

Probabilistic seismic hazard assessment at bedrock conditions for the Jizan Region, Southwestern Saudi Arabia

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Abstract: The current work presents a probabilistic seismic hazard assessment (PSHA) for engineering bedrock conditions ($V_{s30} = 760$ m/s) across the Jizan region of southwestern Saudi Arabia. For this purpose, we compiled a homogenised earthquake catalogue covering 827–2022 CE, including historical and instrumental records from multiple authoritative sources. All magnitude types are converted to moment magnitude (M_w) using orthogonal regression. After declustering and completeness analysis, we defined eight area-source zones to represent the tectonic variations of the Red Sea rift, the Gulf of Aden, the Arabian Shield, and adjacent Yemeni crustal domains. Seismicity in each zone was characterised with a doubly truncated Gutenberg–Richter model. The maximum magnitudes were estimated using the Kijko–Sellevoll–Bayes approach. To account for epistemic uncertainty in ground-motion attenuation, we employed a logic tree with four GMPEs weighted equally: *Abrahamson et al. (2014)*, *Akkar et al. (2014)*, *Chiou and Youngs (2014)*, and *Zhao et al. (2006)*. Resulting bedrock hazard maps show a clear north–south gradient across Jizan. For a 475-year return period ($\approx 10\%$ in 50 years), PGA rises from ~ 0.03 g in northern districts to ~ 0.06 g near the Yemeni border; for a 2,475-year return period ($\approx 2\%$ in 50 years), PGA increases from ~ 0.06 g to ~ 0.13 g. A site-specific Uniform Hazard Spectrum for the Baish development area indicates a peak spectral acceleration of ~ 85 cm/s² at $T \approx 0.2$ s for the 475-year return period and ~ 165 cm/s² for the 2,475-year return period. These results indicate that seismic demand in Jizan is controlled primarily by extensional deformation of the southern Red Sea and active crustal deformation in western Yemen. The study provides a robust bedrock-hazard baseline suitable for engineering design and urban planning in the Baish district.

Key words: Probabilistic Seismic Hazard Assessment (PSHA), uniform hazard spectrum, Jizan Region, Red Sea tectonics, Saudi Arabia

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1. Introduction

Accurate assessment of seismic ground shaking at engineering bedrock is a prerequisite for earthquake-resistant design and urban risk mitigation. Ground-motion intensity at a site results from the interaction of source characteristics, wave propagation effects, and local site geology. For hazard at the bedrock horizon, the source and path terms principally control regional seismic potential and thus provide the reference input motion for subsequent geotechnical and structural analyses (Kramer, 1996; Vessia *et al.*, 2021). Modern PSHA therefore emphasises robust characterisation of bedrock-level probabilistic ground motions using well-constrained seismicity models and empirically validated ground-motion prediction equations (GMPEs) (e.g., El-Hussain *et al.*, 2012; Ezzelarab *et al.*, 2018, 2021, 2025).

Seismic-hazard assessment across the Arabian Peninsula has progressed from early deterministic efforts to mature probabilistic frameworks. Foundational studies (Thenhaus *et al.*, 1989; Al-Haddad *et al.*, 1994) defined first-order hazard patterns for Saudi Arabia, while later work (Al-Amri *et al.*, 2008) highlighted sensitivities and showed that hazard estimates can vary by $\sim 40\%$ with catalogue quality and magnitude scaling. Recent regional maps produced by the Saudi Geological Survey have applied Monte Carlo methods and spatially smoothed seismicity to capture aleatory variability better and mitigate sparse instrumental coverage in low-seismicity areas (Zahran *et al.*, 2015; Sokolov *et al.*, 2017).

The Jizan region occupies a distinctive tectonic setting on the eastern margin of the Red Sea plate boundary, where extension between the Arabian and Nubian plates is measured at $\sim 10\text{--}16$ mm/yr (ArRajehi *et al.*, 2010). Prior investigations indicate hazard concentrating near the Red Sea coast in response to ongoing rifting: deterministic scenarios yielded PGA up to ~ 0.17 g along the coast (Abdelfattah *et al.*, 2022), while recent probabilistic estimates report PGA ≈ 0.04 g for a 475-year return period (Arfa *et al.*, 2024). Nonetheless, many existing assessments are limited by simplified seismicity models, heterogeneous catalogue quality, or incomplete treatment of epistemic uncertainty in GMPE selection. In addition, the Baish district is a rapidly urbanising inland area ~ 80 km from the coast, and it has not received a dedicated bedrock-level hazard characterisation.

Continuous updating of seismicity models and GMPEs is essential as new data emerge (Ezzelarab *et al.*, 2018; Petersen *et al.*, 2018). Compiling

a homogenised earthquake catalogue through 2022 that incorporates recent instrumental records (and benefits from global quality-control analogues such as the 2023 Kahramanmaraş sequence) materially improves the basis for regional PSHA. Implementing a logic tree to explicitly propagate epistemic uncertainty in GMPE choice further strengthens the defensibility of hazard estimates compared with single-model approaches.

This study fills those gaps by performing a comprehensive PSHA at engineering-bedrock conditions ($V_{s30} = 760$ m/s) for the Jizan region, with particular attention to the Baish development area. The objectives are: (1) compile and homogenize an updated catalogue spanning 827–2022 CE; (2) construct a physically consistent seismic-source model representing the Red Sea, Gulf of Aden, and adjacent crustal domains; (3) select and validate GMPEs appropriate for the regional extensional regime; and (4) produce high-resolution bedrock hazard maps and site-specific Uniform Hazard Spectra for Baish at multiple return periods. The resulting bedrock hazard characterisation provides a robust reference frame for seismic design and urban planning in one of Saudi Arabia’s fastest-growing regions.

2. Geology and tectonic setting

The Jizan administrative region lies along the eastern edge of the Red Sea rift system in southwestern Saudi Arabia (Fig. 1). This tectonic position is very important for the seismic hazard of the area because it sits on an active divergent plate boundary where the Arabian Plate moves away from the African (Nubian) Plate at about 10–16 mm/yr, as measured by geodetic studies (*ArRajehi et al., 2010; Baby et al., 2024*). The Red Sea rift shows a typical continental-to-oceanic transition: continental rifting began around 30 million years ago and has progressed to local seafloor spreading in the axial trough since the late Miocene (*Bosworth et al., 2005; Delaunay et al., 2024*).

The geological history of the Jizan region has produced a clear vertical layering that matters for site studies and for identifying the engineering bedrock. Geophysical work and regional geological maps (*Blank and Gettings, 1985; Bohannon et al., 1989*) show a simplified three-layer sequence (Fig. 2). Below about 200–500 m beneath the Baish coastal plain lies the crystalline basement composed of metamorphosed volcanic and plutonic

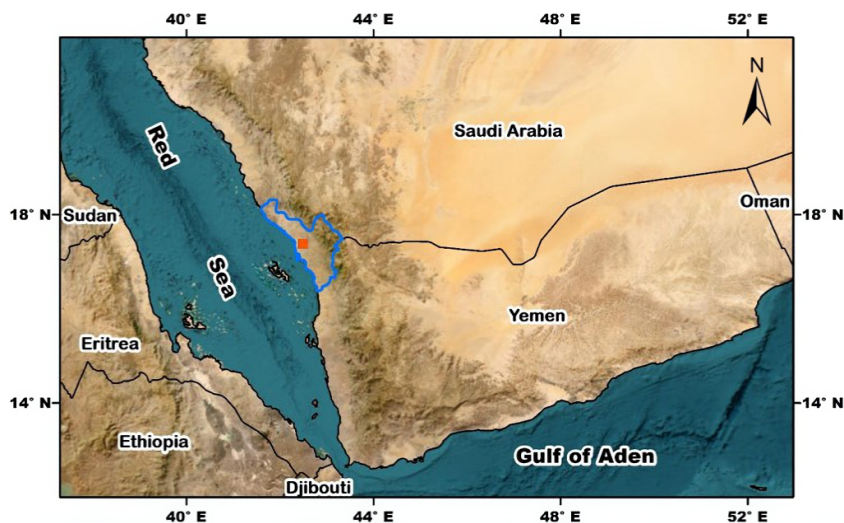


Fig. 1. Regional location map of the study area. The blue polygon outlines the Jizan administrative region in southwestern Saudi Arabia, situated along the eastern margin of the Red Sea rift system and adjacent to the Yemeni border. The Baish district (red box) is located approximately 80 km inland from the Red Sea coast.

rocks. Seismic refraction studies report high velocities for these rocks ($V_p \approx 5,800\text{--}6,200$ m/s, $V_s \approx 3,200\text{--}3,500$ m/s; *Mooney et al., 1985; Gettings et al., 1986*), so this level is used as the engineering bedrock reference ($V_{s30} \geq 760$ m/s) when assessing surface amplification. Above the basement, an intermediate unit at a depth of about 50 to 200 m depth contains interbedded marine carbonates, evaporites, and siliciclastic deposits laid down during the start of Red Sea rifting (*Hughes et al., 1991; Bosworth and Stockli, 2016*). The uppermost 0–50 m is made of unconsolidated to poorly consolidated sands, silts, and clays that come from wadi systems draining the nearby Arabian Shield (*Al-Sayari and Zötl, 1978; Edgell, 1997*).

The structural style of Jizan is controlled by extension. Main structures are high-angle normal faults, often listric, that trend N–S to NNW–SSE and run parallel to the rift. These faults form tilted blocks and half-grabens that step down toward the Red Sea (*Voggenreiter et al., 1988*). Large basaltic dike swarms cut the basement and cover rocks, showing crustal stretching and magma pathways. Thick Miocene salt layers have produced diapirs and related structural traps (*Gillman, 1968*).

The region is considered to have moderate to high seismic hazard because

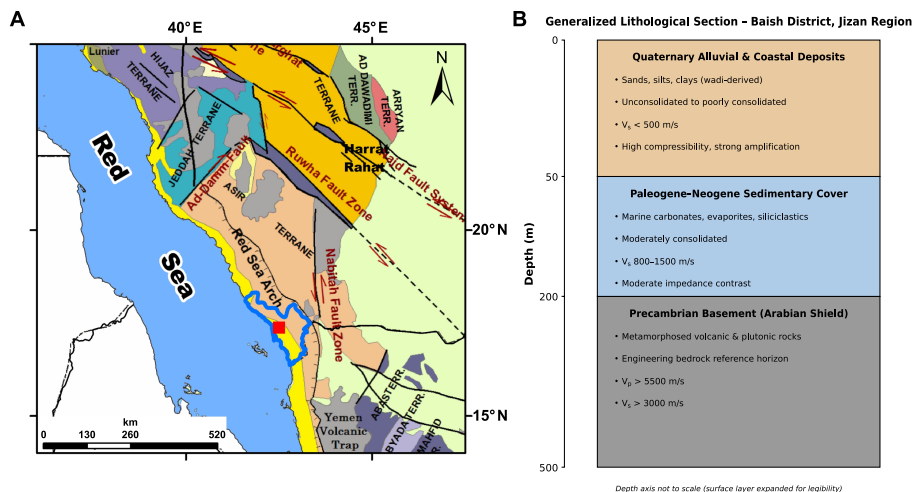


Fig. 2. Geological and tectonic framework of the study area. (A) Regional tectonic map of the southwestern Arabian Shield showing the location of the Jizan region (blue polygon) and the specific study site in the Baish District (red square). The map is modified by *El-Hussain et al. (2018)* after *Johnson (1998)*, *Bosworth et al. (2005)*, and *Al-Farajat et al. (2016)*. (B) Generalised lithological section of the Baish District, Jizan Region.

it lies on an active plate boundary (*Abdelrahman et al., 2021*). Earthquakes mainly come from the active spreading centre in the Red Sea axial trough and from the major normal faults on the rift shoulders. The seismotectonic setting of the Baish district is explained further in Section 3.1.2, where we relate it to the defined source zones.

3. Methodology

The seismic hazard assessment in this study uses a strict probabilistic framework based on the Cornell–McGuire approach (*Cornell, 1968; McGuire, 1976*) and a logic-tree to carry epistemic uncertainty. The work follows three main steps: (1) compile and quality-control an updated earthquake catalogue; (2) define and parameterise area seismic sources; and (3) compute probabilistic bedrock-level ground motions using a set of suitable GMPEs. The main result is the probabilistic ground motion at engineering bedrock ($V_{s30} \geq 760$ m/s), which we use as the reference hazard for the Jizan region and for the Baish development area.

3.1. Probabilistic seismic hazard analysis at bedrock

PSHA needs two main inputs. First is a seismicity model that lists all possible earthquake sources and gives how often they happen. Second are GMPEs that predict how strong the ground shaking will be at a site, depending on earthquake size, distance from the source, and the local ground conditions. We follow the usual procedure: for each source, we consider all combinations of magnitude and distance, multiply their occurrence rates by the probability that they will produce a given intensity, and then sum (integrate) over all sources to get the mean annual rate at which the site will exceed that ground-motion level.

3.1.1. Earthquake catalogue

We built a unified and homogeneous earthquake catalogue as the main input for the hazard assessment. We collected data inside the rectangular area 13°N – 22°N and 37°E – 53°E . This ensures that all seismicity relevant to Jizan is included.

For the historical period (827–1899 CE), we used three historical catalogues in order of priority: the Global Historical Earthquake Catalogue (*Albini et al., 2013*), the Earthquake Model of the Middle East catalogue (*Danciu et al., 2018*), and the Arabian Plate earthquake catalogue (*Deif et al., 2017*). The resulting historical list contains 25 notable events with M_w between 4.8 and 6.3.

Instrumental data (1900–2022) came, in priority order, from the ISC-GEM Global Instrumental Earthquake Catalogue (*Storchak et al., 2013, 2015; Di Giacomo et al., 2018*), the *International Seismological Centre* (2025), the Earthquake Model of the Middle East (*Danciu et al., 2018*), and the Arabian Plate catalogue (*Deif et al., 2017*). We removed duplicate entries using a coincidence window of ± 30 seconds and ± 50 km, keeping the higher-priority source when duplicates occurred. We converted all magnitude types to moment magnitude (M_w) using orthogonal regression relations developed here (Table 1; Figs. 3–4). The regressions show a very high fit ($R^2 = 0.98$ for $M_s \rightarrow M_w$; $R^2 = 0.96$ for $m_b \rightarrow M_w$), which supports the reliability of the homogenization.

We filtered the compiled catalogue to keep only events with $M_w \geq 3.5$, because smaller earthquakes produce high-frequency shaking of little struc-

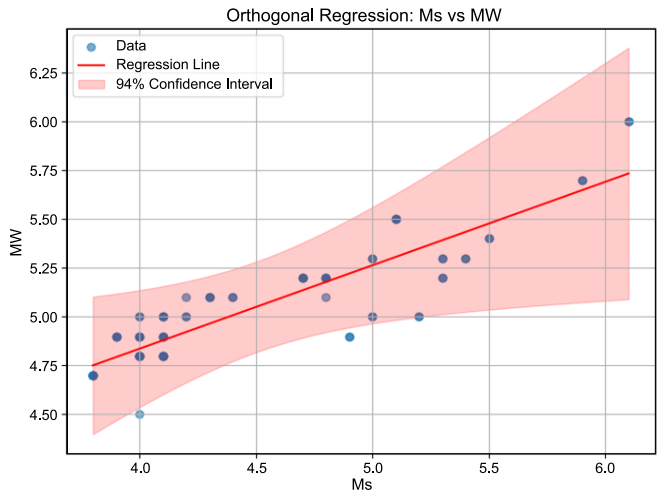


Fig. 3. Orthogonal regression of Surface-Wave Magnitude (Ms) versus Moment Magnitude (Mw).

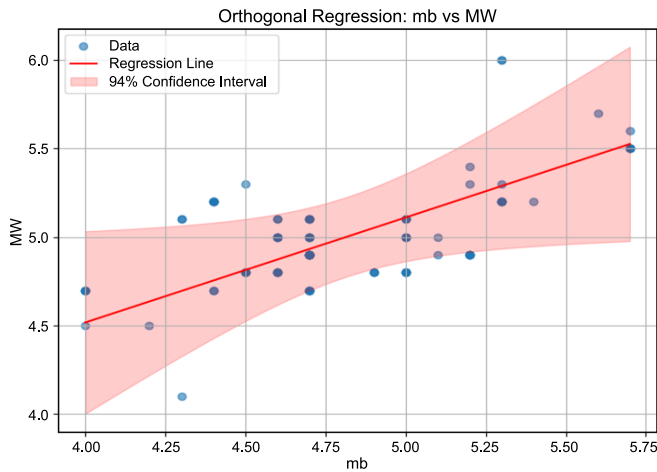


Fig. 4. Orthogonal regression of Surface-Wave Magnitude (mb) versus Moment Magnitude (Mw).

Table 1. Summary of orthogonal regression equations for magnitude conversion to Mw.

Conversion	Regression equation	Slope (β_1)	Intercept (β_0)	R^2
Ms $\rightarrow$ Mw	$Mw = 0.4274 Ms + 3.1262$	0.4274 ± 0.0253	3.1262 ± 0.1152	0.9835
mb $\rightarrow$ Mw	$Mw = 0.5930 mb + 2.1452$	0.5930 ± 0.0601	2.1452 ± 0.2906	0.9593

tural significance. To meet the Poisson assumption used in PSHA, we removed dependent events (aftershocks, foreshocks, and swarms) by applying three declustering methods: *Gardner and Knopoff (1974)*, *Uhrhammer (1986)*, and *Burkhard and Grünthal (2009)*. The results showed a similar overall level of dependent-event removal, with 58.2% events removed by Gardner–Knopoff, 57.7% by Grünthal, and 61.3% by Uhrhammer. Although Uhrhammer removed the largest number of events, the Gardner–Knopoff method was selected for the final analysis because it provides a balanced and widely used declustering approach that is well established in seismic hazard studies. This choice preserves a reasonable number of independent events for recurrence analysis while still effectively reducing aftershocks, foreshocks, and swarm-related dependence in the catalogue (Fig. 5).

We evaluated catalogue completeness using the Cumulative Visual Inspection (CUVI) method (*Tinti and Mulargia, 1985*). The resulting completeness thresholds are: $M_w \geq 3.5$ from 1995 onward; $M_w \geq 4.5$ from 1967; $M_w \geq 5.0$ from 1952; and $M_w \geq 5.5$ from 1912 (Fig. 6 and Table 2). We used these time-dependent thresholds to estimate recurrence parameters using the Weichert maximum-likelihood method. The spatial distribution of events that meet the completeness criteria is shown in Fig. 7.

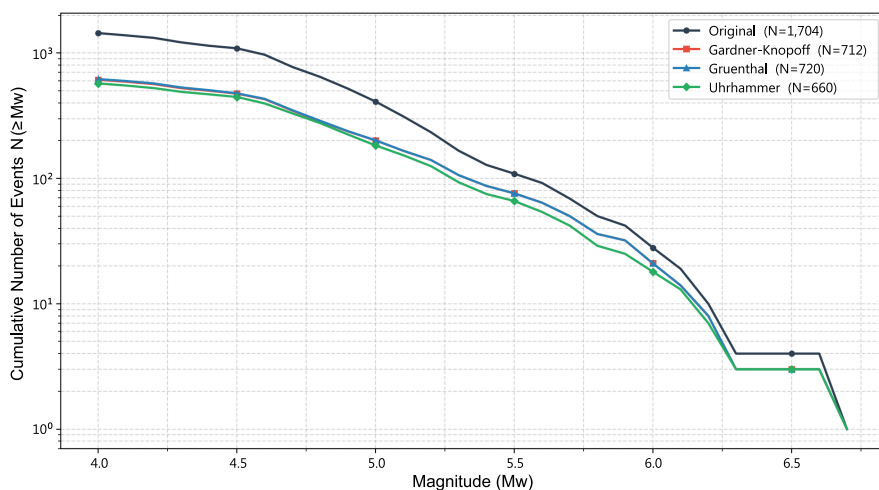


Fig. 5. Comparison of declustering algorithms. The figure illustrates the cumulative number of events retained and removed by the Gardner–Knopoff, Grünthal, and Uhrhammer declustering methods.

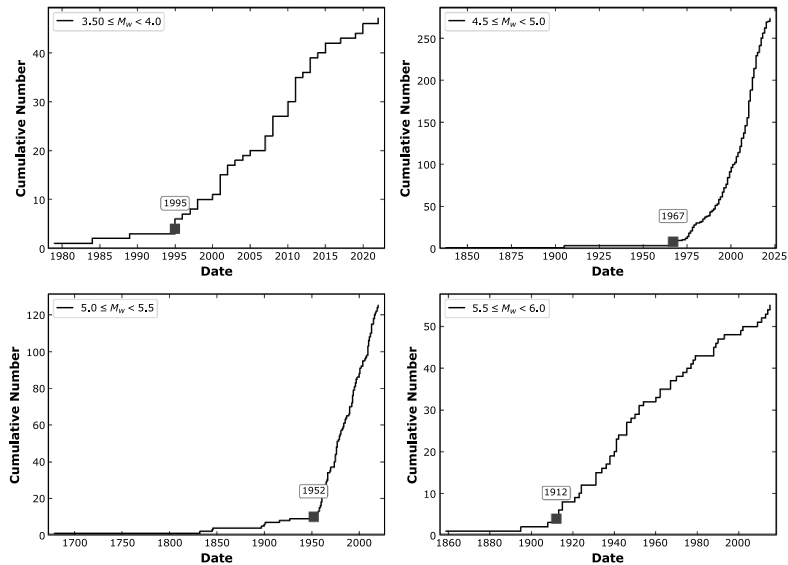


Fig. 6. Completeness analysis of the earthquake catalogue using the Cumulative Visual Inspection (CUVI) method. The plots display the cumulative number of earthquakes versus time for different magnitude (M_w) intervals. The solid squares indicate the year from which the catalogue is considered complete for each specific magnitude.

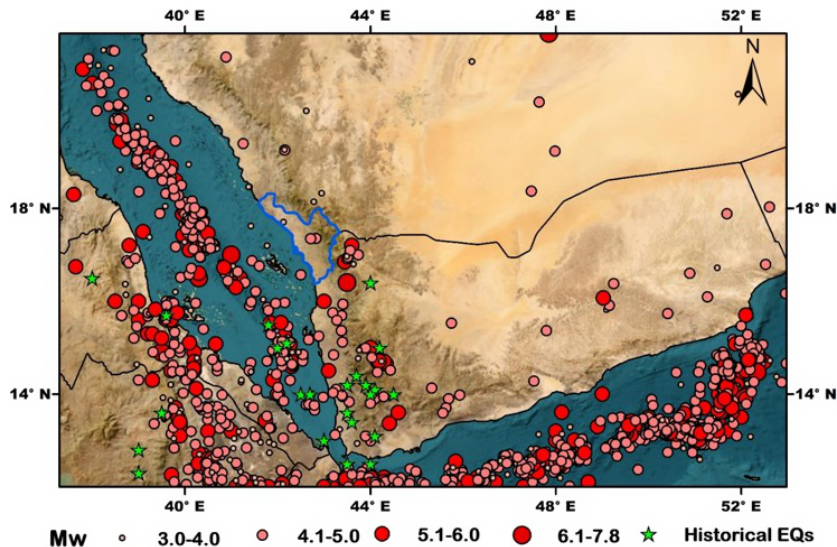


Fig. 7. Spatial distribution of the compiled earthquake catalogue for seismic hazard analysis at Jizan Region (blue polygon).

Table 2. Catalogue completeness thresholds for the compiled earthquake catalogue, determined by the Cumulative Visual Inspection (CUVI) method.

Magnitude class (M _w)	Year of completeness	Complete period	Duration (years)
$3.5 \leq M_w < 4.0$	1995	1995–2022	27
$4.5 \leq M_w < 5.0$	1967	1967–2022	55
$5.0 \leq M_w < 5.5$	1952	1952–2022	70
$5.5 \leq M_w < 6.0$	1912	1912–2022	110

3.1.2. Seismic source characterisation

The seismogenic source model is defined by delineating eight area seismic source zones. Delineation used the homogenised earthquake catalogue, regional geological structures, and existing seismotectonic studies (*Zahran et al., 2015, 2016; El-Hussain et al., 2018*). The study area is controlled by three main tectonic domains: the Gulf of Aden, the Arabian Shield, and the Red Sea Basin (including the East African Rift). The eight source zones are described below and shown in Fig. 8.

- Zone 1 (Gulf of Aden): Encompasses the western segment of the Gulf of Aden, extending from the Owen Fracture Zone to the Afar Triple Junction (*Deif et al., 2023*).
- Zone 2 (Eastern Yemen): Characterised by scattered seismicity controlled by the Jurassic rift and the Najd Fault system (*Stern, 1985; Alrubaidi et al., 2021*).
- Zone 3 (Western Yemen): A region of high seismic activity associated with the intersection of large Proterozoic basement blocks and the NW–SE Jurassic-Cretaceous rift system (*Al-Suba'i, 2008*).
- Zone 4 (Asir-Jizan Terrane): Captures background seismicity within the Asir geologic terrane. NW–SE and NE-trending lineaments dominate, but the broader Arabian province is largely aseismic (*Viltres et al., 2022; Şen and Al-Suba'i, 2001*).
- Zones 5, 6, 7 (Red Sea Basin — Southern, Central, and Transition): The Red Sea rift is segmented into three zones delineated by variations in seismicity rates, transverse faults, and changes in fault trends along the axial rift (*El-Hussain et al., 2018*).

- Zone 8 (East African Rift): Captures activity related to divergence between the Nubia and Somalia sub-plates at a rate of 6 ± 1.5 mm/yr (*Chu and Gordon, 1999*).

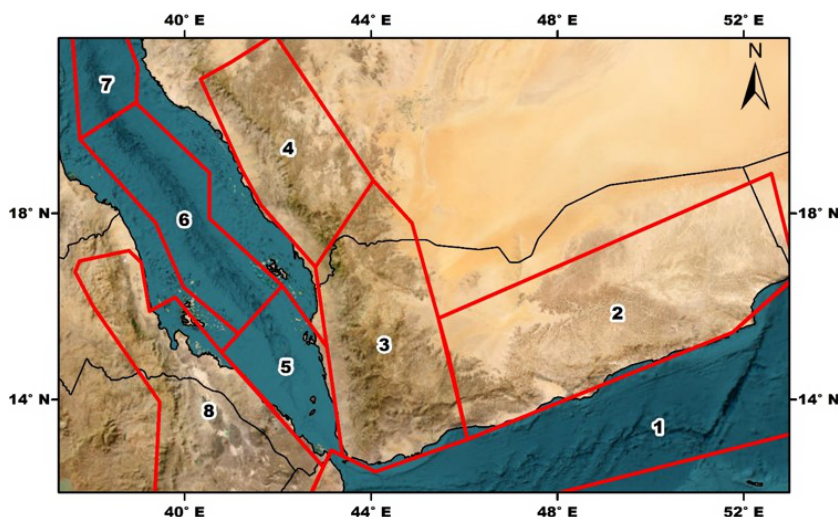


Fig. 8. The seismotectonic models for seismic hazard analysis at the Jizan region.

The seismic recurrence parameters for each source zone were estimated in a two-stage process. First, the standard Gutenberg-Richter relationship (*Gutenberg and Richter, 1944*) was used to ensure a good statistical fit to the observed catalogue data. The final source models employ the Doubly Truncated Gutenberg-Richter (DTGR) formulation (*Cosentino et al., 1977*), which restricts energy release between $M_{\min}$ and $M_{\max}$:

$$\lambda(M) = \lambda_{\min} \cdot \frac{\exp[-\beta (M - M_{\min})] - \exp[-\beta (M_{\max} - M_{\min})]}{1 - \exp[-\beta (M_{\max} - M_{\min})]}. \quad (1)$$

The minimum magnitude $M_{\min}$ was set to 3.5 for all zones. Maximum expected magnitudes were estimated using the Kijko-Sellevoll-Bayes procedure (*Kijko, 2012*). The Gutenberg-Richter b -values and activity rates λ were estimated using the *Weichert (1980)* maximum likelihood method, which correctly accounts for the variable observation periods identified in the completeness analysis. β is the slope parameter of the Gutenberg-Richter relation, controlling the relative proportion of large to small earthquakes. It relates to the b -value by:

$$\beta = b \cdot \ln(10).$$

(2)

A larger β means small earthquakes dominate more strongly. The resulting seismicity parameters for each source zone are summarised in Table 3.

Table 3. Seismicity parameters for each defined seismic source zone.

Zone	Zone name	No. of EQs	$M_{\max}^{\text{obs}}$	$\beta \pm \sigma\beta$	$\lambda(3.5) \pm \sigma\lambda$	$M_{\max} \pm \sigma M_{\max}$
1	Aden	218	6.62	0.7898 ± 0.0879	1.8273 ± 0.1238	6.63 ± 0.25
2	Yemen	9	5.11	2.2653 ± 0.6009	0.1858 ± 0.0619	5.37 ± 0.36
3	W. Yemen	36	6.21	1.0810 ± 0.2143	0.3962 ± 0.0660	6.21 ± 0.25
4	Asir-Jizan	9	4.83	1.8226 ± 0.4986	0.1587 ± 0.0529	4.91 ± 0.26
5	S. Red Sea	40	5.9	1.4169 ± 0.2114	0.5659 ± 0.0895	6.05 ± 0.29
6	C. Red Sea	162	6.7	0.7920 ± 0.1019	1.3610 ± 0.1069	7.00 ± 0.39
7	Trans. Red Sea	34	5.2	1.3700 ± 0.2273	0.4663 ± 0.0800	5.25 ± 0.25
8	E. African Rift	80	6.2	1.0145 ± 0.1435	0.8312 ± 0.0929	6.22 ± 0.25

3.1.3. Ground motion prediction equations

The GMPEs are selected according to the hierarchical exclusion method of *Cotton et al. (2006)* and *Bommer et al. (2010)*. Due to the fact that the Red Sea rift is an extensional, shallow-crust setting and local strong-motion recordings in the Jizan area are scarce, we chose models developed from global datasets or from regions with similar tectonics. Four GMPEs were included in the logic tree:

- *Abrahamson et al. (2014)* — ASK14: an NGA-West2 model built from a large global shallow-crust dataset; it accounts for complex site effects and hanging-wall geometry.
- *Akkar et al. (2014)* — AKK14: calibrated for Pan-European and Middle Eastern conditions, so it is regionally relevant for the Arabian and Mediterranean active crustal domain.
- *Chiou and Youngs (2014)* — CY14: an NGA-West2 model with detailed source scaling and path attenuation terms suitable for active tectonic regions.
- *Zhao et al. (2006)* — ZhaoASC: developed from Japanese strong-motion records for active shallow crust; it is widely used and covers the magnitude-distance range of interest for the Red Sea rift.

Because we do not have enough local strong-motion data to rank the models statistically, we treated all four GMPEs as equally plausible and gave each an equal weight of 0.25 in the logic tree. The balanced weighting reflects a consensus among different attenuation relationships, and it captures epistemic uncertainty in ground-motion prediction (*Bommer et al., 2010*).

3.1.4. Regional seismic hazard at bedrock

The PSHA for the entire Jizan region was carried out within the EZ-FRISK software framework (*Risk Engineering Inc., 2017*), assuming reference bedrock conditions ($V_{s30} = 760$ m/s). This reference corresponds to the NEHRP Site Class B/C boundary and is the commonly used engineering-bedrock horizon for hazard mapping (*BSSC, 2020; Danciu et al., 2021*).

For each defined seismic source the hazard integral combines three elements: the earthquake occurrence rate defined by the doubly-truncated Gutenberg–Richter recurrence model (parameterised by the activity rate, b -value, and $M_{\min} - M_{\max}$ established in Section 3.1.2); the spatial distribution of possible rupture locations within the source; and the ground-motion prediction equations (GMPEs) that give the median ground motion and its aleatory variability (σ) as a function of magnitude, distance, and site condition. The exceedance probability contributed by each magnitude–distance pair is evaluated over the full ground-motion distribution, integrating to $\pm 3\sigma$ to capture aleatory scatter.

We calculated hazard curves for PGA and for spectral accelerations at several periods. To generate the regional hazard maps, calculations were performed at the nodes of a regular grid of sites covering the Jizan region (grid spacing of 0.1°), with each evaluated at bedrock conditions. From each site’s hazard curve, the ground-motion value corresponding to the target annual exceedance rate was extracted by interpolation. These values were spatially interpolated to produce continuous mean-hazard maps for two standard return periods: 475 years ($\approx 10\%$ probability of exceedance in 50 years) and 2,475 years ($\approx 2\%$ probability of exceedance in 50 years). In addition, a site-specific Uniform Hazard Spectrum (UHS) was computed for the Baish district. The UHS was constructed by evaluating the hazard curves at that site across all spectral periods and, at each period, reading off the spectral acceleration corresponding to the chosen return period, so

that every ordinate of the spectrum shares a common annual probability of exceedance.

Epistemic uncertainty in ground-motion attenuation was propagated through a logic-tree framework in which the four selected GMPEs (Section 3.13) were assigned equal weight (0.25 each); the branch results were combined to obtain the mean hazard.

4. Results

4.1. Regional bedrock hazard maps

The spatial distribution of seismic hazard across the Jizan region is presented in Figures 9 and 10 for the 475-year and 2,475-year return periods, respectively. These maps show a clear north–south increase in hazard, with higher PGA and spectral acceleration values toward the southern part of the region.

For the 475-year return period (Fig. 9A), bedrock PGA is about 28 cm/s^2 (0.03 g) in the northern districts and rises to about 57 cm/s^2 (0.06 g) near the Yemeni border in the south. For the 2,475-year return period (Fig. 9B), PGA increases to roughly 61 cm/s^2 (0.06 g) in the north and about 132 cm/s^2 (0.13 g) in the south. This pattern matches the regional seismotectonics, with the strongest activity tied to ongoing rifting in the southern Red Sea (Zone 5) and active deformation in western Yemen (Zone 3).

Short-period spectral acceleration at $T = 0.1 \text{ s}$ shows the same trend (Fig. 10), which is important for low-rise, stiff buildings. Values in the southern zones reach about 133 cm/s^2 for the 475-year return period and about 318 cm/s^2 for the 2,475-year return period. The prominence of short-period spectral energy reflects the effect of moderate-magnitude, near-field events that are common in rift settings and produce strong high-frequency shaking.

4.2. Site-specific uniform hazard spectrum for Baish

A site-specific Uniform Hazard Spectrum (UHS) was computed for the Baish development area at bedrock conditions (Fig. 11). The UHS gives, at each period, the spectral acceleration that has the chosen probability of exceedance, and it integrates contributions from all source zones and all magnitude–distance combinations in the logic tree.

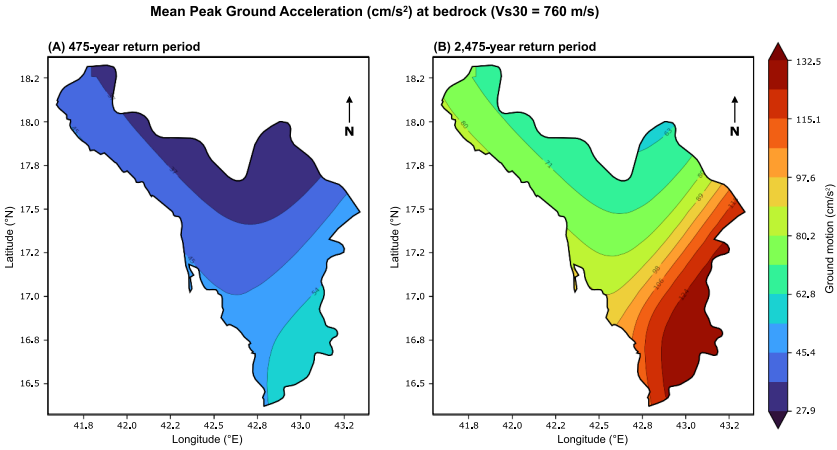


Fig. 9. Mean peak ground acceleration (cm/s²) at bedrock (Vs30 = 760 m/s) for (A) the 475-year return period and (B) the 2,475-year return period.

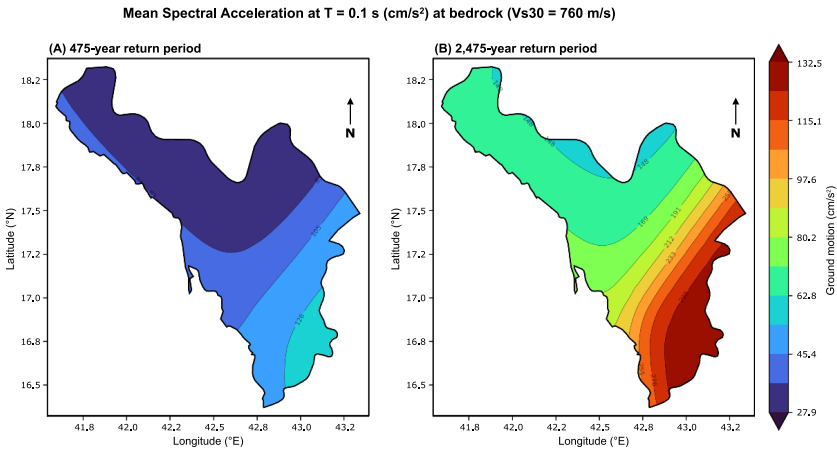


Fig. 10. Mean spectral acceleration at T = 0.1 s (cm/s²) at bedrock conditions for (A) the 475-year return period and (B) the 2,475-year return period.

The Baish bedrock UHS shows the typical form of an active, shallow-crust rift environment, with a clear peak at short periods ($T \approx 0.1 - 0.2$ s). For the 475-year return period (design-basis earthquake, DBE), the peak spectral acceleration is about 85 cm/s² (≈ 0.087 g) for the 2,475-year return period (maximum considered earthquake, MCE). The peak reaches roughly 165 cm/s² (≈ 0.168 g). Spectral accelerations drop quickly at longer

periods ($T > 1.0$ s), which is consistent with the dominance of moderate-magnitude, near-field events that produce strong high-frequency shaking. The bedrock PGA for the 475-year return period is around $40\text{--}45\text{ cm/s}^2$ ($\approx 0.04\text{--}0.05\text{ g}$). It reflects that Baish has moderate inland seismicity compared with the higher hazard along the southern coast.

The shaded bands in Figure 11 show the 16th and 84th percentiles of the UHS curves from the logic-tree ensemble. They illustrate the epistemic uncertainty captured by the four-GMPE framework. The uncertainty envelope is wider at short periods ($T = 0.1\text{--}0.5$ s), where differences between models in near-field attenuation of high-frequency energy are largest. This uncertainty description gives engineers and decision-makers a complete probabilistic picture of the reference bedrock hazard.

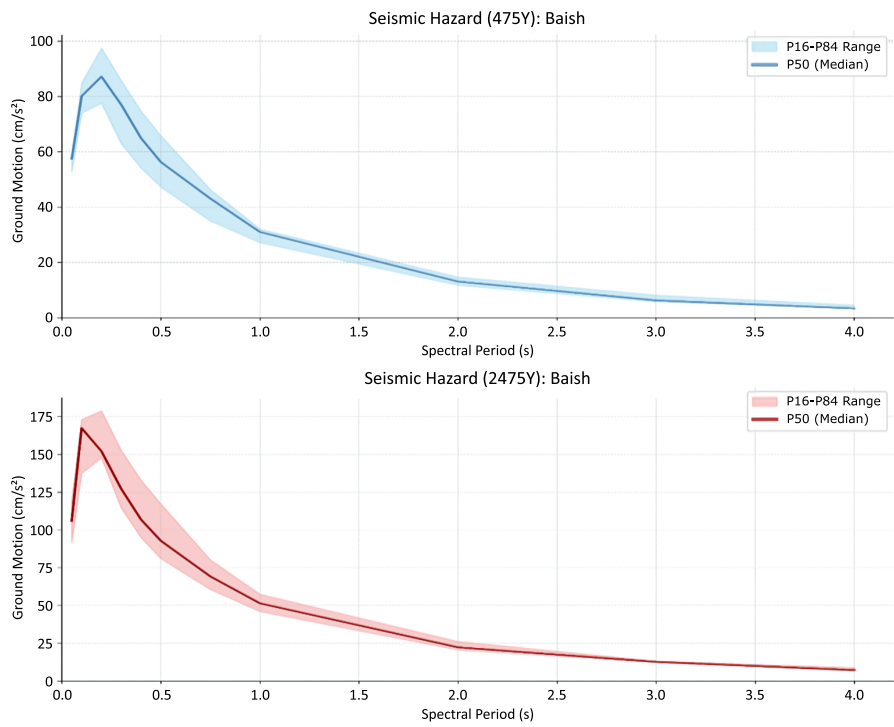


Fig. 11. Uniform Hazard Spectra (UHS) for the Baish site at bedrock conditions ($V_{s30} = 760\text{ m/s}$) for the 475-year and 2,475-year return periods. Solid lines represent the median (50th percentile); shaded regions denote the 16th–84th percentile uncertainty range from the four-GMPE logic tree.

5. Discussion

The bedrock hazard results show that seismic hazard in the Jizan region is not uniform and is mainly controlled by Red Sea extension and active crustal deformation in western Yemen. The strong north–south gradient seen in the PGA and spectral-acceleration maps (Figs. 9–10) agrees with the spatial distribution of seismogenic sources: the southern source zones (Zones 5 and 3) have the highest activity rates and the largest maximum magnitudes. For example, activity rates reach up to $\lambda = 2.856 \text{ yr}^{-1}$ in Zone 8 (Table 3), and M_{max} values are as large as 7.1 in Zone 1 and 6.9 in Zone 6, which together explain the elevated hazard in southern Jizan.

The shape of the bedrock UHS (Fig. 11), with peak spectral acceleration at short periods ($T \approx 0.1\text{--}0.2 \text{ s}$) and strong high-frequency content, is typical of moderate-magnitude, near-field earthquakes. This matches the seismogenic style of the Red Sea rift, where typical events are normal-faulting earthquakes of roughly M_w 5.5–6.9 occurring at source-to-site distances of about 50–150 km. The rapid decrease of spectral amplitudes for $T > 1.0 \text{ s}$ indicates that large, distant sources contribute relatively little to long-period hazard. This has practical engineering implications: tall buildings and long-span structures in Baish are less affected by long-period shaking than low-rise, stiff structures, which are more sensitive to the short-period energy we observe.

The bedrock PGA for the 475-year return period in the Baish inland district ($\approx 0.04\text{--}0.06 \text{ g}$) agrees well with regional values reported by *Zahran et al. (2015)* and *Arfa et al. (2024)*, offering independent cross-validation of our source model and GMPE choices. The improved resolution and reliability of our results relative to earlier studies arise from several methodological advances: (1) an updated earthquake catalogue through 2022 that includes recent instrumental events; (2) magnitude homogenization using orthogonal regression instead of published conversion tables; (3) time-dependent completeness corrections in recurrence estimation; and (4) a formal four-branch GMPE logic tree that quantifies epistemic uncertainty.

To check the robustness of our bedrock hazard estimates, we compare key parameters for the Baish district with those reported in previous Jizan studies (Table 4).

The bedrock PGA of 0.04–0.06 g for the 475-year return period matches well with the recent PSHA by *Arfa et al. (2024)* and falls within the lower

Table 4. Comparison of bedrock seismic hazard parameters with previous studies in the Jizan region.

Study	Methodology	Parameter	Value (g)	Return period (yr)	Soil condition
<i>Abdelfattah et al. (2022)</i>	Deterministic SHA	PGA (Jizan City)	≈ 0.04	N/A	Hard rock
<i>Abdelfattah et al. (2022)</i>	Deterministic SHA	PGA (Coastline)	≈ 0.17	N/A	Hard rock
<i>Arfa et al. (2024)</i>	Probabilistic SHA	Mean PGA	≈ 0.04	475	N/A
<i>Arfa et al. (2024)</i>	Probabilistic SHA	SA (0.2 s)	≈ 0.12	475	B/C Soil
This study	PSHA (Bedrock)	Bedrock PGA	0.04–0.06	475	Vs30 = 760 m/s
This study	PSHA (Bedrock)	Bedrock SA (0.2 s)	≈ 0.087	475	Vs30 = 760 m/s
This study	PSHA (Bedrock)	Bedrock SA (0.2 s)	≈ 0.168	2,475	Vs30 = 760 m/s

range of the deterministic results reported by *Abdelfattah et al. (2022)*. This agreement is reasonable: PSHA weights events by their probability, whereas deterministic seismic-hazard assessments (DSHA) typically consider worst-case scenarios regardless of likelihood, and therefore often yield more conservative values for routine engineering design. The higher PGA values found by *Abdelfattah et al. (2022)* along the coastline reflect the closer proximity to the Red Sea rift and are consistent with the north–south gradient we observe in our hazard maps.

The bedrock spectral acceleration at $T = 0.2$ s in our study is about 0.087 g (475-year return period), which is lower than the 0.12 g reported by *Arfa et al. (2024)* for the NEHRP B/C boundary. This difference is expected: the Arfa et al. value corresponds to a soft-rock B/C condition that can show mild amplification relative to our reference bedrock. Differences in source-zone boundaries and GMPE choices between the studies also explain part of the discrepancy. Overall, the convergence of independent studies using different data and methods increases confidence in the robustness of the present assessment.

A main strength of this work is the formal treatment of epistemic uncertainty through the logic tree. The 16th–84th percentile bands on the UHS (Fig. 11) show that, for short periods ($T = 0.1–0.5$ s), most of the uncertainty arises from differences in GMPE median predictions. At longer periods ($T > 1.0$ s), the uncertainty narrows, reflecting greater agreement among models on far-field, long-period attenuation.

Because no local strong-motion dataset is available, we treated the four selected GMPEs as equally plausible. Installing a permanent strong-motion network in Jizan would enable performance-based model ranking (for example, using log-likelihood scores; *Delavaud et al., 2012*) and could reduce GMPE-related epistemic uncertainty by an estimated 15–25% at short periods. Updating the catalogue, especially for the $M_w \geq 5.5$ class, where completeness extends back to 1928, would also improve activity-rate and b -value estimates for the main source zones.

Using the *Weichert (1980)* maximum-likelihood estimator with period-specific completeness thresholds makes recurrence parameters reflect the true observation windows for each magnitude class, avoiding the suppression of large-event rates that can occur when a single modern completeness cutoff is applied to all magnitudes. This is important for the $M \geq 6.0$ magnitude classes, where long completeness windows (1857–1928) meaningfully constrain $M_{\max}$ and activity rates for the most active zones (Central Red Sea, East African Rift).

The bedrock UHS from this study gives a well-constrained reference hazard for engineering design and urban planning in Baish. Its characteristic spectral shape, peaking at $T \approx 0.1–0.2$ s, means that the main structural demand for typical low- to mid-rise buildings ($T \approx 0.1–0.5$ s) coincides with the range of maximum spectral energy. Engineers should therefore use the site-specific UHS in Fig. 11 rather than generic regional code spectra, which may not capture the spatial detail shown here.

Compared with the Saudi Building Code (SBC-301), our bedrock spectral demands for the 475-year return period are broadly consistent, but the site-specific UHS better resolves the spectral shape. For critical and essential facilities governed by the 2,475-year return period, the bedrock peak spectral acceleration of about 165 cm/s^2 should be used as a design basis, with site amplification applied separately after in-situ geotechnical testing.

6. Conclusions

This study provides a comprehensive probabilistic seismic hazard assessment (PSHA) at engineering bedrock conditions ($V_{s30} = 760$ m/s) for the Jizan region in southwestern Saudi Arabia, with a particular focus on the Baish development area. The main conclusions are:

1. A homogenised earthquake catalogue is compiled covering 827–2022 CE from several authoritative sources and converted all magnitudes to M_w using orthogonal regression relations with $R^2 \geq 0.96$. After declustering (*Gardner and Knopoff, 1974*) and applying period-specific completeness analysis (CUVI), the final catalogue gives a reliable basis for estimating seismicity rates in the eight defined source zones.
2. Seismic hazard in Jizan is controlled mainly by active extension of the Red Sea rift (Zones 5 and 6) and by crustal deformation in western Yemen (Zone 3). The Central Red Sea zone (Zone 6) shows the highest activity rate ($\lambda = 2.800 \pm 0.495$ yr⁻¹ for $M_w \geq 3.5$) and an estimated $M_{\max} \approx 6.92$, while the Gulf of Aden (Zone 1) has the largest $M_{\max}$ in the study area (≈ 7.1).
3. Bedrock hazard maps display a clear north–south gradient. For the 475-year return period, PGA increases from about 0.03 g in the northern districts to about 0.06 g near the Yemeni border; for the 2,475-year return period, PGA rises from roughly 0.06 g to 0.13 g. This spatial pattern is consistent with proximity to active rift spreading centres and the seismogenic nature of the southern Red Sea.
4. The site-specific bedrock UHS for Baish peaks at approximately 85 cm/s² (≈ 0.087 g) at $T \approx 0.1–0.2$ s for the 475-year return period, and at ≈ 165 cm/s² (≈ 0.168 g) for the 2,475-year return period. Spectral amplitudes fall off quickly for $T > 1.0$ s, reflecting dominance of moderate-magnitude, near-field sources.
5. A logic-tree with four equally weighted GMPEs yields quantified 16th–84th percentile uncertainty bounds. Epistemic uncertainty is largest at short periods ($T = 0.1–0.5$ s), when model-to-model differences in near-field attenuation are greatest, which highlights the value of multi-model frameworks in regions without local strong-motion calibration.

The bedrock UHS and hazard maps produced in this study provide a well-constrained reference hazard for the Baish district and should serve as the primary input for any further site-specific amplification analysis, structural design, or urban risk assessment. We recommend adopting the median and 84th-percentile bedrock spectra from the logic-tree ensemble as reference motions for critical infrastructure design and applying site amplification factors derived from in situ geotechnical measurements at each project site.

Declaration of competing interest. The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

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Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Statement on the use of AI. During the preparation of this manuscript, the authors used an AI-based language tool to improve the English style, grammar, and readability of author-written text. No AI tool was used to generate the scientific content, the data analysis, or the interpretation.

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