

Seismic Hazard Assessment of Minab City using the Preliminary Gutenberg-Richter Method

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Abstract: Iran is located on a seismically active belt, making earthquakes a frequent occurrence. Given the country's high seismicity and the potential for destructive earthquakes, understanding Iran's seismic characteristics is crucial. Therefore, studying and assessing the seismic hazard in different regions of Iran is essential. This research evaluates the seismic hazard of Minab city using statistical-probabilistic and analytical methods. In the probabilistic approach, earthquake data from the 20th century within a 200 km radius of the study site were analyzed to estimate the probability of future earthquakes with a magnitude of 4.0 or higher. The study area, Minab County, is located in Hormozgan Province at coordinates 55°00' to 57°00' E longitude and 27°00' to 28°00' N latitude. For the analytical approach, aerial photographs and 1:100,000-scale geological maps of Minab and its surroundings were examined to identify fault structures. Using ArcMap software, fault segments within a 200 km radius of Minab were mapped, and seismic parameters were evaluated. The statistical method was further employed to estimate earthquake probability and recurrence intervals for different magnitudes in the region. This study provides a comprehensive assessment of Minab's seismic hazard, contributing to better risk management and mitigation strategies.

Keywords: Seismic hazard assessment, Gutenberg-Richter method, Minab city, Geotechnics, Earthquake.

I. INTRODUCTION

Seismic Hazard Assessment (SHA) is the process of evaluating the probability and characteristics of earthquake-induced ground motions at a specific location over a defined period (Wang, 2011). This assessment helps identify the potential intensity, frequency, and spatial distribution of seismic activity, enabling engineers, policymakers, and urban planners to design earthquake-resistant structures and implement risk reduction measures (Tavakoli & Ghafory-Ashtiany, 1999). SHA is a fundamental aspect of earthquake engineering and disaster preparedness, as it provides a scientific basis for understanding and mitigating earthquake-related risks (Panza & Bela, 2020).

SHA typically involves analyzing historical earthquake data, geological structures, and tectonic settings to estimate the likelihood of future seismic events (Nath & Thingbaijam, 2012). It incorporates various models, such as deterministic and probabilistic approaches, to quantify seismic hazards based on fault activity, earthquake recurrence intervals, and ground motion propagation (Verma & Bansal, 2013). Additionally, site-specific factors like soil composition, topography, and local seismic response characteristics are considered to refine hazard assessments and enhance prediction accuracy (Vilanova & Fonseca, 2007). The primary goal of SHA is to minimize the potential loss of life and economic damage caused by earthquakes (Ornthammarath et al., 2011). By providing critical insights into seismic hazards, SHA informs the development of building codes, land-use planning strategies, and emergency response plans (McCalpin, 2009). While advancements in technology and data collection have improved SHA's accuracy, uncertainties remain due to the complex and unpredictable nature of seismic activity (Meletti et al., 2008). Nonetheless, SHA remains a crucial tool in promoting earthquake resilience and disaster risk reduction worldwide (Pei et al., 2022).

The SHA plays a crucial role in understanding and mitigating the risks associated with earthquakes (Musson, 2000). Since earthquakes can cause severe structural damage, economic losses, and human casualties, SHA provides essential data to anticipate ground shaking intensity and its potential impact on infrastructure and communities (Kossobokov & Nekrasova, 2012). By assessing seismic hazards, authorities can develop effective disaster management strategies, improve emergency response plans, and enhance public safety in earthquake-prone regions (Ordaz et al., 2014). One of the key applications of SHA is in earthquake-resistant building design (Pei et al., 2022). Engineers use SHA data to establish seismic design codes that ensure structures can withstand expected ground motions (Tavakoli & Ghafory-Ashtiany, 1999). This is particularly important for critical infrastructure such as hospitals, bridges, power plants, and dams, where structural failure could have catastrophic consequences (Lapajne et al., 2003; Meletti et al., 2008; Wang, 2011).

SHA also plays a vital role in geotechnical and engineering geology (Zhang et al., 2021). In infrastructure development, factors such as soil composition, fault locations, and ground stability must be considered to prevent earthquake-induced hazards like liquefaction, landslides, and ground ruptures (Park et al., 2021). By analyzing seismic hazards, engineers can select appropriate construction sites, design foundations that account for soil behavior, and implement reinforcement measures to enhance the resilience of roads, tunnels, and other essential infrastructure (Sawires et al., 2023). From a development and economic perspective, SHA supports sustainable urban planning and land-use management (Abdalla & Al-Homoud, 2004). By identifying high-risk seismic zones, urban planners can avoid constructing important facilities in areas prone to severe ground shaking (Boominathan et al., 2008). Additionally, SHA helps governments and insurance companies estimate potential economic losses due to earthquakes, allowing them to allocate resources efficiently and develop financial risk mitigation strategies, such as earthquake insurance and emergency funds (Beauval et al., 2013).

The SHA can be broadly categorized into two main types: Deterministic Seismic Hazard Assessment (DSHA) and Probabilistic Seismic Hazard Assessment (PSHA). These methods are used to estimate the potential ground shaking intensity and the likelihood of earthquake occurrence at a given location (Krinitzsky, 2003). While both approaches aim to assess seismic hazards, they differ in methodology, assumptions, and applications (Wang, 2011). DSHA focuses on the worst-case scenario for a given site. It assumes that the largest possible

earthquake from a nearby fault will occur and estimates the resulting ground motion (Bommer, 2002). DSHA involves four main steps: identifying active faults, selecting the maximum credible earthquake (MCE), estimating the distance from the fault to the site, and calculating the expected ground shaking intensity (Loi et al., 2018). This method is commonly used for designing critical infrastructure such as nuclear power plants, dams, and emergency response centers, where ensuring safety against the strongest possible earthquake is essential (Ansari et al., 2022). One of the main advantages of DSHA is its simplicity and clarity—it provides a straightforward estimation of the highest seismic risk a location might face (Azarafza et al., 2019). However, DSHA has limitations, as it does not consider the probability of an earthquake occurring within a specific timeframe. By focusing only on extreme scenarios, it may lead to overly conservative designs, increasing construction costs (Nikoobakht et al., 2018).

PSHA, on the other hand, incorporates uncertainties associated with earthquake occurrences and ground motion variations (Krinitzsky, 2003). Instead of focusing on a single worst-case event, PSHA evaluates multiple possible earthquake scenarios, considering their likelihood of occurrence within a given period (Wang, 2011). This method involves statistical modeling of seismic sources, recurrence intervals, and ground motion predictions to estimate the probability of exceeding certain ground shaking levels over a specific time frame (e.g., 50 or 100 years). PSHA is widely used in urban planning, insurance risk assessment, and infrastructure design because it provides a more realistic measure of seismic hazards (Loi et al., 2018).

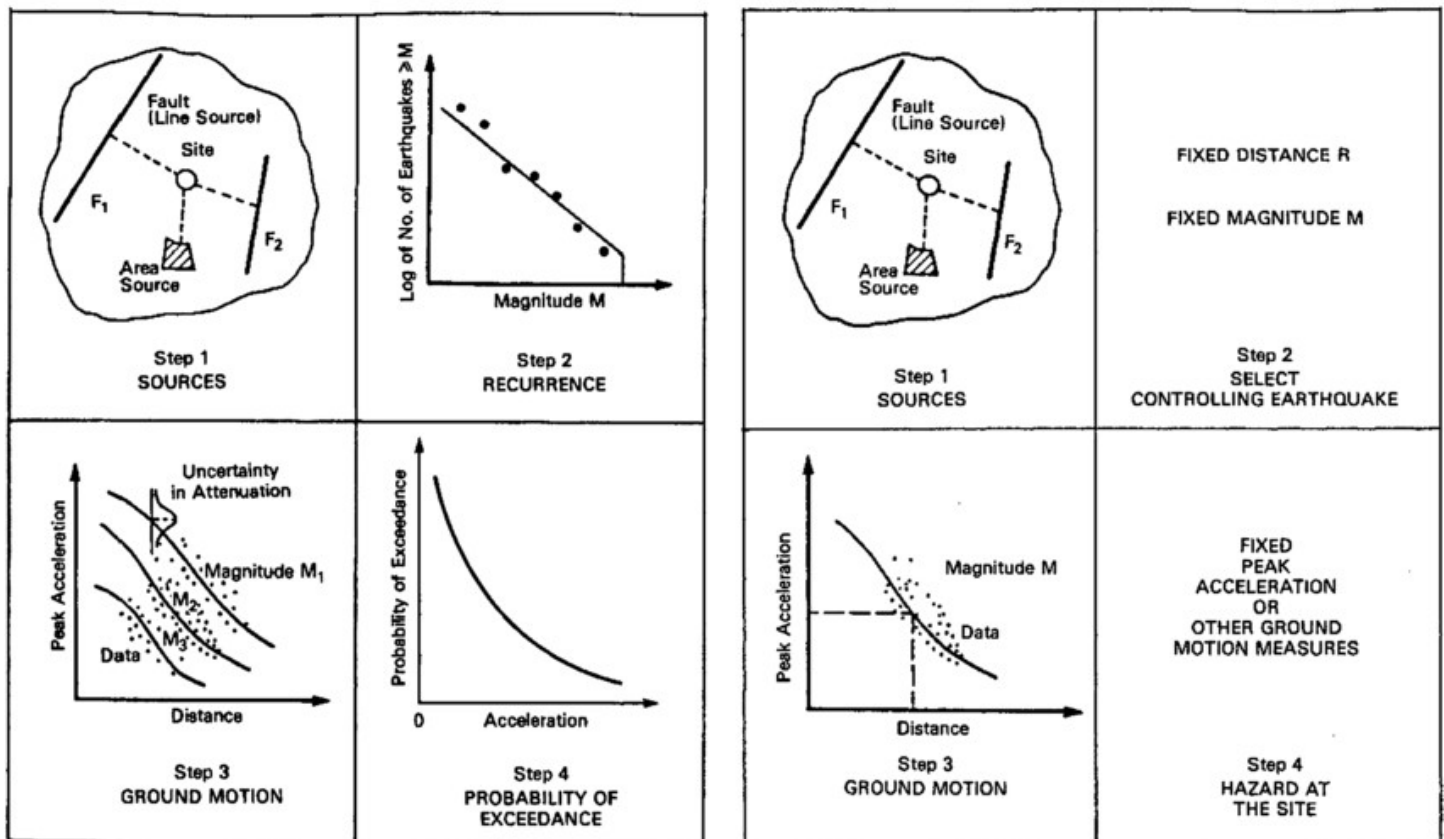


Fig. 1 Difference between DSHA and PSHA (Marmureanu et al. 1993)

By considering different earthquake magnitudes, recurrence rates, and attenuation relationships, PSHA helps in optimizing building codes and risk mitigation strategies. However, it is more complex than DSHA and requires large datasets, advanced statistical models, and computational tools (Aglia et al., 2023). Despite its complexity, PSHA is favored for regional seismic hazard mapping and long-term risk assessment (Ayele et al., 2021). Both DSHA and PSHA have unique advantages and limitations, making them suitable for different applications. DSHA is best suited for designing highly critical facilities where the worst-case scenario must be considered, even if it is rare (Ismail-Zadeh & Kumar, 2021). PSHA, on the other hand, is more appropriate for broader applications like general building codes, land-use planning, and insurance risk assessments, as it provides probability-based estimates (Foyouzati et al., 2024). Often, engineers and policymakers use a combination of both approaches to achieve a balanced and comprehensive seismic hazard assessment (Parashar, 2023).

The primary objective of this research is to assess the seismic hazard of Minab City using both statistical-probabilistic and analytical methods, specifically the Preliminary Gutenberg-Richter Method. By analyzing seismic data from the 20th century and identifying local fault structures, the study aims to estimate the probability of future earthquakes and the potential ground shaking that may affect the region. This assessment will contribute to understanding the seismic risks specific to Minab City and its surroundings, providing valuable insights for urban planning, infrastructure development, and disaster risk mitigation. The necessity of this research stems from the growing importance of earthquake preparedness in seismic-prone areas like Iran, which is situated on a major tectonic boundary. With the increasing frequency of seismic events worldwide and the potential for devastating earthquakes, understanding the seismic hazard in Minab City is crucial for ensuring public safety and minimizing potential damage. This study will support the development of effective building codes, improve land-use planning, and inform emergency response strategies, thereby enhancing the region's resilience to future seismic hazards.

II. STUDIED LOCATION

Minab County is located in Hormozgan Province, within the geographical coordinates of 55°00' to 57°00' E longitude and 27°00' to 28°00' N latitude. Covering an area of 30,952 km², it lies in the southeastern part of Hormozgan and is bordered by Rudan County to the north, Bandar Abbas County to the northwest, Sirik and Jask Counties to the southeast, and Kerman Province to the northeast, while the Gulf of Oman is situated to its southwest. Minab City itself is positioned in the northeastern part of the Strait of Hormuz, at 27°04'20" to 27°19'35" N latitude and 57°01'50" to 57°02'07" E longitude. Figure 2 illustrates the location of the study area, while Figure 3 depicts the major faults within a 200 km, mapped in ArcGIS based on data of Iran International Institute of Earthquake Engineering and Seismology (IIIES) and Geological Survey of Iran (2012).

Geologically, the Minab region occupies the transition zone between the Makran Subduction Zone and the Zagros Fold-and-Thrust Belt (Ghanbarian et al., 2021), which makes it part of one of Iran's most seismically active areas (Figure 4). The presence

of major faults, such as the Minab Fault, Zendan Fault, and Palami Fault, indicates significant tectonic activity, with ongoing convergence between the Arabian and Eurasian plates. The region is characterized by alluvial deposits, sedimentary formations, and active fault lines, contributing to high seismic potential. Due to its proximity to the Strait of Hormuz and the Gulf of Oman, the area's coastal geology and soft sediment layers further influence seismic wave amplification and ground shaking intensity. These geological factors highlight the importance of seismic hazard assessment in the region to mitigate earthquake risks and ensure resilient infrastructure development.

III. GUTENBERG - RICHTER METHOD

The Gutenberg-Richter method is one of the most widely used empirical models for seismic hazard assessment (Godano et al., 2014). This method describes the relationship between the frequency and magnitude of earthquakes in a given region over a specific period (Ko & Yu, 2009). It is based on the observation that smaller earthquakes occur more frequently than larger ones, and their distribution follows a logarithmic pattern (Nava et al., 2017).

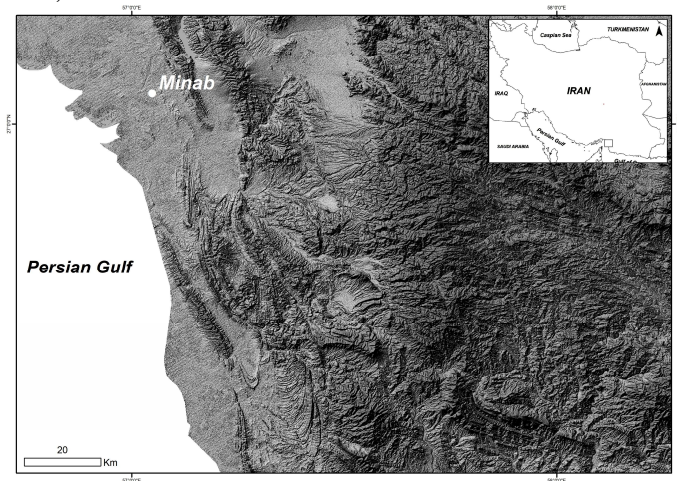


Fig. 2 Location of the study area

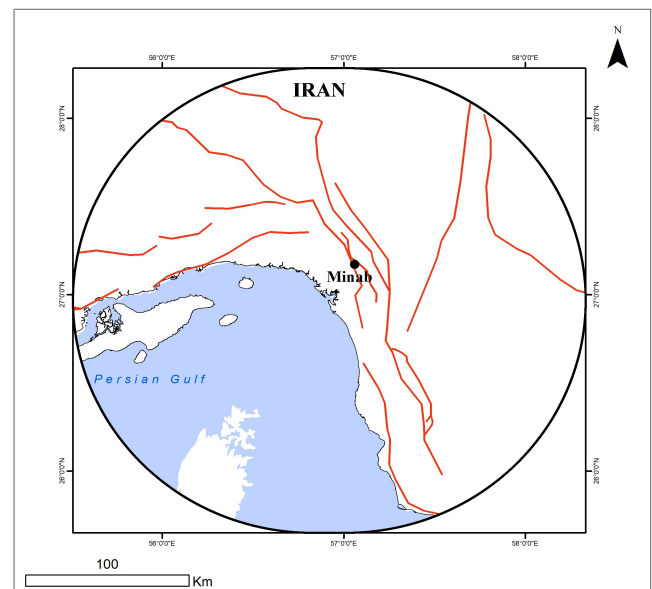


Fig. 3 Major faults within a 200 km radius of the study area

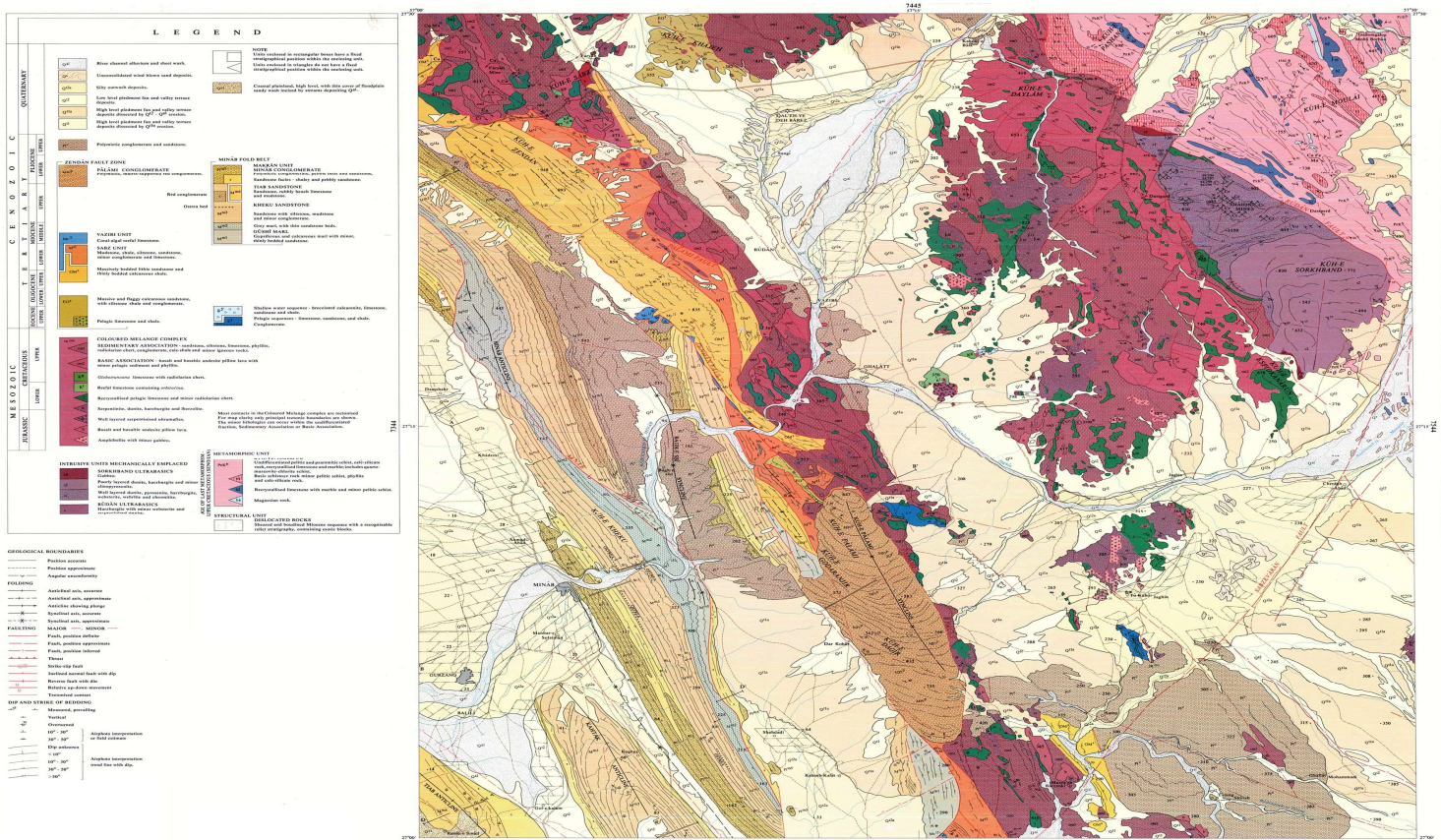


Fig. 4 Geological map for the study region (Geological Survey of Iran, 2012)

The Gutenberg-Richter law is essential for estimating earthquake recurrence rates and assessing seismic hazards in tectonically active regions. The fundamental equation of the Gutenberg-Richter relationship is expressed as (Elnashai & Di Sarno, 2015):

$$\log N(M) = a - bM \quad (1)$$

where, $N(M)$ is the cumulative number of earthquakes with a magnitude greater than or equal to M . a is a constant related to the total seismic activity of the region. b is the b -value, which describes the relative occurrence of small and large earthquakes. M is the earthquake magnitude (Elnashai & Di Sarno, 2015). The a -value represents the overall seismicity level of the region (Urban et al., 2016). A higher a -value indicates a more seismically active area (Rundle, 1989). The b -value, on the other hand, provides insights into the stress conditions of the region. For example (Scholz, 2019):

- $b > 1.0$ suggests that small earthquakes dominate, which is common in regions with low stress accumulation.
- $b < 1.0$ indicates a higher proportion of large earthquakes, often seen in areas with high stress buildup along faults.

These parameters are key for seismic risk assessment, as they help estimate the likelihood of future earthquakes and their potential magnitudes. The b -value typically ranges between 0.8 and 1.2, with a global average of around 1.0. A higher b -value indicates a predominance of small earthquakes, while a lower b -value suggests a higher occurrence of larger earthquakes (Scholz,

2019). The b -value can be determined using the maximum likelihood method, given by (Scholz, 2019):

$$b = \frac{\log e}{M_{\text{mean}} - M_{\text{min}}} \quad (2)$$

where, M_{mean} is the mean magnitude of earthquakes in the dataset. M_{min} is the minimum recorded magnitude. On the other hand, the a -value is calculated by fitting the Gutenberg-Richter equation to the observed earthquake data (Elnashai & Di Sarno, 2015). It is derived from (Scholz, 2019):

$$a = \log N + bM_{\text{mean}} \quad (3)$$

These parameters are computed using statistical techniques applied to earthquake catalogs (Lukk & Popandopoulos, 2012). The Gutenberg-Richter method relies on a high-quality earthquake dataset to accurately determine the statistical relationship between earthquake frequency and magnitude (Scholz, 2019). The most critical requirement is a comprehensive earthquake catalog, which includes detailed records of seismic events over a significant period (Elnashai & Di Sarno, 2015). This catalog should provide essential information such as the magnitude, location (latitude and longitude), depth, and occurrence time of each earthquake (Urban et al., 2016). The accuracy and completeness of this data directly impact the reliability of the estimated a -value and b -value, which define the

seismic activity and magnitude distribution in each region. Another key data requirement is the magnitude completeness threshold ($M_{\min}$), which represents the smallest earthquake magnitude reliably recorded in the dataset. Seismic networks often fail to detect very small earthquakes, especially in regions with sparse instrumentation (Ko & Yu, 2009). To ensure statistical reliability, the analysis must exclude events below this threshold and consider only those magnitudes that have been consistently recorded over time (Godano et al., 2014). Additionally, the catalog should cover a long enough time period to capture meaningful earthquake recurrence patterns, as short-term datasets may lead to biased estimates (Elnashai & Di Sarno, 2015). In addition to earthquake magnitude data, tectonic and geological information is essential for interpreting the Gutenberg-Richter relationship (Godano et al., 2014). Understanding fault structures, seismic source zones, and regional stress conditions helps refine the application of the method and validate the estimated parameters (Scholz, 2019). Modern implementations often integrate Geographic Information Systems (GIS) and remote sensing techniques to enhance data quality (Lukk and Popandopoulos, 2012). By ensuring a robust and complete dataset, the Gutenberg-Richter method can effectively contribute to seismic hazard assessments and earthquake forecasting efforts.

IV. MATERIALS AND METHODS

The Gutenberg-Richter method is implemented in this study to assess the seismic hazard of Minab City by analyzing earthquake frequency-magnitude relationships. The process involves collecting seismic data, processing it statistically, and estimating key parameters that define the regional seismicity. This method helps determine the likelihood of earthquakes of varying magnitudes occurring in the study area, providing essential insights for risk assessment and infrastructure planning. The first step in implementing the Gutenberg-Richter method is gathering a comprehensive earthquake catalog for the Minab region. This dataset is obtained from national and international seismic databases, such as the Iranian Seismological Center (IRSC), the United States Geological Survey (USGS), and the International Seismological Centre (ISC). The dataset includes critical information such as magnitude, epicenter coordinates, depth, and event time for each recorded earthquake. To ensure data reliability, earthquakes below the magnitude completeness threshold ($M_{\min}$) are filtered out.

For this study, seismic events within a 200 km radius of Minab City are selected to capture the regional tectonic activity. The time period covered in the analysis extends from the early 20th century to the present, allowing for a statistically significant dataset. This long-term dataset ensures that the recurrence patterns of earthquakes are accurately captured, reducing biases that may arise from short-term fluctuations in seismic activity. Once the dataset is prepared, the frequency distribution of earthquake magnitudes is analyzed. The earthquakes are grouped based on magnitude intervals (e.g., 0.1 or 0.2 magnitude units), and the cumulative number of events exceeding each magnitude level is calculated. This frequency-magnitude distribution follows a logarithmic trend, aligning with the Gutenberg-Richter relationship was discussed previously. The next step involves

plotting the frequency-magnitude distribution on a logarithmic scale to verify the linearity of the Gutenberg-Richter relationship. A straight-line trend confirms that the earthquake dataset follows the expected distribution, while deviations may indicate incomplete data, magnitude saturation, or changes in regional stress conditions. Advanced visualization tools, such as MATLAB, and GIS-based software (ArcMap), are used to enhance the graphical representation of results.

The estimated b-value is analyzed to understand the seismic behavior of the Minab region. A b-value close to 1.0 suggests a typical tectonic regime where small earthquakes are far more frequent than large ones. A lower b-value (<1.0) indicates a higher likelihood of large earthquakes, often associated with active fault zones under significant stress accumulation. Comparing these values with regional and global averages provides insights into the seismic risk potential. The results of the Gutenberg-Richter analysis are integrated into PSHA models. By combining earthquake recurrence data with ground motion prediction equations (GMPEs), the probability of different intensity levels of ground shaking is estimated. This information is essential for developing earthquake-resistant building codes, land-use planning strategies, and risk mitigation frameworks in Minab City.

V. RESULTS AND DISCUSSION

The seismic hazard assessment of Minab City using the Gutenberg-Richter method and statistical-probabilistic analysis has revealed significant insights into the region's seismic activity. The results indicate that the study area contains numerous active faults, which contribute to frequent seismic events. The earthquake catalog analysis shows that low to moderate-magnitude earthquakes ($M_s \geq 4$) are more common compared to high-magnitude earthquakes ($M_s \geq 7$). This finding aligns with the expected logarithmic distribution of earthquake frequencies, as described by the Gutenberg-Richter law. The b-value obtained from the analysis is within the range typical of tectonically active regions, suggesting that seismic activity is governed by regional fault structures. A higher b-value (~ 1.0 or above) indicates a higher frequency of small earthquakes relative to large ones, whereas a lower b-value (~ 0.8 or below) may signal increased stress accumulation and a greater likelihood of major earthquakes. The results suggest that Minab experiences a relatively high rate of small to moderate earthquakes, but the potential for larger seismic events remains a significant concern (Figure 5).

The recurrence intervals of earthquakes in the study area show that as the return period increases, the likelihood of experiencing a high-magnitude earthquake also increases. For instance, earthquakes of magnitude $M_s \geq 6$ or 7 have longer recurrence intervals, but their occurrence can result in catastrophic damage. This finding underscores the importance of long-term seismic monitoring and hazard preparedness for urban planning and infrastructure development. The spatial distribution of earthquake epicenters confirms that seismic activity is concentrated along major fault zones within a 200 km radius of Minab (Figure 6). By integrating GIS-based fault mapping and seismic data analysis, it was possible to identify high-risk areas where fault interactions may trigger larger seismic events. The

results highlight the necessity of continuously updating seismic hazard maps to reflect changes in fault dynamics and earthquake occurrence. Figure 7 provides the earthquake distribution map provided by IIEES data.

One of the key observations in this study is that the city's proximity to the Makran Subduction Zone and regional fault systems increases its vulnerability to seismic hazards. The tectonic complexity of the region, with interactions between thrust faults, strike-slip faults, and subduction processes, contributes to the observed seismic patterns. Additionally, the influence of deep-seated geological structures on earthquake occurrence suggests that seismic hazard assessments must consider both shallow crustal and deeper subduction-related seismicity. In terms of engineering and risk mitigation, the results emphasize the need for earthquake-resistant building codes and land-use planning in Minab. Structures should be designed to withstand strong ground motions associated with potential $M_s \geq 7$ earthquakes. Furthermore, critical infrastructure such as hospitals, bridges, and emergency response centers should be reinforced to ensure functionality during a seismic event. Implementing early warning systems and enhancing public awareness about earthquake preparedness are also crucial steps in reducing seismic risk. Despite the robustness of the methodology, some limitations exist in the seismic hazard assessment. The accuracy of the Gutenberg-Richter relationship depends on the completeness of the earthquake catalog, particularly for older historical records where data may be missing or inconsistent. Additionally, regional variations in stress accumulation, fault mechanics, and ground motion characteristics introduce uncertainties that require further investigation through advanced numerical simulations and geophysical studies. So, the study provides valuable insights into the seismic hazard of Minab, confirming its vulnerability to both frequent moderate earthquakes and less frequent but potentially destructive large earthquakes.

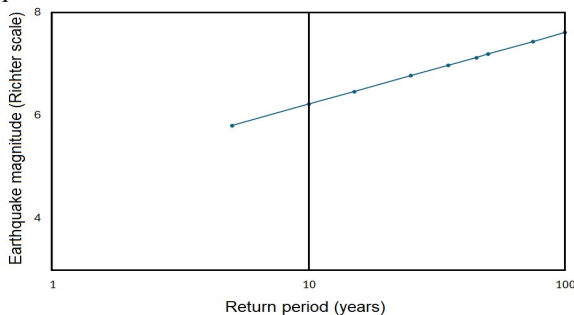


Fig. 5 Results of earthquake magnitude and return period

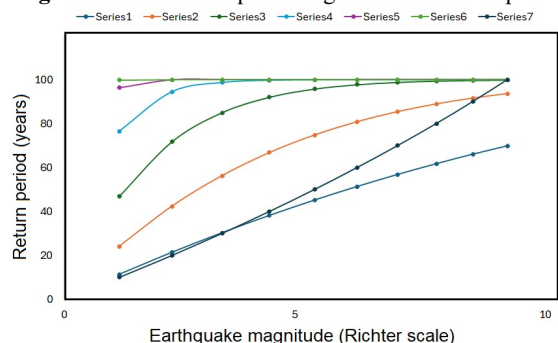


Fig. 6 Return period and percentage probability of earthquakes of different magnitudes

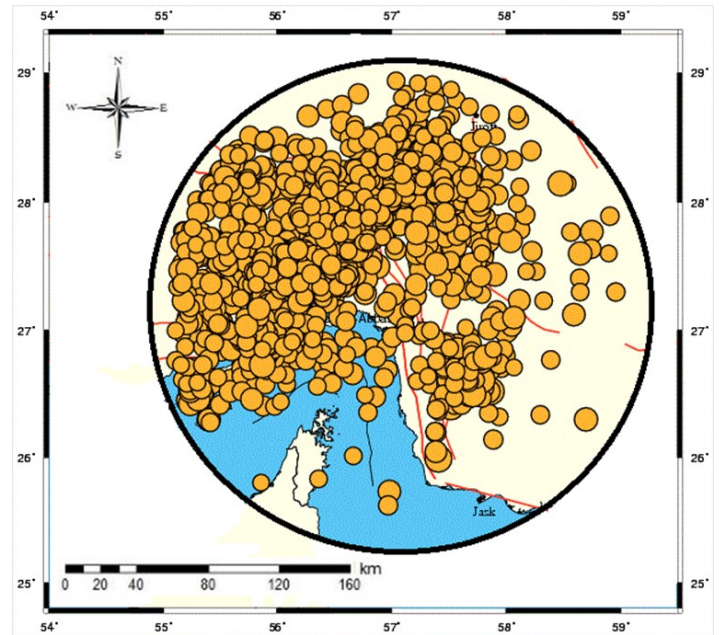


Fig. 7 The distribution of earthquakes in the study area (derived from IIEES data)

VI. CONCLUSION

The seismic hazard analysis of Minab City using the statistical-probabilistic method confirms that the region is highly seismically active, with numerous faults in close proximity. The application of the Gutenberg-Richter relationship demonstrates that earthquakes with a magnitude of $M_s=4$ occur more frequently than larger earthquakes (e.g., $M_s=7$ or $M_s=8$). This aligns with the general pattern observed in seismically active regions, where smaller earthquakes dominate, while larger, more destructive earthquakes occur less frequently but with longer recurrence intervals. The study also highlights the critical relationship between earthquake magnitude and return period. As the return period increases, the probability of experiencing a higher-magnitude earthquake also increases. This finding underscores the importance of long-term seismic hazard assessment in Minab, where historical and instrumental records suggest a substantial risk of major earthquakes in the future. Given the city's geographical location and tectonic setting, the likelihood of destructive earthquakes necessitates proactive disaster preparedness measures to mitigate potential loss of life and property damage. To minimize seismic risks, urban planning, engineering design, and disaster management strategies must integrate the findings of this study. Infrastructure should be constructed in compliance with earthquake-resistant building codes, and early warning systems should be implemented to enhance community resilience. Additionally, continued monitoring of seismic activity and periodic reassessment of hazard models are essential for updating risk assessments based on evolving tectonic conditions. So, the results emphasize the urgent need for preparedness and mitigation efforts to reduce the potential impact of future earthquakes in Minab. By integrating scientific analysis with policy-making and engineering solutions, the region can better withstand seismic hazards and ensure the safety of its residents.

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AUTHORS' CONTRIBUTIONS

Fatemeh Salari conducted the main data analysis, contributed to the data collection, preprocessing, interpretation, and was responsible for drafting the initial and revised manuscript. She provided project administration and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

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