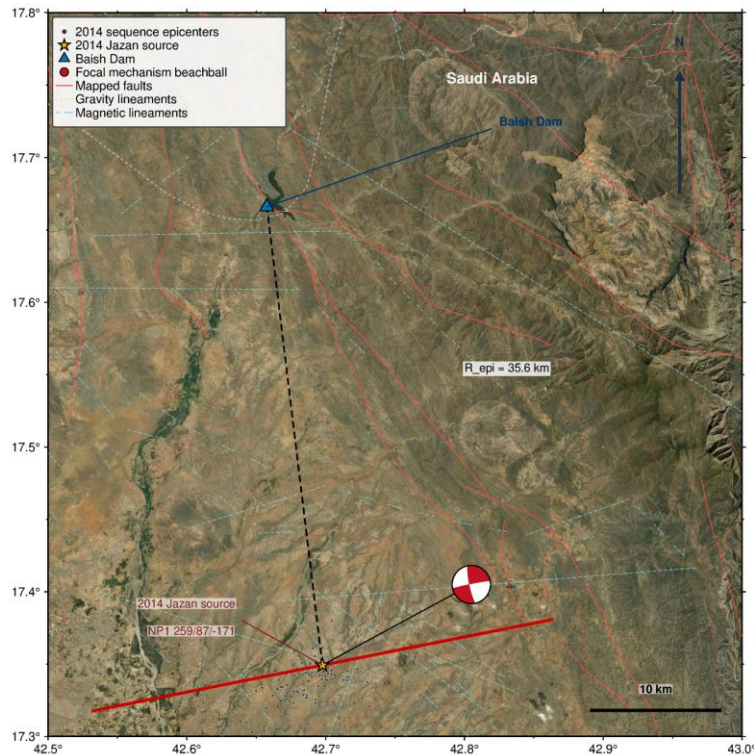
Fig. 1 Regional and geological setting of the Baish Dam catchment. (a) Regional tectonic context of the study area (red box) along the eastern margin of the Red Sea, between the Arabian Shield interior and the Gulf of Aden. (b) Geological map of the Baish Dam catchment, showing the dam location (red star), mapped fault traces, and the distribution of Quaternary, Tertiary, Jurassic, Paleozoic, and Precambrian lithological units

Site condition is therefore treated as an explicit engineering variable rather than being inferred solely from a regional empirical relationship. Two representative shear-wave velocity values are considered for comparison: $V_{S30}=760$ m/s, corresponding to the NEHRP B/C boundary and commonly adopted as a reference rock or very dense soil condition, and $V_{S30}=560$ m/s, representing a stiffer NEHRP Class C condition. The 760m/s value also provides a useful reference condition for comparison with regional ground-motion studies in which station-specific V_{S30} information is unavailable (Borcherdt, 1994; Boore et al., 1997; Stewart et al., 2015). The 560 m/s case represents a stiffer soil condition within the NEHRP Class C range and is consistent with the relatively high shear-wave velocities reported for parts of the Jazan region and coastal plain in previous geophysical and microzonation investigations (Abdelrahman et al., 2021). Together, these two cases provide a practical representation of the sensitivity of the predicted ground motions to site conditions and associated amplification. They should not, however, be interpreted as a substitute for a site-specific V_s profile at the dam foundation. Direct measurement and characterization of the near-surface shear-wave velocity structure should therefore be considered a priority for future site investigation and detailed seismic safety assessment.

Southwestern Saudi Arabia forms part of the actively evolving Arabia–Africa plate boundary, where the separation of the Arabian and African plates is accommodated primarily by spreading along the Red Sea and Gulf of Aden systems. The regional tectonic framework comprises rift-parallel structures, rift-oblique transfer zones, inherited Precambrian basement fabrics, and faults associated with deformation along the western Arabian continental margin (Brown, 1970; Bohannon, 1989; ArRajehi et al., 2010). The present-day deformation and seismicity reflect the interaction between Red Sea spreading, the Gulf of Aden–Afar system, and the reactivation of pre-existing structures within the Arabian Shield (McClusky et al., 2010; Stern & Johnson, 2010). Although instrumental seismicity in southwestern Saudi Arabia is generally moderate, earthquake activity is preferentially associated with the Red Sea margin, volcanic regions, and reactivated basement structures (El-Isa & Al Shanti, 1989; Al-Amri, 1994; Ali & Abdelrahman, 2022), making the identification of well-constrained local earthquake sources important for engineering hazard assessment. The 23 January 2014 Jazan earthquake sequence provides a particularly relevant source for the present analysis because it represents a recent, well-recorded local sequence with precisely relocated events and constrained focal mechanisms. Abdelfattah et al. (2017) interpreted the sequence as dextral strike-slip faulting on a steeply dipping ENE–WSW-trending fault within the Precambrian basement, probably representing the reactivation of a pre-existing structure conjugate to the Red Sea spreading direction and the NNW–SSE Najd fault system. Subsequent analysis of the rupture characteristics also confirmed the strike-slip nature of the event and provided additional constraints on its source process (Abdelfattah et al., 2019). These observations make the 2014 Jazan sequence a suitable physically based source for evaluating deterministic seismic-demand scenarios at Baish Dam. Figure 2 illustrates the source–site configuration adopted for the deterministic stochastic

199 simulations, including the epicentres of the 2014 Jazan earthquake sequence, the preferred mainshock focal
 200 mechanism, mapped faults and regional gravity and magnetic lineaments, the location of Baish Dam, and the
 201 fixed 35.6-km source-to-site path. The preferred causative plane has a strike of 259° , dip of 87° , and rake of
 202 -171° , indicating predominantly dextral strike-slip motion on a steeply dipping ENE–WSW-oriented fault with
 203 a minor dip-slip component (Abdelfattah et al., 2017). In the present analysis, the focal mechanism is
 204 incorporated directly into the ground-motion calculation rather than being used solely to describe the
 205 earthquake source. The strike, dip, and rake parameters define the double-couple moment tensor and the
 206 corresponding S-wave radiation pattern along the source-to-site path (Aki & Richards, 2002). Furthermore, the
 207 Bayesian formulation treats strike, dip, rake, and focal depth as uncertain source parameters and samples them
 208 from their prescribed posterior distributions around the preferred solution. This approach allows uncertainty in
 209 the source geometry and focal mechanism to propagate into the calculated engineering response spectra, rather
 210 than being fixed after the initial source characterization. The resulting scenarios therefore retain both the
 211 physical source characteristics of the 2014 Jazan earthquake and the associated epistemic uncertainty relevant
 212 to seismic-demand assessment.

213



214

215 **Fig. 2** Source-site map showing the 2014 Jazan sequence epicentres, the preferred mainshock focal mechanism characterized by a
 216 strike of 259° , a dip of 87° , and a rake of -171° , the location of Baish Dam, mapped faults, and gravity and magnetic lineaments in
 217 the source area. The thick red line marks the strike of the preferred mainshock fault plane, and the dashed black line marks the
 218 fixed 35.6 km epicentral source-site path used in the deterministic stochastic simulations

219

3 Deterministic Bayesian stochastic method

3.1 Deterministic scenario definition and maximum-magnitude scope

The deterministic analysis considers nine scenario magnitudes, M_w 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0, all located at the source coordinates of the 2014 Jazan earthquake. This magnitude range is used to evaluate the engineering response of Baish Dam to progressively larger hypothetical earthquakes originating from the same source region. The $M_w=8.0$ scenario is included as a conservative upper-bound engineering screening case rather than as a prediction of the expected or most probable earthquake on the source. The rupture-length assessment indicates that a strike-slip event of $M_w=8.0$ would require a rupture length of approximately 230 km, which is not supported by the mapped fault segments in the Jazan–Baish region. The $M_w=8.0$ case is therefore retained solely to examine the sensitivity of dam-site ground motions to an extreme scenario and should not be interpreted as a site-specific maximum credible earthquake. A fault-specific maximum-magnitude assessment, preferably coupled with finite-fault rupture modelling, is identified as an important refinement for future seismic-hazard investigations. Figure 3 summarizes the computational workflow, from the input data and source characterization through the ground-motion calculations and engineering diagnostics. For each scenario magnitude, the predicted ground motion is controlled by the moment magnitude, source-to-site distance, focal-plane orientation, radiation pattern, stress drop, path attenuation, site-specific kappa (κ), site amplification, and oscillator response.

3.2 Explicit focal-mechanism coupling

To ensure that strike, dip, and rake directly influence the resulting spectra, the focal plane is converted to a unit normal vector n and unit slip vector u following standard double-couple formalism. For strike (φ), dip (δ), and rake (λ), the vectors in a local north-east-down frame are

$$n(\varphi, \delta) = \text{strike}(\varphi) \times \text{dip}(\varphi, \delta) \quad (1)$$

$$u(\varphi, \delta, \lambda) = \cos(\lambda) \cdot \text{strike}(\varphi) + \sin(\lambda) \cdot \text{dip}(\varphi, \delta) \quad (2)$$

giving the double-couple moment tensor

$$M_{ij} = M_0(u_i n_j + n_i u_j) \quad (3)$$

The S-wave radiation coefficient for the source-to-site unit ray vector r is then obtained by projecting the radiated displacement perpendicular to the propagation direction:

$$R_S(\varphi, \delta, \text{rake}, r) = \frac{\|(I - r r^T) M r\|}{M_0} \quad (4)$$

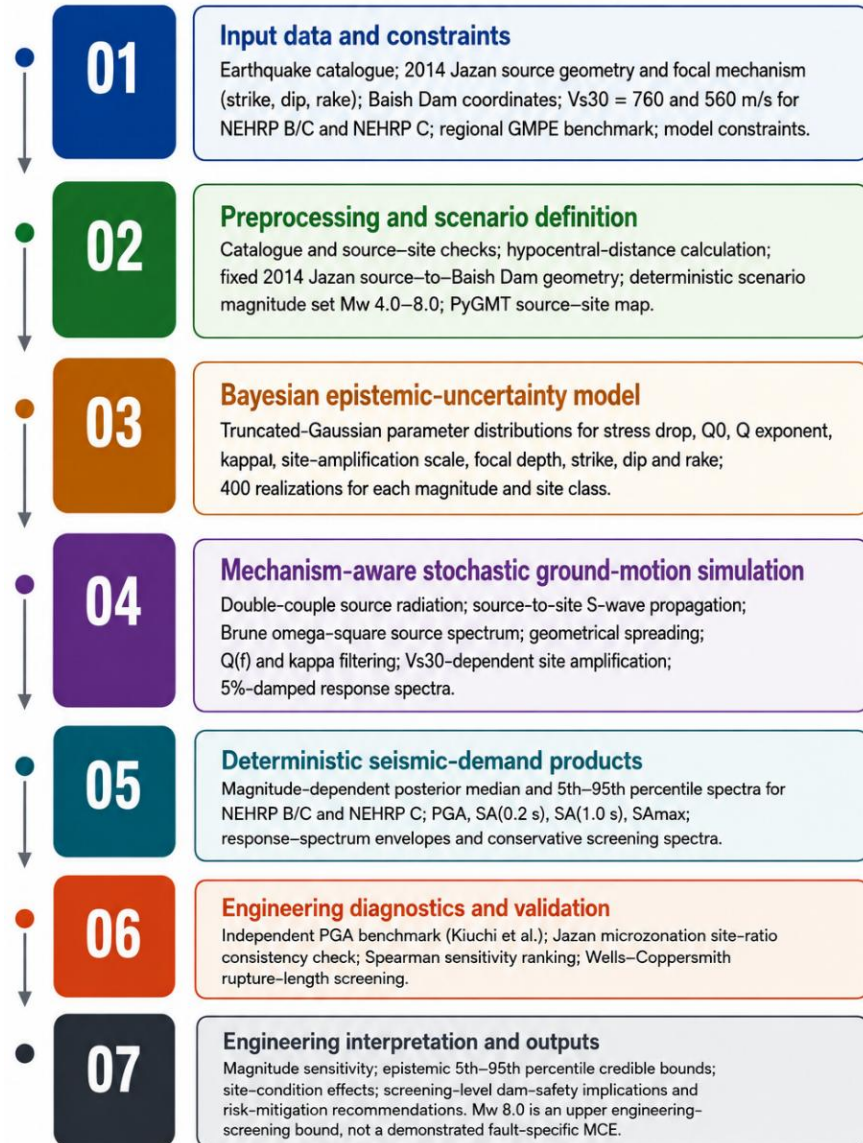


Fig. 3 Workflow implemented for the deterministic Bayesian stochastic assessment, from source, focal-mechanism, and site inputs, through Gaussian posterior sampling and mechanism-aware stochastic simulation, to the engineering diagnostics and dam-safety interpretation

Where I is the 3x3 identity matrix, so that $(I - r r^T)$ projects the moment-tensor-induced displacement onto the plane perpendicular to the ray, isolating the transverse (S-wave) component of radiation actually recorded at the site. For the mainshock plane and the Baish source-to-site ray, the median radiation coefficient is clipped to 0.900 by the adopted engineering bounds of 0.20-0.90. This upper bound follows the usual engineering practice of avoiding singular radiation amplification along nodal-plane geometry, rather than representing a physical maximum, and its influence on the reported spectra should be checked against an unclipped sensitivity run. The rake also applies a small mechanism-sensitive multiplier that raises stress drop slightly for normal or reverse components relative to pure strike-slip motion.

3.3 Source spectrum, path attenuation, and oscillator response

Using the focal-mechanism geometry and radiation coefficient established above, the point-source stochastic calculation follows the Brune omega-square source spectrum in the Fourier domain. Moment magnitude is converted to scalar seismic moment as

$$\log_{10}(M_0) = 1.5 M_w + 9.10 \quad (5)$$

where M_0 is in $\text{N}\cdot\text{m}$. The source corner frequency depends on shear-wave velocity β , stress drop $\Delta\sigma$, and seismic moment:

$$f_c = C_f \cdot \beta \cdot \left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}} \quad (6)$$

with C_f collecting unit-conversion constants; $\beta = 3.6 \text{ km/s}$, $\rho = 2800 \text{ kg/m}^3$, free-surface factor = 2.0, and horizontal partition = $\sqrt{0.5}$. Because $\Delta\sigma$ is specified in bars and M_0 from Eq. (5) is expressed in $\text{N}\cdot\text{m}$, C_f also carries the cgs-to-SI conversion needed to keep f_c in Hz; M_0 is converted internally to dyne-cm for this step only, and the $\text{N}\cdot\text{m}$ convention defined in Eq. (5) is retained throughout the remainder of the analysis. The Fourier acceleration amplitude is

$$A(f, R) = (2\pi f)^2 \cdot C_s \cdot M_0 \cdot \left[1 + \left(\frac{f}{f_c}\right)^2\right]^{-1} \cdot G(R) \cdot P(f, R) \cdot S(f, V_{s30}, \kappa_0) \quad (7)$$

where C_s collects the density, shear-wave velocity, the mechanism-specific radiation coefficient R_S from Eq. (4), free-surface, and horizontal-partition terms; the source-to-site distance dependence is carried separately by the geometrical-spreading function $G(R)$, not by C_s . Geometrical spreading follows $1/R$ to 40 km and $1/\sqrt{R}$ beyond it. Anelastic path attenuation is

$$Q(f) = Q_0 \cdot f^\eta, \quad P(f, R) = \exp\left[\frac{-\pi f R}{\beta \cdot Q(f)}\right] \quad (8)$$

286 The site term is a smooth, frequency-dependent amplification controlled by Vs30, combined with a high-
 287 frequency diminution term $\exp(-\pi \cdot k \cdot f)$ (Anderson & Hough, 1984; Campbell, 2009; Ktenidou et al., 2014). The
 288 oscillator response comes from the 5%-damped single-degree-of-freedom transfer function and random-
 289 vibration-theory peak factors:

$$290 \quad \sigma_a(T)^2 = 2 \Delta_f D^{-1} \sum_f |A(f, R)|^2 |H_T(f, \xi = 0.05)|^2 \quad (9)$$

$$291 \quad SA(T) = pf(D, T) \cdot \frac{\sigma_a(T)}{g} \quad (10)$$

292 where $D = 1/f_c + 0.05R$ is the duration in seconds, R is in km, Δf is the Fourier frequency spacing, and pf is the
 293 duration- and frequency-dependent peak factor.

294 **3.4 Bayesian uncertainty model**

295 Bayesian uncertainty analysis is applied to the principal source, path, and site parameters governing the
 296 deterministic seismic-demand calculations. The parameter distributions are specified as Gaussian and truncated
 297 at physically and regionally plausible bounds, and the parameters are sampled independently. Thus, potential
 298 physical correlations among the uncertain parameters are not represented in the present formulation and
 299 constitute a limitation of the uncertainty model. For each parameter θ_j ,

$$300 \quad \theta_j | data \sim Normal(\mu_j, \sigma_j^2), \text{truncated to } [L_j, U_j] \quad (11)$$

301 with means, standard deviations, and bounds listed in Table 1. For each magnitude and site class, 500 posterior
 302 realizations are propagated through the same deterministic stochastic model (Fig. 4), and the resulting ground-
 303 motion quantity Y is summarized by posterior predictive quantiles:

$$304 \quad Q_p[Y(M_w, V_{s30})] = quantile_p\{Y(\theta_1), \dots, Y(\theta_{500})\} \quad (12)$$

305 The posterior mean and the 5th–16th and 84th–95th percentiles are reported for the scalar ground-motion
 306 ordinates, response spectra, and design spectra. The 5th–95th percentile range is used as the principal epistemic
 307 uncertainty band, whereas the 16th–84th percentile range represents a narrower interval approximately
 308 equivalent to ± 1 standard deviation. Although the input parameters are assigned Gaussian priors, the nonlinear
 309 nature of the forward model results in generally non-Gaussian posterior distributions. Consequently,
 310 uncertainty is characterized using empirical quantiles rather than a single propagated variance throughout the
 311 analysis.

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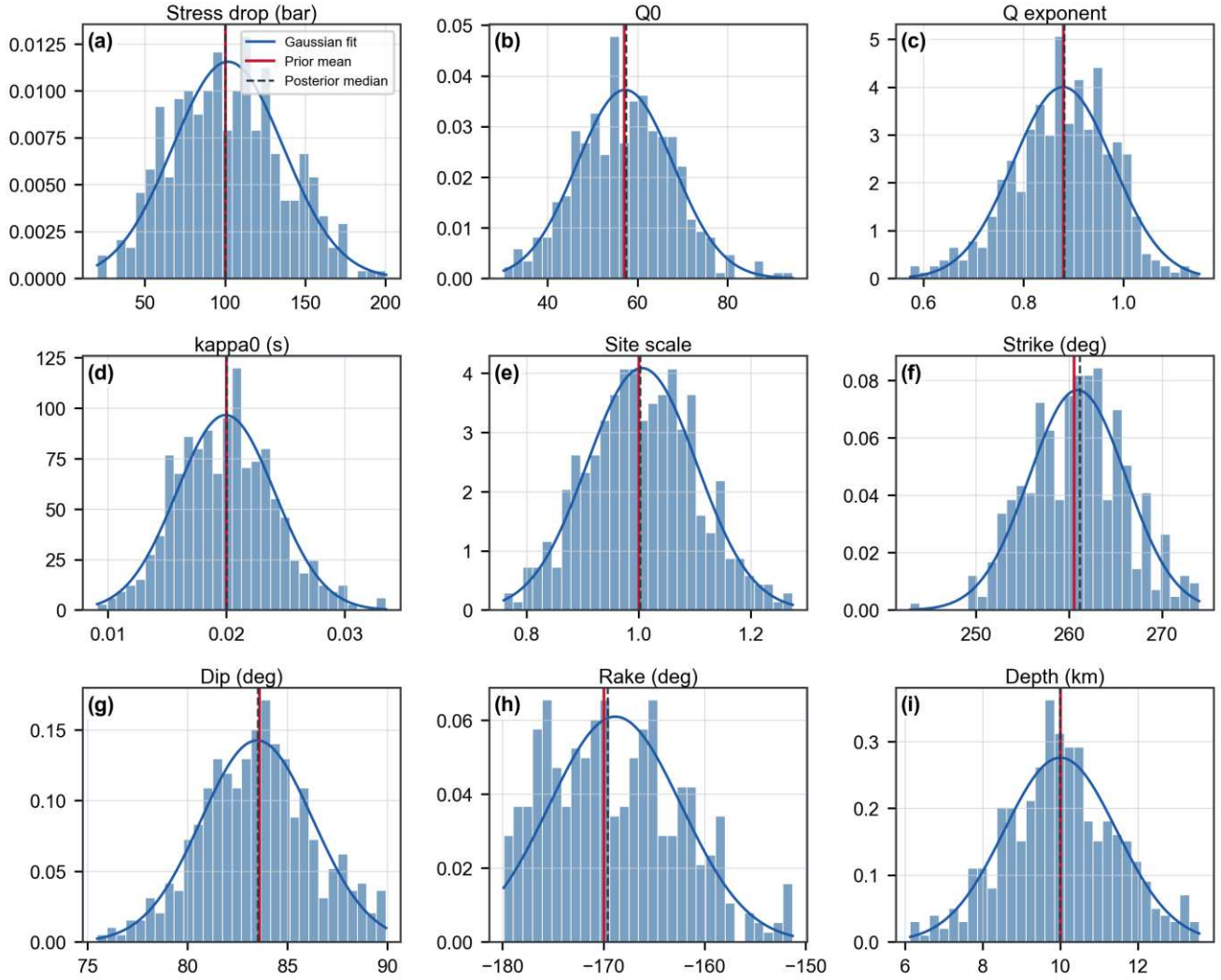


Fig. 4 Gaussian posterior parameter samples used in the deterministic Bayesian stochastic simulations. Histograms show 500 realizations, blue curves show Gaussian fits, red lines show adopted prior means, and dashed black lines show posterior medians

339 **3.5 Engineering design-spectrum envelope**

340 For engineering interpretation, the stochastic response spectrum is also converted to a conservative envelope
341 suitable for screening-level comparison with code-style design spectra. The two-point spectral shape is
342 anchored by SA at period of 0.2 s and 1.0 s:

$$343 \quad T_0 = 0.2 \cdot \frac{SA(1.0s)}{SA(0.2s)}, \quad T_s = \frac{SA(1.0s)}{SA(0.2s)} \quad (13)$$

$$344 \quad S_{2p}(T) = SA(0.2s) \left(0.4 + 0.6 \frac{T}{T_0} \right) \text{ for } T \leq T_0; \quad (14a)$$

$$345 \quad S_{2p}(T) = SA(0.2s) \text{ for } T_0 < T \leq T_s; \quad (14b)$$

$$346 \quad S_{2p}(T) = \frac{SA(1.0s)}{T} \text{ for } T > T_s. \quad (14c)$$

347 and the engineering spectrum, denoted $S_D(T)$ below (the subscript D is for design), is the pointwise maximum
348 of the two-point curve and the stochastic response spectrum:

$$349 \quad S_D(T) = \max[S_{2p}(T), SA_{stochastic}(T)] \quad (15)$$

350 This envelope keeps the deterministic spectral peaks from the stochastic calculation while retaining a simple
351 engineering design shape. It is not a replacement for project-specific dam analysis, but it provides traceable
352 input for prioritizing dynamic analyses, instrumentation, and site-investigation needs. Because $S_D(T)$ is a
353 pointwise maximum, the peak of the median $S_D(T)$ curve, reported for the conservative design spectrum, need
354 not exactly equal the median of the peak stochastic ordinate SA_{max} reported in Table 2, since the two
355 summaries pass through the maximum and median operators in a different order; both are reported for
356 transparency.

357 **3.6 Model validation, benchmarking, sensitivity, and point-source applicability checks**

358 A regional ground-motion equation for western Saudi Arabia (Kiuchi et al., 2019), developed by adjusting the
359 BSSA14 next-generation attenuation model to more than 2700 local strong-motion recordings, provides an
360 independent PGA benchmark. Because that regression assumed a reference V_{s30} of 760 m/s for all recording
361 stations (station-specific V_{s30} was unavailable), it aligns naturally with the NEHRP B/C case used here. It is
362 not used as the governing DSHA engine, because the model covers PGA and PGV only and the response-
363 spectral equations were still under development; it is instead used only to check the NEHRP B/C PGA scale.

364 The benchmark source term FE and path term FP are evaluated as

$$365 \quad \ln[PGA(M, R)] = F_E(M) + F_P(R, M) \quad (16)$$

$$R = \sqrt{R_{epi}^2 + h^2}; \quad F_P = [c_1 + c_2(M - M_{ref})] \cdot \ln\left(\frac{R}{R_{ref}}\right) + c_3(R - R_{ref}) \quad (17)$$

$$F_E(x) = e_{FM} + e_4x + e_5x^2 \text{ for } x \leq -0.5; \quad (18a)$$

$$F_E(x) = \text{cubic interpolation for } -0.5 < x \leq 0.5; \quad (18b)$$

$$F_E(x) = e_{FM} + e_6x \text{ for } x > 0.5. \quad (18c)$$

with $x = M - M_h$. The coefficients used are $e_0 = -1.24$, $e_1 = -0.897$, $e_2 = -0.920$, $e_4 = 0.26$, $e_5 = -0.222$, $e_6 = -0.1662$, $c_1 = -0.96$, $c_2 = 0.192$, $c_3 = -0.0073$, $M_{ref} = 4.5$, $R_{ref} = 1$ km, $h = 4.5$ km, and $M_h = 5.5$; because the Jazan source is strike-slip, $e_{FM} = e_1$. The original regression used local magnitudes from about M 3 to M 5.5 and was smoothed and extrapolated by its authors to about M 7, so the Mw 7.5 and 8.0 benchmark values are treated here as diagnostic only and are never used to scale the stochastic response spectra. Four checks make the scenario results auditable against this benchmark and against independent physical constraints. First, the NEHRP B/C PGA values computed above are compared against the regional benchmark just introduced, over the magnitude range where that empirical model is best constrained. Second, the computed NEHRP C to NEHRP B/C PGA ratio near Mw 6.25 is compared against the lower amplification bound reported in the Jazan microzonation literature. Third, each posterior input parameter is ranked by its monotonic influence on the log ground-motion ordinates using the Spearman rank correlation,

$$\rho_s(\theta_j, Y) = \text{corr}[\text{rank}(\theta_j), \text{rank}(\ln Y)] \quad (19)$$

Fourth, because very large magnitudes cannot be represented realistically by a point source, a separate rupture-dimension screen is applied. For the strike-slip Jazan mechanism, the Wells and Coppersmith (1994) surface-rupture-length relation is used as a diagnostic only:

$$\log_{10}(L_{SRL}) = -3.55 + 0.74 \cdot M_w \quad (20)$$

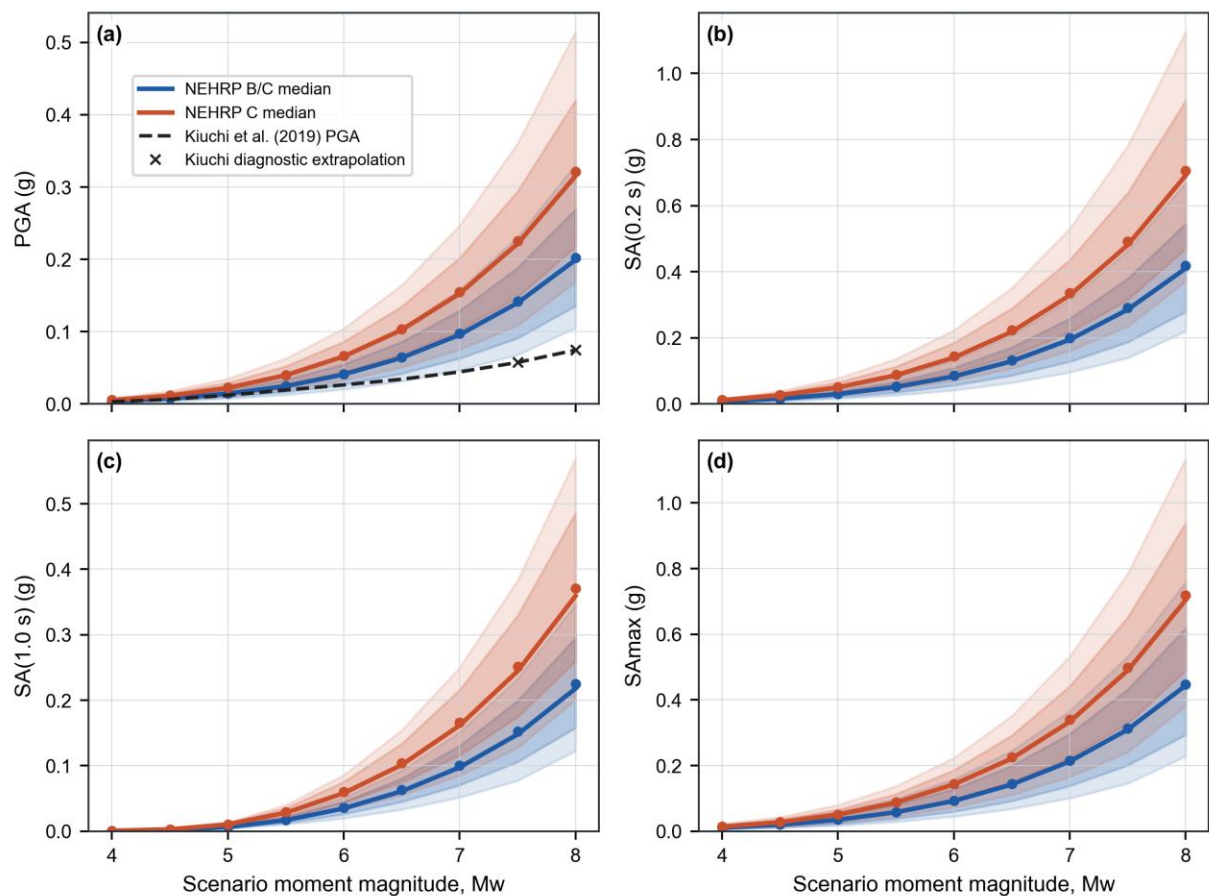
Finite-fault simulation is recommended when the estimated rupture length approaches at least one-half of the fixed source-to-site distance or when the scenario magnitude reaches $M_w \geq 7.0$. These criteria do not modify the point-source spectra reported in this study; rather, they identify scenarios that warrant further evaluation using finite-fault or broadband simulation before being considered for final design-basis applications. At the highest magnitudes, they also provide a basis for assessing whether the assumed earthquake scenario is physically plausible for the source region.

4 Results

The deterministic seismic-demand spectra increase systematically with moment magnitude for both site classes (Fig. 5). For the Mw 4.0 scenario, the predicted ground motions at Baish Dam remain low, with PGA values

of 0.004 g for NEHRP B/C and 0.005 g for NEHRP C. At Mw 6.0, the predicted demand increases to PGA = 0.041 g, SA(0.2 s) = 0.085 g, and SA(1.0 s) = 0.036 g for NEHRP B/C, compared with PGA = 0.066 g, SA(0.2 s) = 0.144 g, and SA(1.0 s) = 0.060 g for NEHRP C. For the Mw 8.0 upper engineering-screening scenario, the predicted demand reaches PGA = 0.202 g, SA(0.2 s) = 0.419 g, SA(1.0 s) = 0.225 g, and S_{Amax} = 0.448 g at T = 0.112 s under NEHRP B/C conditions. Under NEHRP C conditions, the corresponding values are PGA = 0.321 g, SA(0.2 s) = 0.705 g, SA(1.0 s) = 0.371 g, and S_{Amax} = 0.719 g at T = 0.266 s. The systematically higher seismic demand predicted for NEHRP C relative to NEHRP B/C represents a site-condition effect, primarily associated with the lower Vs30, frequency-dependent site amplification, and the response characteristics of short-period oscillators. Thus, the difference between the two site classes reflects site-response sensitivity at a given earthquake magnitude and fixed source-to-site geometry, rather than a magnitude-dependent effect. The results demonstrate that site condition can substantially modify the engineering seismic demand predicted for the same deterministic earthquake scenario.

The regional ground-motion benchmark predicts PGA values of 0.003 g at Mw 4.0, 0.026 g at Mw 6.0, 0.044 g at Mw 7.0, and 0.074 g at Mw 8.0 for the fixed Baish Dam source-to-site distance. The corresponding ratios of the stochastic NEHRP B/C median predictions to the benchmark values are 1.28, 1.57, 2.20, and 2.72, respectively. Thus, the stochastic simulations systematically predict higher PGA than the empirical benchmark across the entire magnitude range considered, with the positive offset increasing progressively with magnitude. This pattern is more appropriately interpreted as a systematic, magnitude-dependent difference between the two ground-motion approaches than as a discrepancy that emerges only at larger magnitudes. Several factors may contribute to this systematic offset, including the adopted mean stress drop of 100 bar, the relatively high radiation coefficient (up to 0.90) used for the near-source strike-slip geometry, and differences in the tectonic and faulting characteristics represented by the two approaches. In particular, the regional empirical benchmark is derived largely from normal-faulting earthquakes associated with a broad regional swarm and therefore may not fully represent the mechanism-specific radiation characteristics of the 2014 Jazan strike-slip source. The comparison is consequently most informative at small to moderate magnitudes, where the empirical model is better constrained by observations. At larger magnitudes, the increasing discrepancy should be interpreted cautiously because the benchmark involves extrapolation beyond its principal empirical magnitude range. The sources and implications of this systematic offset are examined further in the subsequent uncertainty and sensitivity analysis.



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429 **Fig. 5** Magnitude scaling of deterministic scalar ground-motion ordinates at Baish Dam. Solid curves show posterior median
430 ordinates, shaded bands show 16-84% and 5-95% Bayesian uncertainty, and point markers show the deterministic median scenario
431 values. Panel (a) also shows the regional PGA benchmark introduced earlier; the crossed markers beyond about Mw 7 mark values
432 obtained by extrapolating that benchmark beyond its supported magnitude range

433

434 **Table 2.** Deterministic median scenario demand at Baish Dam for selected future magnitudes. SA(1.0 s) = 0.000 g for the Mw 4.0 /
435 NEHRP B/C case reflects rounding to three decimal places, not a null value.

Site class	Mw	PGA (g)	SA(0.2 s) (g)	SA(1.0 s) (g)	SAmx (g)	T at SAmx (s)
NEHRP B/C	4.0	0.004	0.007	0.000	0.011	0.079
NEHRP B/C	6.0	0.041	0.085	0.036	0.093	0.106
NEHRP B/C	8.0	0.202	0.419	0.225	0.448	0.112
NEHRP C	4.0	0.005	0.012	0.001	0.014	0.100
NEHRP C	6.0	0.066	0.144	0.060	0.145	0.237
NEHRP C	8.0	0.321	0.705	0.371	0.719	0.266

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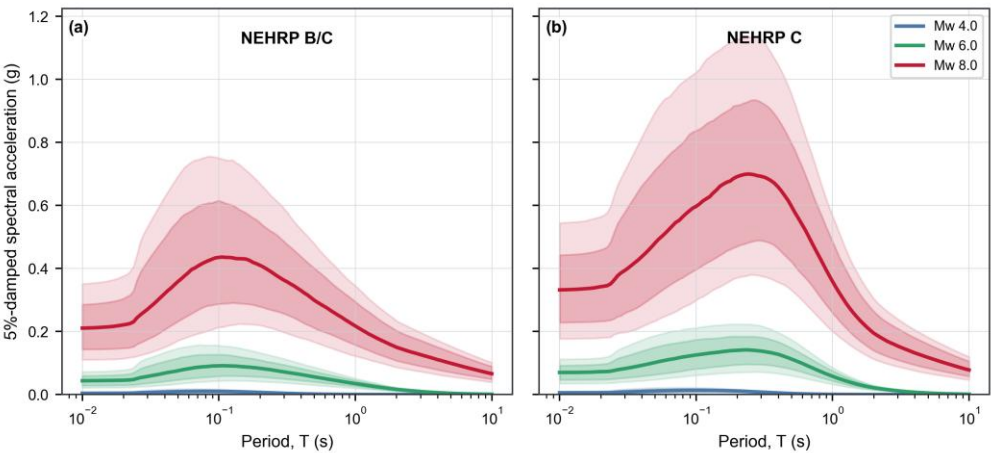
The damped response spectra of 5% demonstrate (Fig. 6) that the difference between the two site classes is not a uniform amplification across the period range. Instead, the NEHRP C condition produces stronger amplification over the short- to intermediate-period range, which encompasses the periods associated with the principal spectral peaks. At Mw 8.0, the ratios of NEHRP C to NEHRP B/C demand are approximately 1.59 for PGA, 1.69 for SA(0.2 s), 1.65 for SA(1.0 s), and 1.61 for SAmax (Fig. 7). These results indicate that the contrast between the two site conditions is period dependent, reflecting the combined effects of Vs30-dependent site amplification and kappa-controlled high-frequency attenuation, rather than a simple constant scaling of the entire response spectrum.

The Bayesian framework quantifies epistemic uncertainty in the deterministic seismic-demand scenarios while preserving their deterministic source–site configuration. The parameter distributions are specified as Gaussian and truncated where physically or empirically justified, with their central values and bounds constrained by the published source, path, and site information. The uncertainty model is therefore conditioned on seismological and engineering parameter constraints rather than earthquake recurrence statistics, which are not used to define the governing deterministic spectra. For the Mw 8.0 upper engineering-screening scenario, the NEHRP B/C posterior distributions yield posterior median values and 5th–95th percentile credible bounds (Table 3; Fig. 8) of $PGA = 0.105\text{--}0.199\text{--}0.330$ g, $SA(0.2\text{ s}) = 0.220\text{--}0.410\text{--}0.669$ g, $SA(1.0\text{ s}) = 0.122\text{--}0.218\text{--}0.346$ g, and $SA_{max} = 0.228\text{--}0.444\text{--}0.759$ g, respectively. Under NEHRP C conditions, the corresponding values are $PGA = 0.168\text{--}0.315\text{--}0.515$ g, $SA(0.2\text{ s}) = 0.371\text{--}0.691\text{--}1.127$ g, $SA(1.0\text{ s}) = 0.201\text{--}0.359\text{--}0.569$ g, and $SA_{max} = 0.380\text{--}0.704\text{--}1.134$ g. Here, the central values represent the posterior medians, while the lower and upper values define the 5th and 95th percentile credible bounds, respectively, thereby quantifying the epistemic uncertainty in the predicted seismic demand. The median values represent the central deterministic scenario estimates, whereas the 5th–95th percentile bounds quantify the propagated epistemic uncertainty associated with the source, path, and site parameters. The wider credible ranges for NEHRP C further demonstrate the sensitivity of the predicted seismic demand to site conditions under the upper-bound magnitude scenario. For Mw 8.0, NEHRP B/C posterior 5-50-95% intervals are $PGA = 0.105\text{--}0.199\text{--}0.330$ g, $SA(0.2\text{ s}) = 0.220\text{--}0.410\text{--}0.669$ g, $SA(1.0\text{ s}) = 0.122\text{--}0.218\text{--}0.346$ g, and $SA_{max} = 0.228\text{--}0.444\text{--}0.759$ g. For NEHRP C, the corresponding intervals are $PGA = 0.168\text{--}0.315\text{--}0.515$ g, $SA(0.2\text{ s}) = 0.371\text{--}0.691\text{--}1.127$ g, $SA(1.0\text{ s}) = 0.201\text{--}0.359\text{--}0.569$ g, and $SA_{max} = 0.380\text{--}0.704\text{--}1.134$ g.

471 **Table 3.** Bayesian 5-50-95% credible intervals for selected scalar ordinates at Baish Dam.

Site class	Mw	PGA (g)	SA(0.2 s) (g)	SA(1.0 s) (g)	SAmix (g)
NEHRP B/C	6.0	0.020-0.041-0.067	0.041-0.083-0.132	0.020-0.035-0.051	0.045-0.092-0.158
NEHRP B/C	8.0	0.105-0.199-0.330	0.220-0.410-0.669	0.122-0.218-0.346	0.228-0.444-0.759
NEHRP C	6.0	0.033-0.066-0.104	0.070-0.140-0.223	0.033-0.058-0.086	0.072-0.143-0.223
NEHRP C	8.0	0.168-0.315-0.515	0.371-0.691-1.127	0.201-0.359-0.569	0.380-0.704-1.134

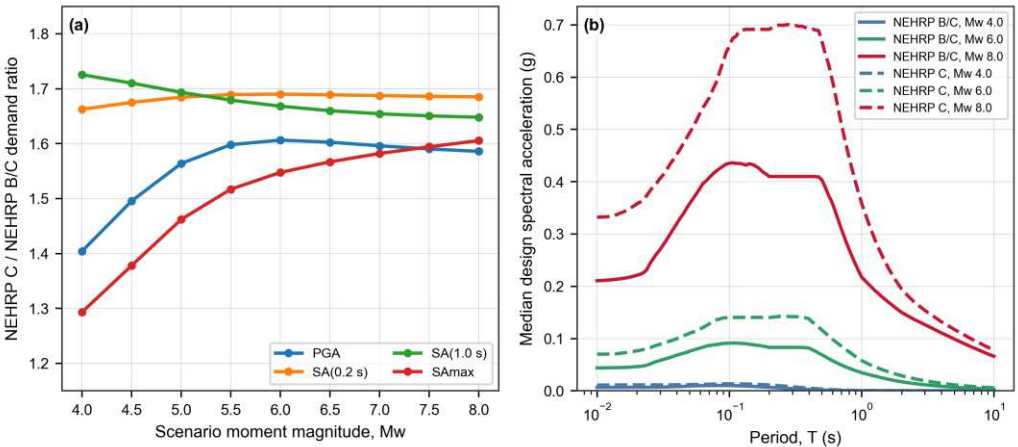
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474 **Fig. 6** Deterministic response-spectrum families for selected future magnitudes under NEHRP B/C and NEHRP C conditions.
475 Shaded bands show 5-95% and 16-84% Bayesian credible intervals. The periodic ripple beyond about T = 2 s is a Fourier-
476 discretization artifact, not a physical feature, and is not used in the engineering interpretation

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478

479 **Fig. 7** Engineering comparison of site-class effects. Panel (a) shows NEHRP C to NEHRP B/C demand ratios for scalar ordinates.
480 Panel (b) shows deterministic design-spectrum envelopes; as in Fig. 6, ordinates beyond about T = 2 s reflect a discretization
481 artifact

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The Mw 8.0 NEHRP B/C design-spectrum posterior median peaks at 0.436 g near $T = 0.106$ s, and its q95 peak reaches 0.756 g near $T = 0.084$ s; this q95 curve should be read as an epistemic upper design envelope for screening, not as a probability-of-exceedance spectrum. The Mw 8.0 NEHRP C design-spectrum posterior median peaks at 0.701 g near $T = 0.282$ s, and its q95 peak reaches 1.134 g near $T = 0.251$ s. As noted earlier, these design-envelope peaks are close to, but not required to exactly match, the S_{Amax} values in Table 2, because the two summaries are computed in a different order.

For the Mw 8.0 upper engineering-screening scenario, the NEHRP B/C posterior-median screening spectrum reaches a maximum spectral acceleration of 0.436 g at approximately $T = 0.106$ s, while the corresponding 95th-percentile posterior spectrum (q95) reaches 0.756 g at approximately $T = 0.084$ s (Fig. 9). The q95 spectrum represents an epistemic upper envelope of the predicted seismic demand for engineering screening and should not be interpreted as a probability-of-exceedance spectrum or as a formal design-basis spectrum. For NEHRP C conditions, the Mw 8.0 posterior-median screening spectrum reaches 0.701 g at approximately $T = 0.282$ s, whereas the corresponding q95 spectrum reaches 1.134 g at approximately $T = 0.251$ s (Fig. 10). The higher spectral demand and the shift in the period of maximum response relative to NEHRP B/C conditions reflect the period-dependent influence of site response associated with the lower V_{s30} and frequency-dependent amplification. The peak values of these screening envelopes are close to, but are not expected to exactly match, the S_{Amax} values reported in Table 2 because the two quantities are derived using different statistical aggregation procedures. S_{Amax} is obtained by first determining the maximum spectral acceleration for each stochastic realization and then summarizing the resulting distribution, whereas the q95 spectrum is obtained by determining the 95th percentile of spectral acceleration independently at each oscillator period and subsequently identifying the maximum of the resulting percentile curve. Consequently, the q95 spectral peak and the S_{Amax} statistic characterize different aspects of the posterior seismic-demand distribution and need not have identical amplitudes or peak periods.

The validation and engineering-diagnostic analyses indicate that the stochastic simulations reproduce the correct order of magnitude of PGA at small to moderate scenario magnitudes, but exhibit a persistent positive offset relative to the regional empirical benchmark that increases systematically with magnitude (Table 4). The mean absolute log-PGA residual is 0.226 for $M_w \leq 5.5$, corresponding to an average multiplicative difference of approximately 1.25, and increases to 0.398 when the smoothed empirical relation is extended to $M_w 7.0$, corresponding to a factor of approximately 1.49. This increasing discrepancy indicates a systematic difference between the stochastic and empirical ground-motion formulations rather than validation of the high-magnitude scenarios by the regional model. At $M_w 6.25$, the NEHRP C-to-B/C PGA ratio is 1.61, which is consistent with the lower end of the amplification range reported for the Jazan region from local microzonation studies, without applying the substantially larger amplification factors associated with softer coastal sites to

the Baish Dam site. The rupture-length screening further indicates that the point-source approximation is most defensible for Mw 4.0–6.0, for which the estimated strike-slip rupture lengths remain small relative to the 35.6 km source-to-site distance. At Mw 6.5, the estimated rupture length reaches approximately 0.51 times the source-to-site distance, increasing to approximately 6.6 times that distance at Mw 8.0, corresponding to a rupture length of about 230 km. Accordingly, the higher-magnitude results should be interpreted exclusively as deterministic engineering-screening scenarios, rather than as physically resolved finite-fault predictions. A formal design-basis assessment should incorporate finite-fault stochastic or broadband simulations and an explicit fault-specific maximum-magnitude assessment. The sensitivity analysis identifies the parameters that contribute most strongly to uncertainty in the largest scenario (Fig. 11). For Mw 8.0 SAm_{max}, the leading parameters for NEHRP B/C are stress drop ($\rho = 0.72$), Q0 ($\rho = 0.43$), and the Q exponent ($\rho = 0.34$). For NEHRP C, stress drop is the dominant parameter ($\rho = 0.81$), followed by Q0 ($\rho = 0.42$) and the site-amplification scale ($\rho = 0.29$). These results indicate that reducing epistemic uncertainty in stress drop, regional attenuation (Q0 and its frequency dependence), and site amplification would provide greater benefit than further refinement of the less influential source-orientation parameters for the upper-bound scenario.

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532 **Table 4.** Model validation, sensitivity, and point-source applicability checks.

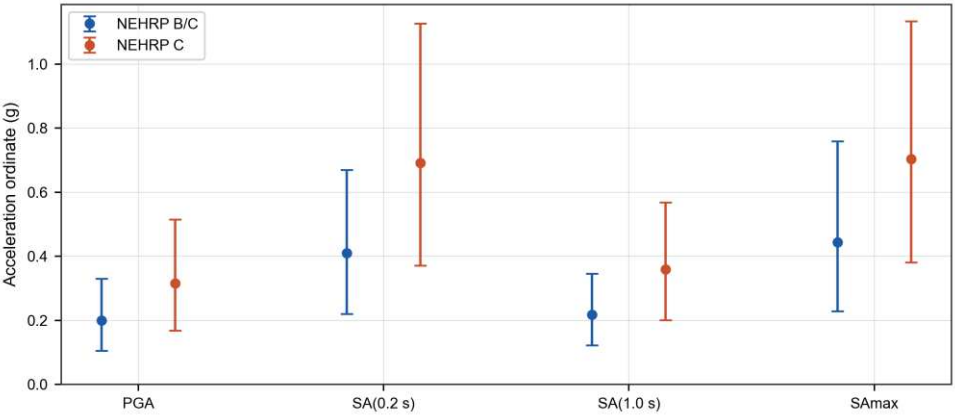
Check	Computed result	Reference or criterion	Interpretation
Regional PGA benchmark, Mw ≤ 5.5	Mean ln ratio = 0.226; factor = 1.25	Regional PGA regression range	Stochastic B/C PGA is systematically higher than the empirical benchmark by about 25% on average, even within the constrained magnitude range; the source of this offset should be investigated further.
Regional PGA benchmark, Mw ≤ 7.0	Mean ln ratio = 0.398; factor = 1.49	Author-smoothed extrapolation	The offset grows with magnitude, reinforcing caution for high-Mw cases.
Jazan site amplification	C/B-C PGA ratio at Mw 6.25 = 1.61	Local amplification lower bound, about 1.6	Class-C scaling is consistent with the lower local microzonation constraint.
Point-source applicability	First flagged at Mw 6.5; rupture length / site distance = 0.51	Finite-fault check when this ratio ≥ 0.5, or Mw ≥ 7.0	Mw 6.5-8.0 scenarios should be followed by finite-fault simulation before final design-basis use.
Mw 8.0 SAm _{max} sensitivity	B/C: stress drop ($\rho=0.72$), Q0 ($\rho=0.43$); C: stress drop ($\rho=0.81$), Q0 ($\rho=0.42$)	Ranked Spearman correlations	Stress drop and regional attenuation dominate the posterior spread of the largest spectral demand.

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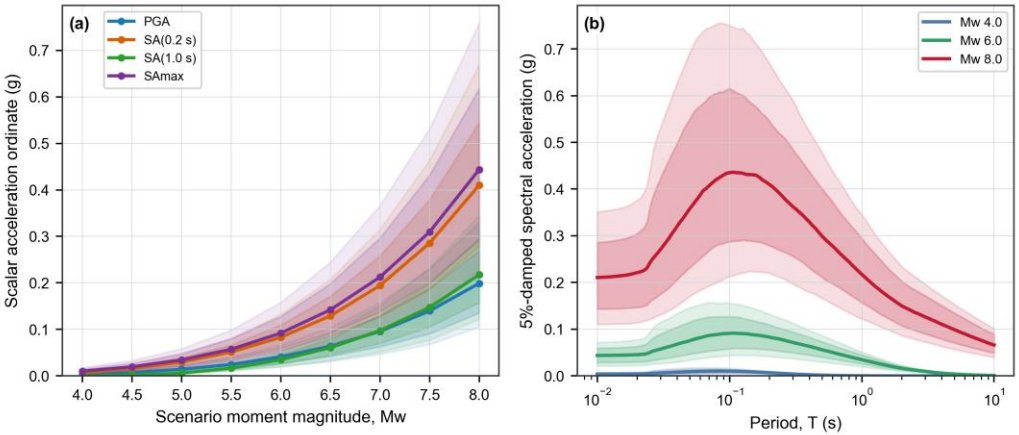


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Fig. 8 Mw 8.0 posterior uncertainty in the principal engineering ground-motion ordinates. Symbols are posterior medians and whiskers are 5-95% credible intervals

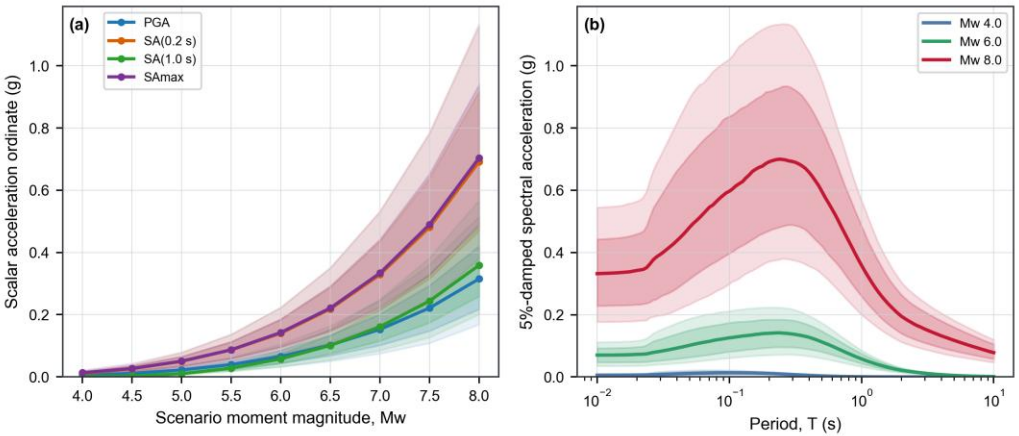


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Fig. 9 Bayesian uncertainty for NEHRP B/C conditions at Baish Dam. Panel (a) shows scalar ground-motion ordinates against moment magnitude; panel (b) shows response spectra for Mw 4.0, 6.0, and 8.0



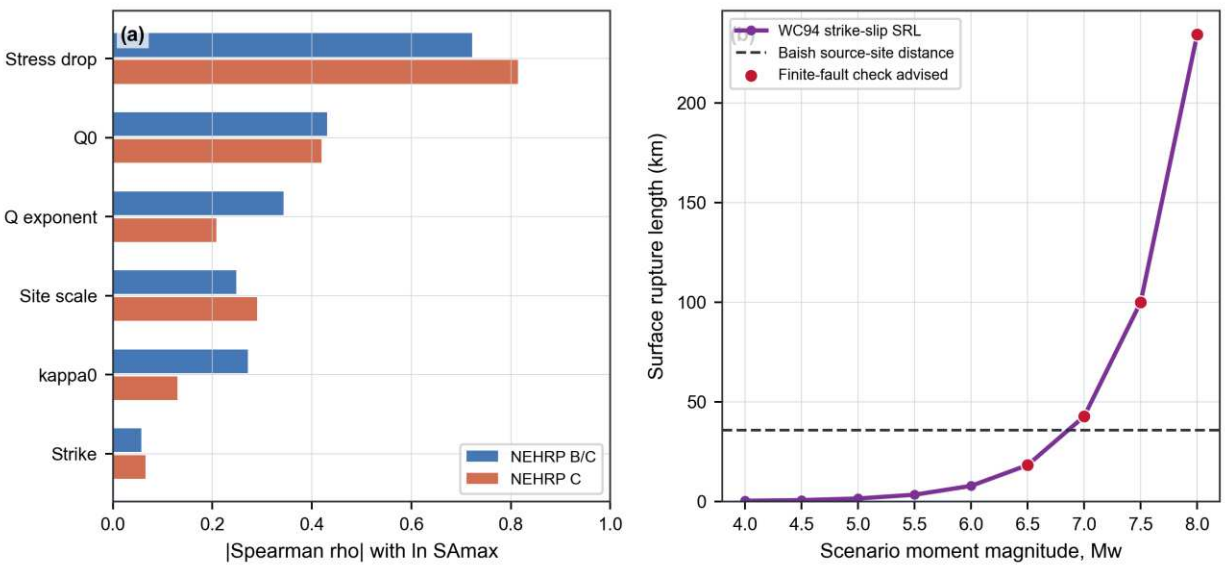
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Fig. 10 Bayesian uncertainty for NEHRP C conditions at Baish Dam. Panel (a) shows scalar ground-motion ordinates against moment magnitude; panel (b) shows response spectra for Mw 4.0, 6.0, and 8.0

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Fig. 11 Engineering diagnostic checks. Panel (a) ranks the dominant posterior inputs for M_w 8.0 S_{Amax} by absolute Spearman correlation with log spectral demand. Panel (b) compares the Wells and Coppersmith (1994) strike-slip surface rupture length with the fixed Jazan-Baish source-site distance; scenarios at or beyond the crossover are flagged for finite-fault follow-up

5 Discussion

The results are consistent with local microzonation evidence that Jazan-area ground motion is strongly sensitive to near-surface conditions; borehole-based studies of the coastal area report substantial amplification variation, with the largest amplifications associated with thick soft deposits. The present Baish Dam scenarios do not import those high coastal-basin amplification factors directly, since the dam site is treated through two specified engineering V_{s30} classes rather than a full borehole-calibrated profile. Even so, the computed NEHRP C/B-C ratios of about 1.6-1.7 for the important short- and intermediate-period ordinates are directionally consistent with the conclusion that site condition can materially alter engineering demand. The adopted Q relation is also consistent with recent regional attenuation work, and near-surface attenuation studies on the onshore southeastern Red Sea flank show that measured κ varies with geology and distance; κ_0 is nonetheless held to the same range for both site classes here so that the NEHRP comparison is controlled by V_{s30} -based amplification rather than by different assumed κ values. The regional ground-motion equation used for benchmarking is the most directly relevant empirical check available for western Saudi Arabia, since it was developed from more than 2700 local records, including the 2014 Jazan sequence itself. Three aspects of that model are used here: its reference V_{s30} of 760 m/s, its use of epicentral distance for a fixed source-site path, and its magnitude and distance scaling for PGA. The comparison shows that the stochastic PGA scale is of the same order of magnitude as the benchmark over the primary magnitude range, but is systematically

570 higher by a growing margin, from about 28% at Mw 4.0 to a factor of about 2.7 at Mw 8.0. This divergence is
571 not treated here as a simple calibration failure, since the benchmark model was developed mainly from local-
572 magnitude data between about M 3 and M 5.5, does not publish response-spectral equations, and is dominated
573 by normal-faulting events from a regional swarm rather than by strike-slip sources comparable to Jazan. It is,
574 however, a clear and so far unresolved discrepancy that should be investigated directly, for example by testing
575 a lower stress-drop prior or revisiting the radiation-coefficient bound, before the stochastic PGA scale is treated
576 as fully validated.

577 Compared with regional source-zone hazard assessments for southwestern Saudi Arabia (e.g., Arfa et al.,
578 2024), the present analysis has a narrower and complementary purpose. It does not attempt to map annual
579 exceedance probability or regional recurrence; instead, it converts one tectonically justified, focal-mechanism-
580 explicit nearby source into a family of deterministic response spectra and uncertainty envelopes for a single
581 critical facility. This distinction matters for engineering use, because the spectra are controlled by the source-
582 site scenario itself rather than by the long-term frequency of that scenario, and a direct numerical comparison
583 against areal-source regional hazard results was not attempted here, since the two approaches use different
584 source models and site assumptions; such a comparison is a useful cross-check for future studies.

585 Because this distinction is central to how the results should be used, it is discussed here in full rather
586 than left to a single introductory paragraph. The classical deterministic seismic hazard analysis procedure, as
587 formalized by Reiter (1990) and applied routinely in dam and critical-facility engineering, proceeds through
588 four fixed steps: (1) identify and characterize the causative source or fault; (2) select a single controlling
589 earthquake, usually the maximum credible earthquake (MCE) for that source, placed at its closest physical
590 approach to the site; (3) estimate the resulting ground motion for that one magnitude-distance-mechanism
591 combination, typically through an attenuation relationship; and (4) express the hazard as a single scenario
592 spectrum, with no reference to annual-exceedance probability. Table 5 compares each of these four steps
593 against what is actually implemented in this study.

594 Based on Table 5, the method is faithful to classical DSHA at step 1 and at step 4. It departs from steps
595 2 and 3 by design, not by omission. The departure at step 2 is the more consequential one: the classical
596 procedure derives its “worst case” character specifically from combining a rupture-justified MCE with a
597 closest-approach source-to-site distance, so that the single reported scenario is defensible as an upper bound.
598 Substituting a magnitude sweep at a fixed, historically observed epicenter removes that worst-case guarantee
599 for any individual magnitude in the sweep, since the Mw 8.0 case is explicitly not underpinned by a fault-
600 specific rupture-capacity study, and the fixed 35.6 km epicentral distance is not necessarily the closest approach
601 a larger rupture could achieve. The departure at step 3 moves in the opposite direction: replacing a single

attenuation-equation evaluation with a full stochastic simulation and Bayesian parameter propagation adds a quantified epistemic-uncertainty dimension that classical DSHA, being a single-valued procedure by construction, does not provide at all.

Table 5. Comparison between the classical single-controlling-earthquake DSHA procedure and the method implemented in this study.

Classical DSHA step	Classical requirement	What this study does
1. Source characterization	Identify and characterize the causative fault or source zone	Uses the well-located 2014 Jazan earthquake focal mechanism, coupled explicitly through the double-couple radiation model
2. Controlling-earthquake selection	Select one governing magnitude (the MCE), placed at its closest approach to the site	Sweeps nine scenario magnitudes (Mw 4.0-8.0) at the fixed 2014 epicentral location; Mw 8.0 is an engineering screening bound, not a fault-specific MCE, and closest-approach geometry is not invoked
3. Ground-motion estimation	Estimate ground motion for the single selected magnitude-distance pair, usually via one attenuation equation	Runs a mechanism-aware stochastic simulation for every swept magnitude, with Bayesian propagation of source, path, and site parameters (500 realizations each)
4. Hazard expression	Express the hazard as a single scenario spectrum	Reports a family of scenario spectra plus posterior median, 5-16% and 84-95% credible intervals at each magnitude; consistent with the classical criterion

The practical implication is that the results presented herein should be interpreted as magnitude-sensitive seismic-demand scenarios and an engineering-level site-screening assessment, rather than as a certified controlling or worst-case design earthquake for Baish Dam. This is consistent with how the manuscript already frames Mw 8.0 (Section 3.1) and with the future-work items listed in Section 5.5: a fault-specific maximum-magnitude study and, where relevant, a closest-approach source geometry would need to be established before any single magnitude in this sweep could be adopted as a classical MCE for final design-basis use. Until then, the appropriate use of this dataset is exactly the one recommended in Table 6: screening, prioritization, and sensitivity analysis, run alongside, rather than in place of, a facility-specific probabilistic hazard analysis and a subsequent fault-specific deterministic study.

The method follows international scenario-based practice for critical infrastructure, in which deterministic motions are used to examine credible earthquake impacts, sensitivity to site condition, and the adequacy of screening-level design spectra, consistent with international guidance on selecting seismic parameters for large dams. The stochastic simulation follows established engineering-seismology practice, and the design-envelope step makes the spectral output easier to use in structural analysis and code-style comparison. The Bayesian uncertainty model adds transparency by showing how stress drop, Q_0 , η_a , κ_0 , site amplification, focal mechanism, and depth affect the posterior spread of engineering demand, and the sensitivity ranking shows that stress drop and regional attenuation dominate the Mw 8.0 S_{Amax} uncertainty,

so future field and inversion work should focus first on source stress parameterization, $Q(f)$, and local site response rather than treating every uncertain input as equally important. For a large scenario such as Mw 8.0, a point-source model should be read as conservative screening input rather than a finite-fault design basis, and, as discussed earlier, the physical feasibility of an Mw 8.0 rupture on the local source structure has not itself been demonstrated. The rupture-length check indicates that finite-fault effects become important from about Mw 6.5-7.0 for the fixed Jazan-Baish geometry. Directivity, rupture dimensions, asperity layout, near-fault fling, and basin-edge effects are not explicitly represented. The point-source framework nonetheless remains useful at this screening stage, because it isolates source, path, and site sensitivity and can be applied consistently across a full magnitude sweep before more expensive finite-fault simulations are commissioned for the upper end of the range.

The engineering implication is that the seismic-safety screening of Baish Dam should not rely exclusively on a single posterior-median response spectrum. For the Mw 8.0 upper engineering-screening scenario, the NEHRP C q95 spectrum reaches a maximum spectral acceleration exceeding 1.1 g, whereas the corresponding NEHRP B/C q95 spectrum remains below 0.76 g. These results demonstrate a substantial epistemic spread in the predicted short-period seismic demand, which may be relevant to prioritizing dam instrumentation, foundation and site characterization, spillway and appurtenant-structure assessments, and emergency-action planning. From a risk-mitigation perspective, the results support three practical actions. First, site characterization at and beneath the dam should be improved to determine whether the controlling engineering site condition is more appropriately represented by the NEHRP B/C or NEHRP C case, because this choice produces differences of approximately 60–70% in spectral demand over portions of the analyzed period range. Second, subsequent dynamic assessment of the dam system should consider a range of seismic-demand inputs, including the posterior-median spectrum and the q95 epistemic upper envelope, rather than relying on a single median scenario. Such analyses should be complemented by a facility-specific PSHA and, where warranted, finite-fault ground-motion simulations, because the present DSHA is an engineering-screening assessment and does not establish the probabilistic design hazard or a fault-specific design-basis earthquake. Third, continued regional seismic monitoring and periodic updates of earthquake locations and focal mechanisms should be incorporated into future assessments, because the source-specific radiation contribution is sensitive to the assumed strike, dip, rake, and source depth.

658 **Table 6.** Recommended engineering use of the deterministic Bayesian spectra for Baish Dam.

Application	Recommended use	Caution
Dam-safety screening	Use median and q95 design spectra as input envelopes for preliminary dynamic checks.	Not a substitute for nonlinear dam-reservoir-foundation modelling or a facility-specific probabilistic hazard analysis.
Site investigation	Prioritize Vs30, depth-to-bedrock, and material-damping measurements near the dam axis and appurtenant structures.	Do not transfer high coastal-basin amplification factors without local profiles.
Instrumentation	Use the scenario spectra to guide strong-motion station placement and trigger-level review.	Instrumentation thresholds require owner-specific operational criteria.
Emergency planning	Use Mw 6-8 spectra to support scenario exercises and consequence screening.	The spectra do not provide event probabilities or annual exceedance rates.
Future refinement	Move from point-source to finite-fault stochastic simulations for final design-basis review; establish a fault-specific maximum magnitude; resolve the benchmark offset.	Finite-fault geometry, rupture directivity, and maximum magnitude remain major uncertainties.

659

660 The principal limitations of this study follow directly from its intended deterministic, engineering-screening
661 scope. As stated in the Introduction, the analysis represents a scenario-sweep extension of DSHA rather than
662 the classical single-controlling-earthquake procedure. Accordingly, it explores a prescribed magnitude range
663 at the historically observed 2014 Jazan epicentral location rather than identifying a single governing maximum
664 credible earthquake (MCE) and placing its rupture at the closest physically credible approach to the dam. This
665 methodological choice is the principal source of several limitations. First, the earthquake source is fixed at the
666 2014 Jazan epicentre, and finite-fault dimensions and rupture directivity are not explicitly modelled. Moreover,
667 the rupture-length screening indicates that no fault-specific maximum-magnitude assessment presently
668 supports the Mw 8.0 upper scenario. This magnitude should therefore be interpreted strictly as a conservative
669 upper engineering-screening bound, rather than as a demonstrated site-specific maximum magnitude or design-
670 basis earthquake. Second, local dam-foundation conditions are represented using two engineering Vs30 site
671 classes rather than measured, depth-dependent site-response models. Third, the Bayesian uncertainty model
672 uses truncated Gaussian distributions, which provide a transparent and reproducible representation of epistemic
673 uncertainty but may not fully capture strongly skewed, asymmetric, or multimodal parameter distributions. In
674 addition, a common κ prior is adopted for both site classes, potentially limiting differentiation of high-
675 frequency attenuation between the two site conditions. Fourth, comparison with the regional PGA benchmark
676 reveals a systematic, magnitude-dependent positive offset that remains unresolved and therefore represents an
677 important modelling uncertainty rather than a confirmed physical bias. Finally, the analysis does not evaluate
678 dam-system fragility, structural or geotechnical damage, loss, liquefaction, slope instability, or reservoir-
679 induced seismic effects. These processes require coupled geotechnical, structural, and risk models beyond the
680 present screening framework. Future study should therefore: (i) establish a fault-specific maximum magnitude

using rupture-length and/or seismogenic-width scaling before extending the upper magnitude range to design applications; (ii) develop finite-fault stochastic and broadband simulations for selected Mw 6.5–8.0 scenarios; (iii) constrain site response at Baish Dam using downhole, surface-wave, or other in-situ measurements; (iv) diagnose the systematic PGA offset and, where justified, reassess the adopted stress-drop prior and radiation-coefficient bounds; (v) evaluate alternative regional and NGA-style ground-motion models within a formal logic-tree framework and directly compare the results with areal-source regional hazard assessments; and (vi) couple the resulting ground motions with dam-system fragility, vulnerability, and consequence models.

6 Conclusions

A deterministic, focal-mechanism-explicit Bayesian point-source stochastic framework was developed to screen seismic demands at Baish Dam from the 2014 Jazan earthquake source. The focal mechanism is explicitly incorporated through its double-couple moment tensor and the resulting S-wave radiation coefficient. For the Mw 8.0 upper engineering-screening scenario, the median PGA/S_{Amax} values are 0.202/0.448 g for NEHRP B/C and 0.321/0.719 g for NEHRP C. The associated epistemic uncertainty is substantial: for S_{Amax}, the 5th percentile, posterior median, and 95th percentile credible bounds are 0.228, 0.444, and 0.759 g for NEHRP B/C, and 0.380, 0.704, and 1.134 g for NEHRP C, respectively. The estimated ~230 km rupture length required for Mw 8.0 greatly exceeds the dimensions of mapped local fault segments; therefore, this scenario represents a conservative engineering upper bound, not a demonstrated site-specific MCE. Comparison with the regional PGA relationship shows a systematic, magnitude-dependent positive offset, increasing from ~28% at Mw 4.0 to ~2.7 times at Mw 8.0, highlighting the need for further calibration. Stress drop and regional attenuation are the dominant uncertainty controls. Rupture-dimension screening indicates that Mw ≥6.5 scenarios should be evaluated using finite-fault simulations. The resulting spectra are conditional engineering demands for specified magnitudes and source-to-site geometry and are therefore intended for preliminary hazard screening, scenario development, and risk-mitigation planning, rather than final dam-design criteria. Further work should establish the fault-specific maximum magnitude, resolve the empirical-model discrepancy, and independently validate upper-magnitude scenarios using finite-fault simulations and facility-specific seismic-hazard and risk analyses.

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Statements and Declarations

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Competing interests

The authors declare that they have no competing interests.

782 **Author contributions**

783 Hashim Al Aoun: Formal analysis, Investigation, Project administration, Resources, Writing, review &
784 editing; Ali Abdelfattah: Conceptualization, Data curation, Formal analysis, Investigation, Methodology,
785 Software, Supervision, Validation, Visualization, Writing original draft, Writing, review & editing; Abdullah
786 Al-Amri: Project administration, Resources, Supervision, Writing, review & editing; Hassan Alzahrani:
787 Funding acquisition, Investigation, Project administration, Resources, Visualization.

788

789 **Data availability**

790 The earthquake source parameters, focal-mechanism solutions, computed spectra, Bayesian samples,
791 validation summaries, sensitivity rankings, finite-fault screening results, and figure source data are available
792 in the project files and can be supplied by the corresponding author upon reasonable request.

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