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PROBABILISTIC SEISMIC HAZARD ASSESSMENT OF THE POTWAR PLATEAU AND SALT RANGE REGION USING R-CRISIS

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Abstract
The Khewra Salt Mine, located within the seismically active Salt Range and Potwar Plateau region of Pakistan, is a critical industrial and tourist site situated near the convergence of major thrust and strike-slip fault systems. Despite its structural significance, no site-specific probabilistic seismic hazard assessment has previously been conducted for this facility. This study performs a rigorous Probabilistic Seismic Hazard Analysis (PSHA) of the Khewra Salt Mine and surrounding region using the R-CRISIS software platform, following Cornell-McGuire methodology. Four primary seismogenic sources are modeled: the Salt Range Thrust (SRT), Main Boundary Thrust (MBT), Jhelum Fault (JF), and Kalabagh Fault (KF), with seismicity parameters derived from regional earthquake catalogs and structural literature. The Bounded Gutenberg-Richter recurrence model is employed with a uniform threshold magnitude of $M_0 = 4.5$*, and ground motion attenuation is characterized using the Akkar et al. Next Generation Attenuation model. A 300 km integration radius and a computation grid of 3,575 target points are used to generate high-resolution Peak Ground Acceleration (PGA) hazard contour maps. Results indicate that PGA values across the study area range from 0.00g to 0.23g, with both the Khewra Salt Mine and the Civil Hospital Khewra falling within a moderate hazard zone of 0.06g to 0.12g. A five-tier seismic zonation scheme is developed to support risk-informed infrastructure planning. The findings provide baseline design parameters for underground structural reinforcement, healthcare facility retrofitting, and regional disaster preparedness frameworks.*

1 INTRODUCTION

Pakistan lies within one of the world's active seismic belts due to the collision of the Indian and Eurasian tectonic plates. Northern and northeastern Pakistan is affected by major thrust systems including the Himalayan Frontal Thrust, Main Boundary Thrust and associated fold-and-thrust structures. The Salt Range and Potwar Plateau represent a tectonically significant region characterized by compressional deformation[1] Khewra Salt Mine is an destination and located within the Salt Range[2]. Due to growing tourism and associated infrastructure, understanding seismic hazard is important for safe planning and structural design.

Probabilistic Seismic Hazard Analysis (PSHA) is an essential framework for quantifying seismic risk, accounting for the inherent uncertainties in earthquake size, location, and recurrence[3]. For critical infrastructure, site-specific PSHA provides the foundational data required for resilient structural and geotechnical design. This study conducts a rigorous PSHA for the Khewra Salt

Mine, one of the world's largest and oldest salt mining operations and adjoining areas. Given its high structural significance and its location within the active deformation front of the sub-Himalayas, defining precise expected ground motions—specifically Peak Ground Acceleration (PGA)—is imperative for the safety of its expansive underground chambers and surface tourist facilities[4].

This study uses R-CRISIS to perform a regional hazard analysis. By combining local fault data with past earthquake history, the software calculates the expected ground shaking (PGA). These results help us understand the actual seismic risk to the Khewra mine and adjoining areas.

2 Objectives

The primary objectives of this study are to:

- Perform a regional PSHA for the Khewra Salt Mine and surrounding Salt Range region using R-CRISIS, following Cornell-McGuire methodology within a 300 km integration radius.
- Generate spatial PGA hazard maps and develop a seismic zonation scheme for engineering risk classification.
- Evaluate the seismic exposure of critical infrastructure, including the Khewra Salt Mine and Civil Hospital Khewra, and propose site-specific mitigation recommendations.

3 Study Area, Tectonic Setting and Historical Seismicity

The Khewra Salt Mine is located in the Jhelum District of Punjab, Pakistan, at the foothills of the Salt Range. The specific coordinate evaluated for this study is anchored at the main tourist and administrative entrance: Latitude 32.6481 N, Longitude 73.0081 E[5].

The regional terrain and study area layout are shown below in the Figure 1. This satellite view of the Salt Range highlights the exact locations of the mine entrance and the main mine.

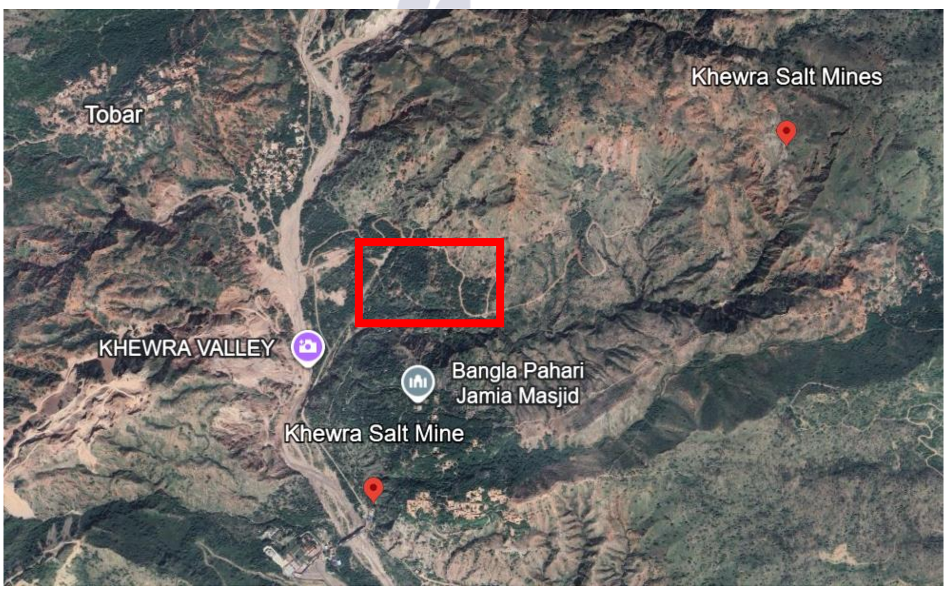

Figure 1: Satellite view of the project area showing the regional topography and the highlighted entrance to the Khewra Salt Mine

The Salt Range is an active fold-and-thrust belt formed by the Indian-Eurasian plate collision. A thick evaporite sequence (the Salt Range Formation) acts as a basal decollement, driving southward thrusting over the Punjab foreland and producing complex strain partitioning that necessitates localized hazard modeling[6].

The tectonic regime governing the seismic hazard of the site is dominated by a complex network of thrust and strike-slip faults. Four primary

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seismogenic sources were identified and modeled for this study:

1. Salt Range Thrust (SRT): The dominant near-field structure bounding the southern edge of the Potwar Plateau. It accommodates significant crustal shortening via low-angle, thin-skinned thrusting[7].
2. Main Boundary Thrust (MBT): A major crustal-scale compressional fault located north of the site. It is a highly active plate boundary interface responsible for significant historical strain release[7].
3. Jhelum Fault (JF): A north-south trending left-lateral strike-slip transform fault bounding the eastern margin of the Potwar structural block[8].
4. Kalabagh Fault (KF): A right-lateral ramp fault bounding the western termination of the Salt Range, accommodating differential slip of the thrust sheet[9].

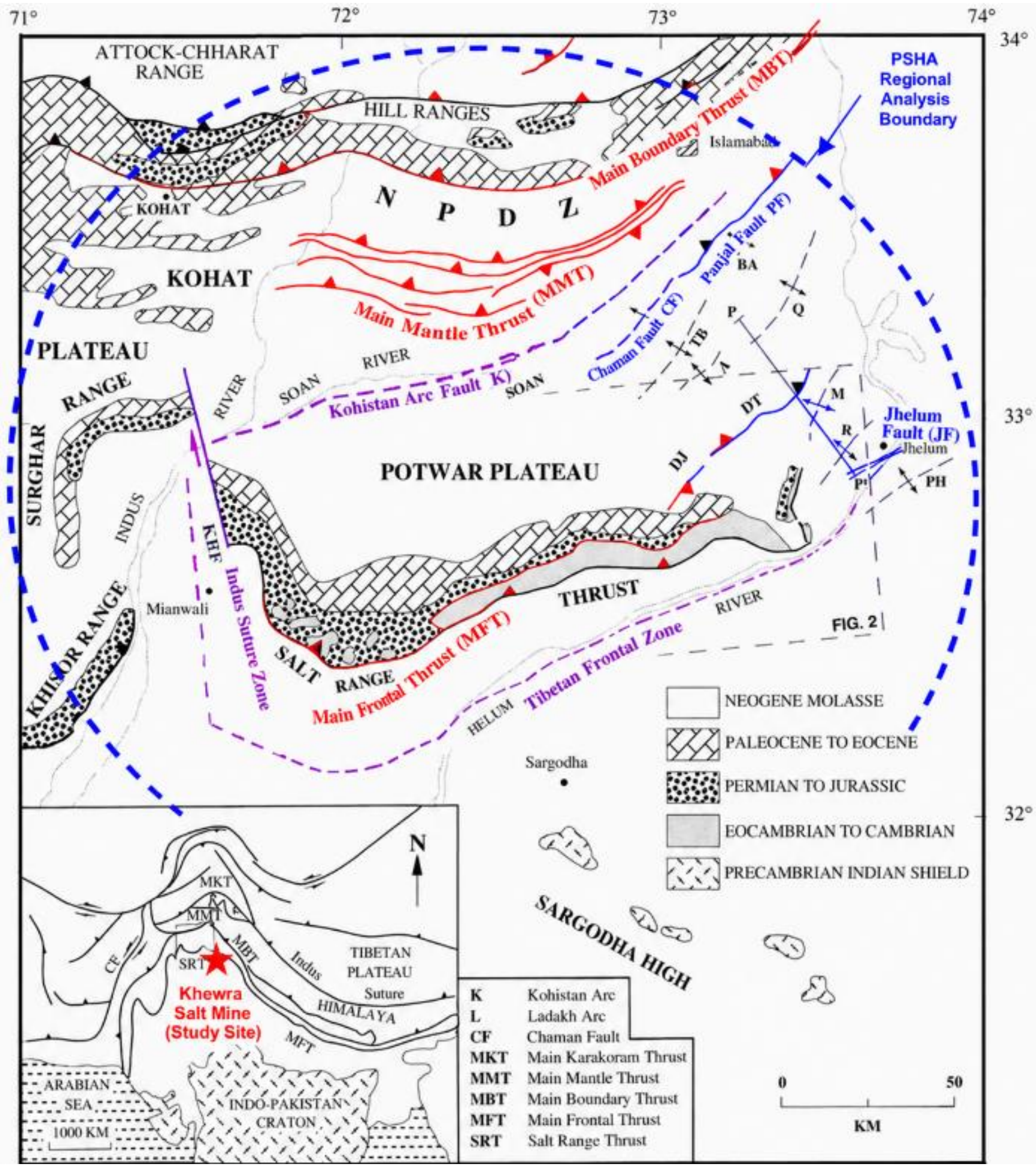

Figure 2: Modified structural map of the Potwar Plateau and Salt Range showing the 300 km PSHA regional analysis boundary, highlighted primary seismic fault sources, and the location of the Khewra Salt Mine study site (inset). Modified from[10].

Figure 2 presents the regional tectonic framework used for the R-CRISIS hazard model. The 300 km analysis boundary encompasses the active Potwar Plateau and Salt Range, capturing all primary seismic sources including the Main Frontal Thrust and Jhelum Fault. The inset map marks the exact location of the Khewra Salt Mine relative to these regional structures.

The sub-Himalayan region of Pakistan possesses a rich history of instrumental and historical seismicity. The MBT and its associated splays have generated highly destructive events, most notably the 2005 Kashmir Earthquake (M_w 7.6). While the immediate vicinity of the Salt Range typically exhibits moderate seismicity with frequent small-to-medium magnitude events, the historical record suggests that the underlying decollement and regional bounding faults are capable of accumulating elastic strain sufficient to generate large-magnitude ($M_w \geq 7.0$) earthquakes[11].

The Salt Range and Potwar Plateau region exhibits persistent low-to-moderate seismicity, dominated by shallow earthquakes in the range $4.0 \leq M_w \leq 5.9$, with no large damaging event ($M_w \geq 6.0$) recorded directly along the main detachment front during the instrumental period. For catalog preparation, a magnitude of completeness of $M_c \geq 4.0$ was applied to retain only independent mainshock events. A conservative modeling threshold of $M_0 = 4.5$ was subsequently adopted as the lower-bound input to the Bounded Gutenberg-Richter recurrence equation within R-CRISIS, as earthquakes below this level are generally insufficient to generate structurally significant ground motions[12].

This seismicity pattern reflects ongoing crustal compression driven by the Indian-Eurasian plate collision, with the sedimentary sequence sliding southward over the low-friction Salt Range Formation decollement. Seismic strain is consequently distributed across the Salt Range Thrust and associated structures, including the Choa Saidan Shah and Kallar Kahar fault systems[13].

4 Research Methodology

The study was conducted using the R-CRISIS software environment, following these distinct phases:

- Spatial grid generation and boundary definition.
- Geometric source modeling of regional faults.
- Seismicity parameterization using the Bounded Gutenberg-Richter model.
- Ground motion characterization via modern empirical attenuation relationships.
- Numerical integration and spatial map generation.

4.1 R-CRISIS Modelling Procedure

Step 1: Spatial Grid Setup and Integration Radius

To ensure complete mathematical closure of the hazard integral and capture the long-period resonant effects critical to large underground structures, a maximum integration radius (R_{max}) of 300 km was established around the site coordinates. Modern performance-based design frameworks require capturing distant crustal boundaries that can produce structural resonance. A computation grid of 3,575 target points was generated to encapsulate this zone, providing the spatial density required for high-resolution contour mapping.

Step 2: Seismic Source Modeling

The four primary faults (SRT, MBT, JF, KF) were explicitly modeled as distinct geometric sources. Thrust interfaces (SRT, MBT) were modeled as dipping area sources to simulate the down-dip extension of the rupture planes, while strike-slip boundaries (JF, KF) were assigned constrained geometries.

Step 3: Seismicity Parameters

The earthquake recurrence rate for each modeled fault was computed using the Bounded Gutenberg-Richter recurrence law:

$$n(M)=\lambda_0 \frac{\exp[-\beta(M-M_0)]-\exp[-\beta(M_{max}-M_0)]}{1-\exp[-\beta(M_{max}-M_0)]} \quad (1)$$

The mean annual rate of occurrence for earthquakes originating from each modeled fault source was parameterized using the truncated or Bounded Gutenberg-Richter recurrence relationship[14]. A uniform lower-bound threshold magnitude of M_0 = 4.5 was selected across all zones to remove minor background seismicity that does not pose structural risks to engineered installations.

The seismic scaling parameter β was uniformly defined as 2.303, which mathematically corresponds to a classic Gutenberg-Richter b-value of exactly 1.0 ($\beta = b \cdot \ln(10)$). This value represents a highly stable tectonic regime under continuous compressional stress, a baseline validated for the northern Pakistani thrust sheets by regional seismicity catalog analyses[12].

The annual activity rates (λ_{M0}) and maximum credible magnitudes (M_{max}) assigned to each source reflect historical seismic energy release and empirical fault-rupture lengths available in sub-Himalayan structural literature:

- The Salt Range Thrust (SRT) was assigned an activity rate of λ_{M0} = 0.15 and a maximum magnitude of M_{max} = 7.4, capturing the extensive down-dip potential of the basal decollement layer[10, 12].
- The Main Boundary Thrust (MBT) represents the most active compressional interface in the region, assigned a high baseline activity rate of λ_{M0} = 0.25 and an upper bound M_{max} = 7.8, consistent with its capacity for generating major regional detachments[15, 16].
- The strike-slip systems bounding the Potwar block—the Jhelum Fault (JF) and Kalabagh Fault (KF)—were assigned activity rates of 0.08 and 0.05 with M_{max} limits of 7.3 and 7.5, respectively, accounting for the segmented nature of the lateral ramp transform boundaries [10, 17].

To preserve the deterministic nature of the maximum physical boundaries of the faults within the R-CRISIS computational engine, the statistical coefficient of variation for β and the uncertainty range for M_{max} were maintained at 0. The comprehensive input dataset is structured below in Table 1.

Table 1: Input Seismicity Recurrence Parameters for the Regional Fault Sources

Source ID	Fault Name	Threshold Mag (M_0)	Activity Rate (λ_{M0})	Seismicity Factor (β)	Coeff. of Variation (β)	Number of Mags	Max Expected Mag (M_{max})
S1	Salt Range Thrust (SRT)	4.5	0.15	2.303	0	9	7.4
S2	Main Boundary Thrust (MBT)	4.5	0.25	2.303	0	9	7.8
S3	Jhelum Fault (JF)	4.5	0.08	2.303	0	9	7.3
S4	Kalabagh Fault (KF)	4.5	0.05	2.303	0	9	7.5

Step 4: Ground Motion Prediction Equation (GMPE)

To predict the attenuation of seismic waves from the modeled sources to the Khewra site, the Next Generation Attenuation model developed by Akkar[18] for crustal regimes was utilized. This empirical model is highly suitable for the compressional and strike-slip tectonics of the sub-Himalayas. To satisfy the mathematical constraints of the equation within the R-CRISIS framework while precisely capturing Peak Ground Acceleration (PGA), the spectral anchor period was set to an infinitely rigid structural period of T = 0.005[15]. The evaluation grid was configured for a hard rock/stiff soil baseline equivalent to the consolidated evaporites present at the site.

Step 5: Hazard Computation

The probabilistic integration was executed across 25 logarithmic intensity levels ranging from a lower limit of 0.01g to an upper limit of 2.0g to ensure smooth, continuous hazard curves. The computational engine synthesized the spatial distances, recurrence rates, and ground motion attenuation to yield annual frequencies of exceedance for the 3,575 grid nodes.

5 Results and Analysis

5.1 Spatial Distribution of Peak Ground Acceleration

The PSHA executed via R-CRISIS yields a high-resolution spatial distribution of PGA across the 3,575-point computation grid. Computed accelerations range from **0.00g** in peripheral stable zones to a maximum of **0.23g** in the near-field fault rupture core. As shown in Figure 3, the hazard contours exhibit a distinct elongated "bullseye" geometry concentrated in the center-east portion of the map, directly reflecting the orientation and trace density of the four modeled fault sources. The dominant contributors are the MBT and SRT, consistent with their elevated activity rates and M_{max} values. Civil Hospital Khewra is additionally marked on the Figure 3 as the region's sole designated lifeline structure, the rationale for which is discussed in Section 5.2.

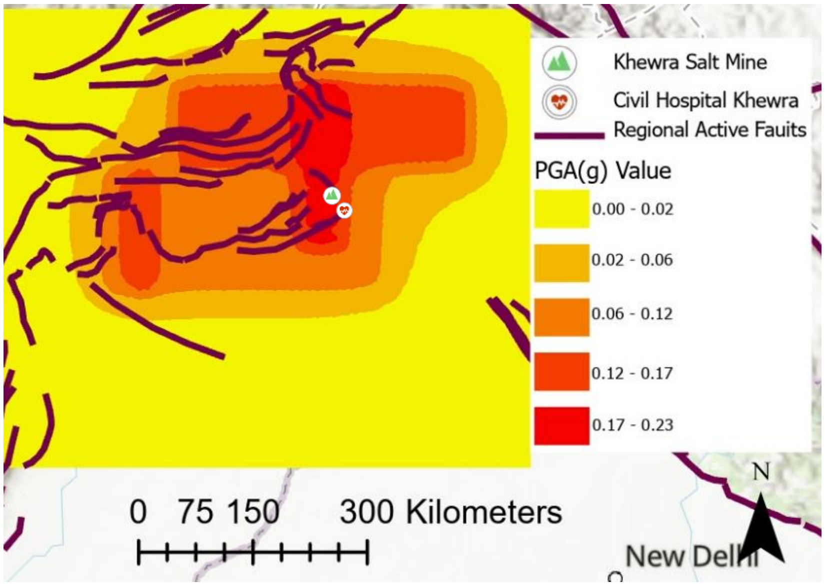

Figure 3: PGA hazard zonation map of the Salt Range region showing five acceleration zones (0.00g – 0.23g) with Khewra Salt Mine and Civil Hospital Khewra both located within the moderate hazard zone (0.06g – 0.12g)

5.2 Seismic Hazard Zonation and Infrastructure Exposure

Given the Khewra Salt Mine's role as a critical industrial and tourist facility, Civil Hospital Khewra was co-mapped within the hazard framework as the region's sole designated lifeline structure. Under the Building Code of Pakistan, hospitals must remain operational post-disaster to support emergency response, making their seismic exposure directly relevant to regional disaster preparedness. The computed PGA field is therefore stratified into five operational hazard zones for both facilities, as presented in Table 2.

Table 2: Seismic hazard zonation scheme based on computed PGA ranges for the Salt Range region

Hazard Zone	PGA Range (g)	Exposure Profile
Zone I	0.00 – 0.02	Peripheral stable zones; minimal hazard
Zone II	0.02 – 0.06	Low-to-moderate transitional zone
Zone III	**0.06 – 0.12**	**Moderate hazard; all target infrastructure**
Zone IV	0.12 – 0.17	High hazard; major fault approach paths
Zone V	0.17 – 0.23	Maximum hazard; near-field rupture core

Overlaying both facilities onto the zonation map confirms that the Khewra Salt Mine and Civil Hospital Khewra fall within **Zone III (0.06g – 0.12g)**, indicating that the region's primary emergency healthcare node shares the same moderate hazard footprint as the mine and justifying enhanced structural stringency for both facilities.

5.3 Site-Specific Hazard Curve and Design Ground Motions

Figure 4 presents the site-specific hazard curve for the Khewra coordinates (X = 73.0081, Y = 32.6481), plotting exceedance probability in 50 years against PGA on a log-log scale. The curve aggregates contributions from all four fault sources attenuated through the Akkar et al. GMPE. Table 3 presents the extracted PGA values at all five configured return periods.

Table 3: Site-specific PGA values at standard engineering return periods for Khewra Salt Mine

Return Period (years)	PE in 50 years	Design Level	Site PGA (g)
100	3.93E-01	Serviceability	0.0318
250	1.81E-01	Occasional	0.0660
475	**9.99E-02**	**DBE**	**0.0912**
1000	4.88E-02	Rare	0.1280
2475	**2.00E-02**	**MCE**	**0.1783**

The DBE-level PGA of 0.0912g confirms a moderate hazard regime, while the MCE-level PGA of 0.1783g represents the upper-bound design ground motion for performance-based assessment of critical underground structures.

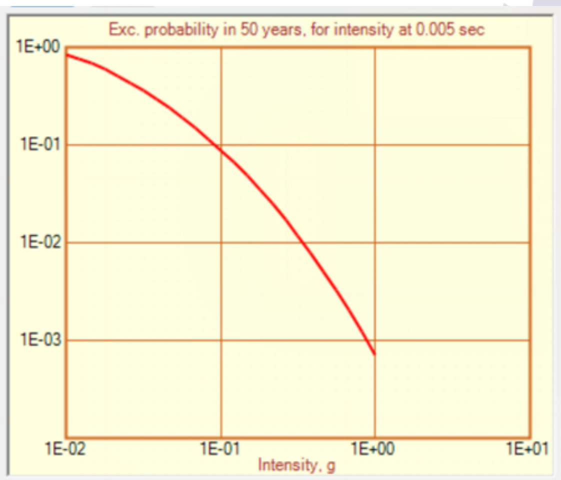

Figure 4: Site-specific seismic hazard curve for Khewra Salt Mine (X=73.008, Y=32.644) showing exceedance probability in 50 years versus PGA intensity

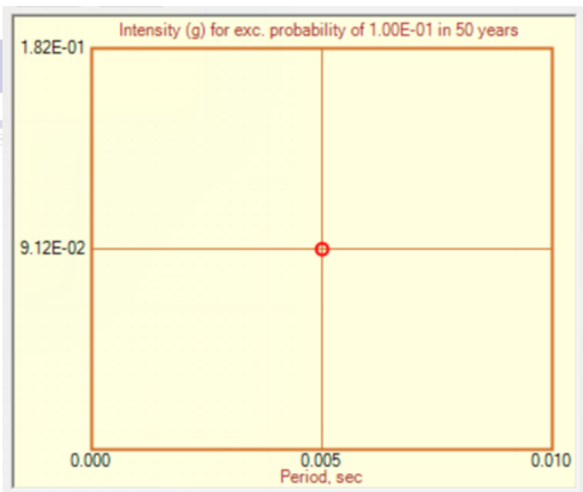

Figure 5: Uniform Hazard Spectrum (UHS) at DBE level (10% PE in 50 years) confirming a spectral acceleration of 0.0912g at T=0.005 sec for Khewra Salt Mine

5.4 Uniform Hazard Spectrum

The UHS computed at DBE level (Figure 5) confirms a spectral acceleration of **0.0912g** at T = 0.005 seconds, consistent with the hazard curve extraction. This value aligns with the Building Code of Pakistan Zone 2A (Moderate Hazard classification and serves as the primary design parameter for structural assessments of both facilities.

6 Practical Implementation

The computed DBE-level PGA of 0.0912g and MCE-level PGA of 0.1783g for the Khewra Salt

Mine serve as direct design inputs for geomechanical stabilization. The 0.12g Zone III threshold must be integrated into numerical modeling software such as FLAC or RS2 to re-evaluate safety factors of existing room-and-pillar configurations under dynamic loading. High-span tourist chambers should be outfitted with corrosion-resistant rock bolting and wire mesh systems to absorb lateral shear energy. A micro-seismic monitoring network inside the mine workings is recommended to detect micro-fissure propagation in real time. For Civil Hospital Khewra, structural retrofitting and non-structural lifeline anchorage of critical medical assets are recommended to ensure post-disaster operational continuity under the BCP Zone 2A classification.

7 Conclusion

Following conclusions can be drawn from the conducted study:

1. The PSHA model bounds the regional seismic hazard between 0.00g and 0.23g, forming a concentric bullseye pattern driven by the Salt Range Thrust and Main Boundary Thrust.
2. The DBE-level PGA of 0.0912g and MCE-level PGA of 0.1783g provide site-specific design ground motions for performance-based structural assessment of the Khewra Salt Mine.
3. Both the Khewra Salt Mine and Civil Hospital Khewra fall within the moderate hazard Zone III (0.06g – 0.12g), consistent with BCP Zone 2A classification.
4. The computed zonation values provide baseline parameters for localized building codes, rock-bolting designs, and regional disaster preparedness planning.

These findings establish the first site-specific probabilistic seismic hazard baseline for the Khewra Salt Mine, with future work recommended to incorporate multi-period UHS and site amplification effects for full performance-based design.

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