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ARTICLE

Probabilistic Seismic Hazard Assessment of Umnugobi aimag (province), Mongolia

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Abstract: This study presents a probabilistic seismic hazard assessment (PSHA) for Umnugobi (South Gobi) aimag (province), Mongolia, under rock site conditions using a probabilistic model. The analysis was based on integrated data from regional studies of seismic activity, seismotectonics, and active fault investigations. Seismic wave attenuation from earthquake sources was evaluated using a logic-tree approach with four ground-motion prediction equations (GMPEs): Chandra (1979), BSSA-14, CB-14, and CY-14. In total, 28 active faults and five seismotectonic zones were included in the hazard model. The results provide peak ground acceleration (PGA) values corresponding to exceedance probabilities of 63 %, 10 %, and 2 % in 50 years, equivalent to return periods of 50, 475- year, and 2475- year, respectively. According to the current Mongolian seismic building code, the PGA values in Umnugob province are estimated at 134–165 cm/s² for a 475-year return period and 317–396 cm/s² for a 2475-year return period. These findings provide an important scientific basis for engineering seismology, infrastructure planning, seismic risk assessment, and land-use management in the Umnugobi region of Mongolia.

Keyword: *Probabilistic seismic hazard analysis (PSHA), peak ground acceleration (PGA), logic-tree approach, ground-motion prediction equations (GMPEs), active faults, seismotectonic zones, Umnugobi province;*

INTRODUCTION

Seismic Hazard Assessment (SHA) plays a critical role in disaster risk reduction and urban resilience planning. The outcomes of SHA studies provide foundational data for anticipating potential strong earthquakes, formulating disaster mitigation strategies, updating urban development plans, revising construction codes and standards,

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and optimizing the siting of strategically important industrial and infrastructure facilities.

SHA calculations are not only essential for evaluating the seismic resistance of high-rise structures, but also for modeling seismic wave propagation, estimating ground motion amplification, and quantifying earthquake forces. These calculations are instrumental in assessing the engineering-geological conditions of a region. The magnitude of seismic forces varies depending on the geological structure of the site, the physical and mechanical properties of the soil, and the characteristics of seismic wave propagation. To analyze these interdependencies, both probabilistic and deterministic assessment methodologies, commonly used in international practice, are employed.

This study presents the results of a probabilistic seismic hazard assessment, conducted under rock site conditions for the territory of Umnugobi province, Mongolia. The assessment incorporates detailed data on active seismic zones, levels of seismic activity, and fault line characteristics within the region.

The analysis draws upon the “General zonation map of Mongolia’s Territory” (scale 1:2500000, 1983), which synthesizes tectonic, geological, historical, and instrumental seismic data, as well as, seismogeological studies conducted in areas of strong seismicity. According to this map, approximately 75% of Mongolia's territory is classified as being at risk of experiencing earthquakes of magnitude 7.0 or higher on the Richter scale.

In 2020, the Institute of Astronomy and Geophysics (IAG) revised and enhanced this map using probabilistic assessment methodologies, resulting in an updated and more accurate representation of seismic hazard zones.

Previous studies: Seismic hazard studies in Mongolia have evolved significantly over the past decades, providing foundational insights into the seismic characteristics of Umnugobi province.

1983 General Seismic Zoning Map: In 1983, researchers from the former Soviet Union and the Mongolian People's Republic jointly developed the “General seismic zonation map of Mongolia” at a scale of 1:2500000. This map classifies Umnugobi province within seismic intensity zones of IX or higher (MSK/MMI), indicating a high potential for strong ground shaking.

1985 Microzonation study of Dalanzadgad: A microzonation study of Dalanzadgad, the provincial center, was conducted in 1985. The resulting map, at a scale of 1:4000, placed the area within the IX–X intensity zone. However, the study covered only about 900 hectares, which is significantly smaller than the current urban footprint, limiting its applicability to modern urban planning.

2020 Updated seismic zonation map: In 2020, the IAG released an updated “General seismic zonation map of Mongolia” at a scale of 1:1000000. This revision classified Umnugobi province within the VIII intensity zone. The study incorporated detailed paleoseismological investigations along active faults and enriched the seismic database, resulting in a more refined and accurate hazard assessments compared to earlier maps.

These studies highlight the progression of seismic hazard understanding in the region and underscored the need for updated, high-resolution assessments like the one presented in this paper.

Study area: The seismic hazard assessment (SHA) for this study was conducted based on the geological structure, distribution of active faults, and seismic activity patterns within the territory of Umnugobi province, Mongolia.

From a geological and tectonic perspective, Mongolia’s territory is influenced by two distinct geodynamic environments associated with microplates in Central Asia [9, 17]. Western Mongolia lies within a transpressional zone-oriented north–south, characterized by high seismic activity. In contrast, while Eastern Mongolia is affected by extensional forces trending southeast, resulting in relatively lower seismic activity.

Umnugobi province is situated at the transitional boundary between these two tectonic regimes. This unique positioning significantly influences the region's seismic activity and the morphological characteristics of fault systems. The convergence of compressional and extensional forces contributes to complex tectonic behavior, making this area particularly important for seismic hazard evaluation.

Geological and tectonic setting

Mongolia is located within a key tectonic junction in Central Asia, connecting the Siberian Craton and the North China Plate. The southern region of Mongolia, including Umnugobi province, is characterized by rift-related depressions formed during the Late Mesozoic era. These non-marine sedimentary basins span approximately 1.5 million square kilometers, extending from northern China to the southern and southeastern margins of the Amur Plate.

One of the prominent basins in this region is the East Gobi Basin, which trends northeast and is structurally aligned with the East Bayankhongor fault system. Together, they represent two major geomorphological features of the Southeastern Gobi region. Multiple studies suggest that the East Gobi Basin is of extensional origin, and its surrounding geological structure was shaped by a combination of compressional and extensional processes during the Late Mesozoic period [14]. The basement rocks of the basin primarily consist of marine-derived flysch sequences and volcanic arc-related rocks from the Upper Paleozoic.

This region is notable for its rich mineral resources, including the Oyu Tolgoi copper deposit, Dornogobi uranium deposit, Tavan Tolgoi coking coal deposit, and the Zuunbayan and Tsagaan Els oil fields. However, the tectonic origin and evolutionary history of this region remain subjects of ongoing debate. Some researchers consider the rock assemblages of Southeastern Mongolia to be a part of the Central Asian orogenic belt or the Altai orogen, reflecting the complex history of continental collision and accretion that contributed to the formation of the Asian continent [15].

Tectonically, the region's active deformation is closely linked to the Tien-Shan fault system [13]. The Tien-Shan Mountain belt extends from Uzbekistan through Umnugobi province, forming a thrust–strike-slip fault system, approximately 2500 km in length [14]. The Harlag Tag Mountain (4886 m) marks the easternmost high point of this system.

As the Tien-Shan fault system progresses eastward, its tectonic morphology changes significantly, from predominantly compressional thrust faults to dominantly horizontal strike-slip faults. Major elevations in the region include Arts Bogd (2695 m) and Nemegt (2768 m) in the west, and Gurvan Saikhan (2825 m) in the east. The fault system spans roughly 850 km from west to east, with the western segment composed of long, linear faults, while the eastern segment exhibits a complex structure of twisted and offset faults [13]. Notable fault zones along the eastern margin include those near Baruun Saikhan, Dund Saikhan, and Zuun Saikhan mountains, which are bounded by the Unegt transverse fault system. Additionally, the Bulagt fault at the eastern end of the Tien-Shan system is believed to be a branch of the Gurvan Saikhan fault.

Seismic activity analysis

Over the past century, approximately 50% of all earthquakes in Mongolia with magnitudes greater than M≥5.0 have occurred in Umnugobi province and its adjacent regions. Among these, seven major earthquakes with magnitudes exceeding M≥7.3 were recorded in the years 1903, 1915, 1931, 1938, 1957, 1958, and 1960 respectively. Historical and instrumental data confirm that this region is one of the most seismically active zones in Mongolia [10, 11, 16].

Significant seismic sources within Umnugobi and surrounding areas include the 1903 Unegt earthquake ($M_w = 7.3$) and the 1960 Buuryn Khyar earthquake ($M_w = 6.8$). Within a 50 km radius of the study area

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lies the epicenter of the strong Khankhongor earthquake. Additionally, on August 27 and 28, 2011, two moderate earthquakes ($M_w = 5.4$ and $M_w = 5.0$, respectively) occurred near the northeastern end of the Bulagt fault in the Takhilgalt Mountains, followed by a series of aftershocks.

Between 1900 and 2024, a total of 123,276 earthquakes were recorded in this region, of which 2,582 events had magnitudes of $M_w \geq 3.5$, indicating perceptible seismic activity.

In seismic regime analysis, the frequency–magnitude relationship is characterized by parameters $\boldsymbol{a}$ and $\boldsymbol{b}$, which are critical for understanding the spatial and temporal distribution of earthquake magnitudes and estimating regional seismicity and recurrence intervals. Recurrence analysis shows magnitude 4 events occur ~5 times annually, while magnitude 6 events occur once every 10 years. Seismic regime parameters were calculated as $\mathbf{a} = \mathbf{4.2}$ and $\mathbf{b} = \mathbf{0.87}$, classifying the region as moderately active (see Figure 1.).

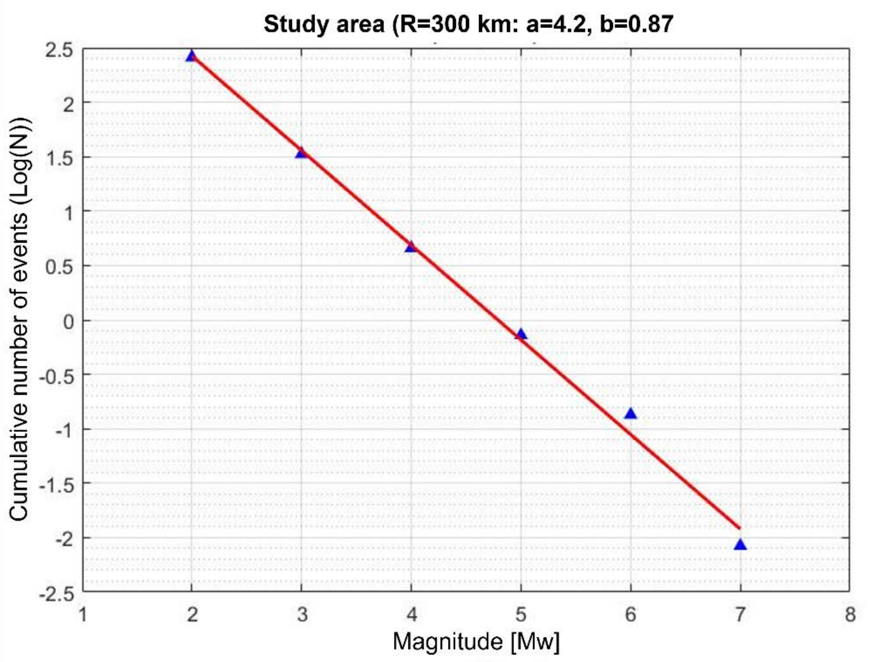

Figure 1. Magnitude–Frequency Curve for earthquakes in Umnugobi region (R = 300 km).

Additionally, the magnitude–frequency parameters of the 28 active faults located within the territory of Umnugobi Province were individually calculated and incorporated into the probabilistic seismic hazard assessment (PSHA) model.

MATERIALS AND METHODS

This study employs the Probabilistic Seismic Hazard Analysis (PSHA) method [2, 12] to assess seismic hazards in Umnugobi province under rock site conditions. PSHA is based on regional seismicity, tectonic fault structures, earthquake recurrence rates, and magnitude–distance relationships [3]. In recent years, PSHA has become widely adopted due to its ability to incorporate recurrence probabilities, site response effects, and tectonic influences with greater precision. The PSHA methodology [2] used in this study consists of the following components:

- *Seismotectonic zone:* Seismotectonic zones were delineated by considering regional seismic activity, geological and tectonic structures, and crustal deformation. Since strong earthquakes often originate from multiple sources rather than a single fault, a seismotectonic model [1] was developed by integrating the location, distribution, and activity levels of active faults. This model was used as the basis for hazard calculations. The spatial distribution of the five seismotectonic zones and the

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locations of the 28 identified active faults are illustrated in Figure 2.

- *Seismicity parameters:* For each of the five defined zones, seismicity and recurrence parameters were calculated using frequency–magnitude relationships [8]. These parameters were incorporated into the hazard assessment.

Core steps of the PSHA computation

1. Identification of Seismic Sources: Potential seismic sources, affecting the study area, were identified, including active faults and seismotectonic zones. Parameters, such as geometry, length, orientation, and depth were defined.
2. Recurrence Analysis: For each seismic source, recurrence analysis was conducted using the Gutenberg–Richter law [8] to estimate the frequency and return period of earthquakes of specific magnitudes. This analysis provided the basis for defining seismicity and recurrence parameters for each source.
3. Site Ground Motion Probability Estimation: For each source, the probability of exceeding a specific ground acceleration value **a** at a given site was calculated using attenuation relationships [9].
4. Integrated Ground Motion Calculation: By combining parameters, such as source location, magnitude, recurrence probability, attenuation distance, and peak ground acceleration, seismic hazard curves were generated. These curves represent the probability of exceeding specific ground motion levels over a given time period (e.g., 50 years) and form the core output of the hazard assessment.

The primary objective of the seismic hazard assessment is to estimate the probability that ground shaking, expressed as peak ground acceleration (PGA), will exceed a specified threshold within a given time frame (e.g., 50, 475- year, or 2475 years) in the study area.

PSHA uniquely aggregates the annual average occurrence rates of all possible earthquakes from all potential seismic sources affecting the region. This approach [12] enables a comprehensive and realistic evaluation of expected ground motion levels resulting from future seismic events. In other words, the method considers the location, magnitude, and recurrence distribution of all plausible seismic sources within the region.

The probabilistic seismic hazard calculation is expressed by the following fundamental equation:

$$\lambda(a) = \sum_{source} v_{source} \times \iint_{(m,r)esource} I\left[PGA \geq \frac{a}{m}, r\right] f_m(m) f_R(r) dmdr$$

Where: $\boldsymbol{v}_{\mathbf{source}}$: Annual rate of potentially hazardous earthquakes from a given source (in this study, earthquakes with $M > 4.0$ are considered hazardous).

$\boldsymbol{I}[\mathbf{PGA} \geq \boldsymbol{a} \mid \boldsymbol{m}, \boldsymbol{r}]$: Probability that an earthquake of magnitude m at distance $\boldsymbol{r}$ will produce ground shaking exceeding acceleration $\boldsymbol{a}$.

$\boldsymbol{f_m(m)}$, $\boldsymbol{f_R(r)}$: Probability density functions for magnitude and distance from the source to the site.

Using this methodology, the seismic hazard assessment for Umnugobi province was completed, providing foundational data for disaster hazard evaluation, urban planning, and updates to building codes and regulations.

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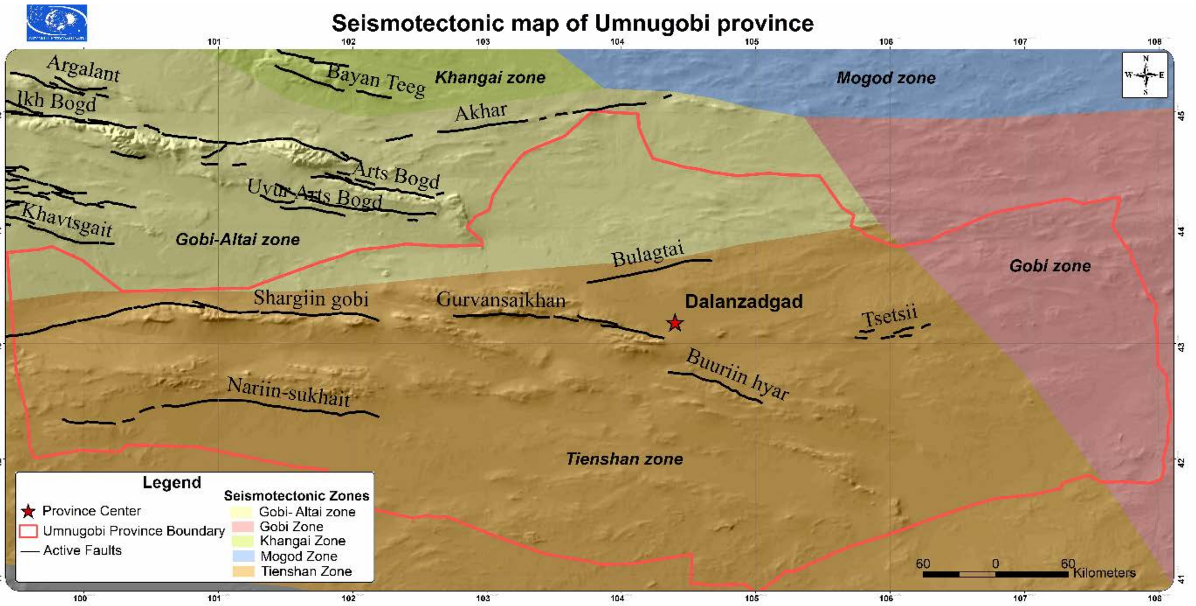

Figure 2. Seismotectonic map of Umnugobi province showing the spatial distribution of 5 seismotectonic zones (color coded) and the locations of active faults within the provincial boundary (black lines). Only faults located within Umnugobi province are displayed for clarity and map readability; additional faults used in the hazard model are listed in Table 1.

RESULTS AND DISCUSSION

Seismic hazard analysis result

PSHA results under rock site conditions:The probabilistic seismic hazard assessment (PSHA) for Umnugobi province was conducted under rock site conditions. The study area was defined by the provincial boundaries, and a grid of 6,609 points was established using a 5 km spacing to calculate peak ground acceleration (PGA) values across the region [9].

Attenuation relationships used in the analysis included models by Chandra [4], BSSA-14 [4], CB-14 [5], and CY-14 [6]. These models were integrated using a logic-tree approach to account for epistemic uncertainty in ground motion estimation.

In most PSHA studies, a single hazard curve is used for representing ground shaking intensity, which may not fully capture the variability of seismic source characteristics and attenuation behavior. To address this limitation, this study applied a logic-tree framework that combines multiple hazard curves derived from different source models and GMPEs. Each branch of the tree was assigned a weight, and the final hazard curve was computed as a weighted average of all scenarios.

In this study, two source models were developed for Dalanzadgad soum (the provincial center of Umnugobi).

- Model 1 includes the newly identified Dalanzadgad fault located southwest of the soum.
- Model 2 excludes this fault from the source characterization.

All four GMPEs were assigned equal weights of 0.25. Both source models were assigned equal weights of 0.5.

This logic-tree structure allowed for a more robust and realistic estimation of seismic hazard by incorporating variability in both source geometry and ground motion behavior.

Figure 3 presents the weights assigned to each parameter in the logic-tree.

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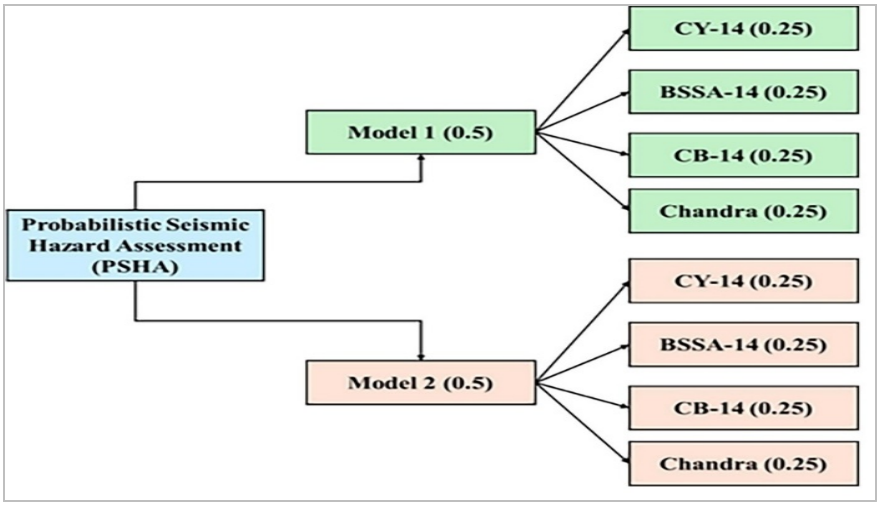

Figure 3. Logic-tree structure used in the seismic hazard assessment, showing weighted parameters for source models and attenuation relationships.

The frequency and magnitude distributions of seismic ground motion were modeled using a Poisson distribution, which aligns with the natural statistical behavior of earthquake occurrences.

This curve is a core input for probabilistic seismic hazard modeling. It helps estimate how often earthquakes of different magnitudes are expected to occur, which is essential for calculating ground motion probabilities and designing earthquake-resistant infrastructure. As a result, annual exceedance probabilities and hazard curves were generated for each seismic source (see Figure 4).

Figure 4 illustrates the hazard curve for the study area, showing how the mean annual rate of exceedance decreases as PGA increases. The intersections between the curve and the horizontal dashed lines represent the PGA values associated with return periods of 50, 475, and 2,475 years. Accordingly, the expected PGA values are 0.0424 g, 0.165 g, and 0.369 g for these return periods, respectively. This relationship reflects the probabilistic nature of the PSHA results and provides the basis for seismic design levels used in the study.

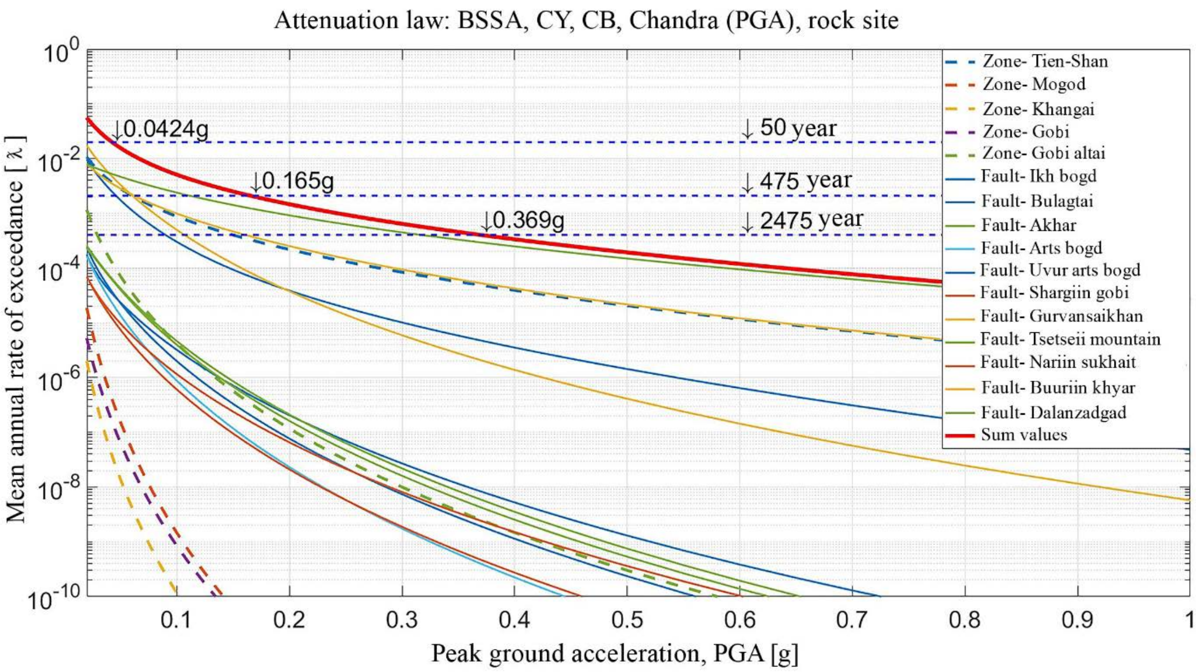

Figure 4. Hazard curve showing the mean annual rate of exceedance as a function of PGA. Horizontal dashed lines correspond to return periods of 50, 475, and 2,475 years. PGA values of 0.0424 g, 0.165 g, and 0.369 g are taken from the hazard curve.

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From the hazard curve, the PGA corresponding to a 10% probability of exceedance in 50 years (equivalent to a 475-year return period) is estimated to be 0.165 g. In contrast, the mean annual rate of exceedance associated with a PGA level of 0.4 g at the same location is approximately 4.0×10^{-4}, which corresponds to a return period of about 2,475 years. These values represent fundamentally different quantities, namely ground-motion intensity and exceedance probability, and should not be interpreted interchangeably.

Using this approach, the expected ground motion levels for rock site conditions were calculated for the following return periods:

- 50 years (63% probability of exceedance)
- 475 years (10% probability of exceedance in 50 years)
- 2,475 years (2% probability of exceedance in 50 years).

According to current Mongolian building codes, seismic design for rock site conditions is based on a 475-year return period using probabilistic assessment methods (Figures 5, 6, and7). It is important to note that this analysis did not incorporate detailed site-specific geotechnical conditions and was based solely on rock site assumptions.

These results provide essential baseline data for disaster risk assessment, urban planning, updating building codes and standards, and the strategic siting of critical infrastructure.

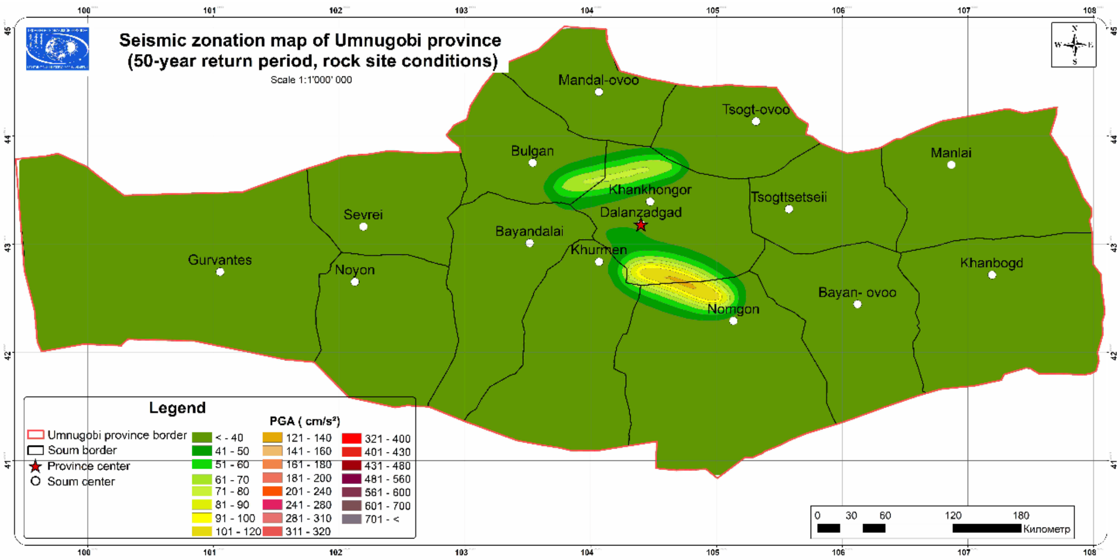

Figure 5. Peak ground acceleration (For a 50-year return period).

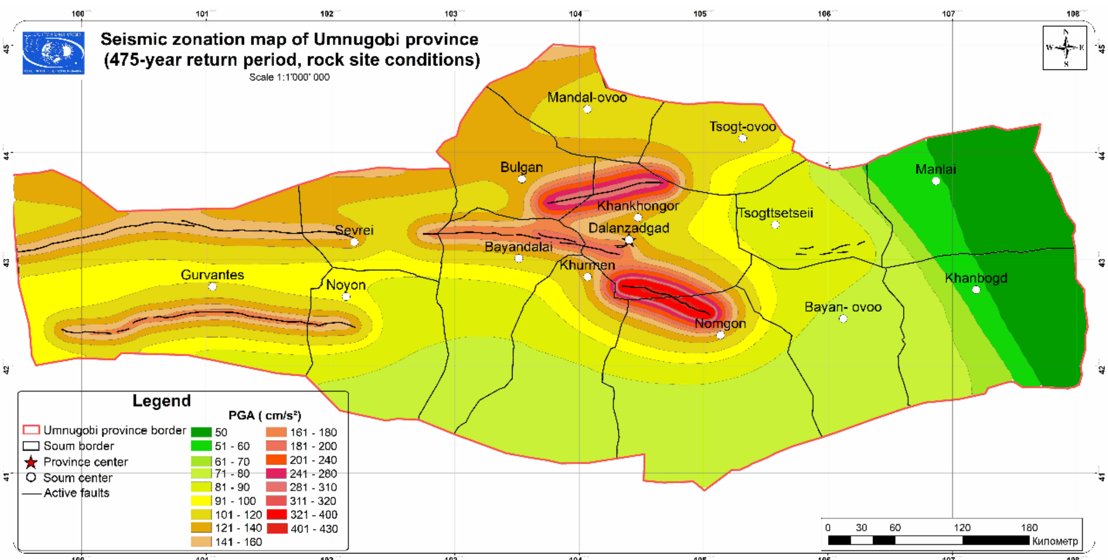

Figure 6. Peak ground acceleration (For a 475-year return period).

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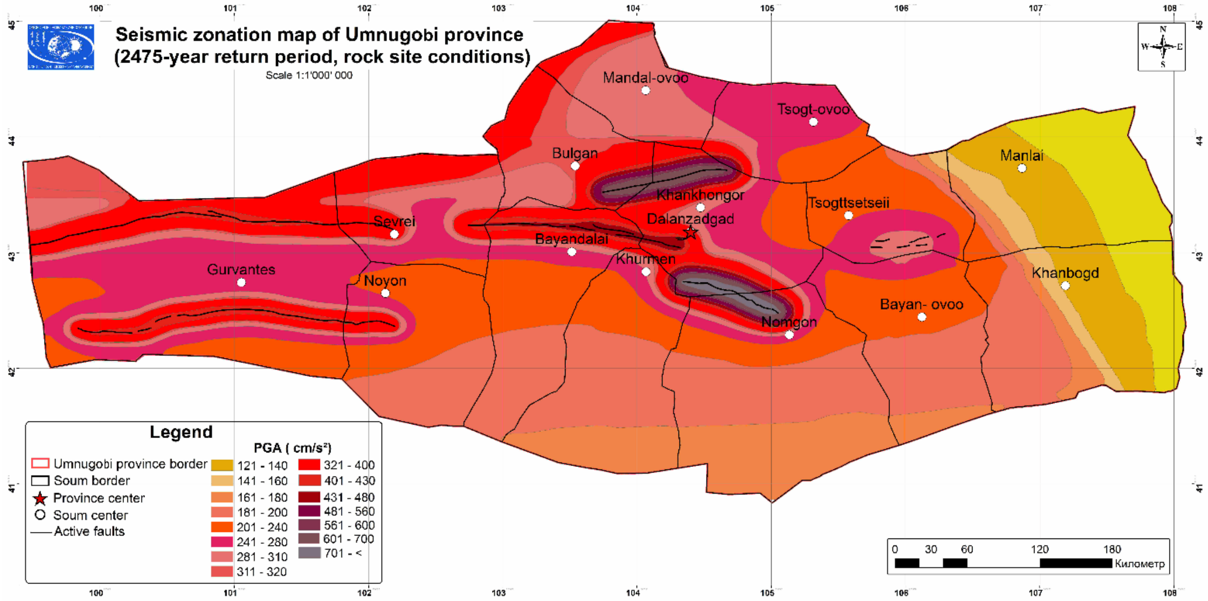

Figure 7. Peak ground acceleration (For a 2475-year return period).

The seismic hazard levels, potentially affecting Umnugobi province, were estimated using a probabilistic seismic hazard assessment (PSHA) approach, grounded in regional seismicity and active fault investigations. The results represent the expected peak ground acceleration (PGA) values under rock site conditions.

Seismicity and Recurrence Analysis: In order to evaluate the seismic regime of the region, earthquake data recorded between 1900 and 2024, within a 300 km radius of the provincial center, were analyzed. This analysis produced a seismicity map, identified seismotectonic zones intersecting the region, and characterized the recurrence behavior of active seismic sources. The findings indicate that earthquakes of magnitude 4 occur approximately five times per year, while magnitude 6 events are likely to occur once every ten years.

Active Fault Investigation: Comprehensive field and laboratory studies were conducted across Umnugobi province and its surrounding areas, incorporating remote sensing, seismological, geological, and geophysical methods. The study area falls within the Tien Shan seismic belt, which spans southwestern Mongolia, Gobi-Altai, the Trans-Altai Gobi, and the high ranges of the Tien Shan Mountains. A total of 28 active faults were identified as potentially hazardous to the region. For each fault, key parameters were determined, including geographic coordinates (latitude, longitude), fault length (L, km), maximum expected magnitude (Mw, moment magnitude), estimated return period, and seismotectonic zone classification, as summarized in Table 1 [1]. For visualization purposes, Figure 2 displays only the active faults located within the administrative boundary of Umnugobi province, whereas the full set of 28 faults incorporated in the hazard model is documented in Table 1.

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Table 1. Geometric and seismotectonic characteristics of 28 active faults in Umnugobi province used in the seismic hazard model.

Zone name	Fault name	Latitude (^{0}N)	Longitude (^{0}E)	Fault length (km)	Mw	Return period (years)	Date of Last Event (AD year)
Tien Shan Zone	Bulagtai	43.99	104.26	77	7.1	3500	-
	Buuriin Khyar	43.15	104.73	-	6.7	10000	-
	Gurvansaikhan	43.61	103.82	140	7.5	10000	-
	Nariin Sukhait	43.02	101.16	188	7.5	6000	-
	Tsetseii mountain	43.52	106.05	45	6.9	3500	-
	Shargiin gobi	43.45	98.87	213	7.7	3500	-
Mogod Zone	Deren	46.18	106.58	27	6.8	3500	1300
	Khujirt	46.87	102.86	21	7.0	6500	1650
Khangai Zone	Bat Ulziit	46.80	102.14	70	7.5	6500	-
	Bayan Teeg	45.38	101.75	80	7.2	3500	-
	Bayankhongor	46.54	99.89	80	7.2	6500	5400
	Nariin Teel	46.32	101.77	80	7.2	6500	-
Gobi Zone	Tavan Khar	44.06	109.42	63	7.1	10000	-
	Urgun	44.81	110.99	35	6.8	10000	-
Gobi-Altai Zone	Akhar	45.11	103.48	140	7.5	3500	-
	Argalant	45.31	99.95	60	7.0	3500	-
	Arts bogd	44.59	102.18	80	7.2	3500	-
	Batkhaan	47.07	104.36	23	6.6	6500	346
	Budargana	45.90	98.46	-	7.4	3500	-
	Chandmani	45.38	98.54	-	7.8	3500	-
	Dalanzadgad	43.55	104.33	7	7.0	10000	-
	Ikh Bogd	44.93	101.06	270	8.1	3500	59
	KhamarDavaa	46.61	102.20	40	6.9	6500	-
	Khavtsgai	44.54	99.62	120	7.4	3500	-
	Mustiin Tsagaan	47.06	103.41	25	7.0	6500	-
	Uvur Arts Bogd	44.44	102.00	70	7.4	3500	-
	Uyanga	46.47	102.33	10	6.2	6500	-
	Zarman	44.76	97.85	160	7.6	3500	-

Note: "–" indicates that the date of the last event is not available or not constrained.

Probabilistic Hazard Modeling: Using the PSHA method, ground motion levels were calculated for return periods of 50, 475, and 2,475 years, corresponding to exceedance probabilities of 63%, 10%, and 2% in 50 years, respectively. While current Mongolian building codes adopt the 475-year return period for seismic design under rock site conditions, this study also includes estimates for rare and extreme events in line with international best practices. The estimated PGA values for Umnugobi province, based on recurrence intervals, are presented in Table 2.

Table 2. PGA values.

№	Return period (Probability of exceedance in 50 years)	Value of PGA (cm/s²)	Intensity MSK64
1	50- year (63%)	35- 40	VI
2	**475- year (10%)**	**134- 165**	**VIII**
3	2475- year (2%)	317- 396	IX

CONCLUSIONS

This study conducted a probabilistic seismic hazard assessment (PSHA) for the territory of Dalanzadgad soum, Umnugobi province, under rock site conditions. The analysis incorporated detailed modeling of regional seismicity, active fault systems, geological and tectonic settings, attenuation relationships, and ground motion parameters.

The results indicate that, based on current Mongolian building codes and a 475-year return period, Dalanzadgad falls within a seismic intensity zone of **134–165 cm/s²**, corresponding to **VIII–IX** on the MSK-64 scale. For a 2,475-year return period, the estimated peak ground acceleration ranges from 317–396 cm/s², placing the area in the IX–X intensity zone.

Due to the relatively low amplification of seismic waves in rock site conditions, the ground shaking intensity is reduced, which positively influences seismic resilience assessments for buildings and infrastructure. Compared to previous studies, this research offers a more refined and comprehensive evaluation, incorporating multiple parameters. The findings provide a robust foundation for disaster risk management, urban planning, and the revision of building codes and regulations in Mongolia.

Acknowledgements

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Ethical approval

This study does not involve human participants or animals, and therefore, does not require ethical approval.

Author contribution

The authors confirm their contributions to the paper as follows: Study conception and design, investigation, writing, and review: DM, CO; Data collection and analysis: DM, MD, MA; Field investigation and technical validation: DM, ChO; Writing- original draft preparation: DM, CO, MD; Writing – review and editing: CO, DM, MD. All authors reviewed and approved the final version of the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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