

Seismic Hazard Evaluation and Structural Design Guidelines for the Southern Region of Saudi Arabia

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How to cite this paper: Alrubaidi, M. (2025) Seismic Hazard Evaluation and Structural Design Guidelines for the Southern Region of Saudi Arabia. *Open Journal of Earthquake Research*, 14, 7-27.

<https://doi.org/10.4236/ojer.2025.141002>

Received: December 28, 2024

Accepted: February 18, 2025

Published: February 21, 2025

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Abstract

The southern region of Saudi Arabia exhibits a distinct seismic profile shaped by the Red Sea Rift and local fault systems, necessitating rigorous seismic hazard evaluations and tailored structural design strategies. This study applies a robust Probabilistic Seismic Hazard Analysis (PSHA) framework to compute Maximum Considered Earthquake (MCE) and Risk-Targeted Maximum Considered Earthquake (MCER) values for major cities, including Jazan, Abha, and Najran. Utilizing local seismotectonic models, ground motion prediction equations (GMPEs), and soil classifications, the study generates precise ground motion parameters critical for infrastructure planning and safety. Results indicate significant seismic hazard variability, with Jazan showing high seismic risks with an MCER SA (0.2 s) of 0.45 g, compared to Najran's lower risks at 0.23 g. Structural design guidelines, informed by MCE and MCER calculations, prioritize the integration of site-specific seismic data, enhanced ductility requirements, and advanced analytical methods to ensure resilient and sustainable infrastructure. The study underscores the necessity of localized seismic assessments and modern engineering practices to effectively mitigate seismic risks in this geologically complex region.

Keywords

Seismic Hazard, PSHA, Maximum Magnitude, Rupture Characteristics, SA, KSA, PGA

1. Introduction

Earthquakes represent one of the most prominent natural phenomena threatening the safety of communities and infrastructure, especially in regions with variable tectonic activity. Saudi Arabia lies on the edge of the Arabian Plate, making it

susceptible to seismic activity induced by surrounding fault movements, such as the transform fault in the Red Sea and the Gulf of Aqaba. Although seismic activity in the Kingdom is generally moderate, certain areas in the southern region exhibit notable activity, necessitating thorough scientific evaluation to identify hazards and establish suitable design guidelines to ensure the safety of structures and inhabitants.

The southern region, encompassing cities such as Abha, Najran, and Jizan (**Figure 1**), is a focal point for seismic activity assessment. The tectonic map of Saudi Arabia (**Figure 2**) highlights concentrated seismic activity in these areas near major fault zones, emphasizing the need for a comprehensive seismic hazard evaluation [1]. Additionally, geological and tectonic data indicate that seismic activity is further influenced by the soil and rock properties unique to this region [2]. This study aims to provide a comprehensive assessment of seismic hazards in Saudi Arabia's southern region, based on recent data on seismic activity and the distribution of active faults. It also seeks to develop structural design guidelines that align with best engineering practices, ensuring sustainability and safety. The methodology incorporates a thorough analysis of historical and current seismic data, tectonic models, and local soil characteristics, to offer precise recommendations for enhancing design standards and mitigating potential seismic risks [3].

This research contributes to the current understanding of seismic activity in the southern region, providing accurate data that support the development of safe building policies. It also offers a practical framework for engineers and planners to improve the seismic resilience of structures, thereby protecting lives and assets in the event of future earthquakes [4].



Figure 1. Map of Saudi Arabia highlighting the southern region (Source: Encyclopædia Britannica, <https://www.britannica.com>).

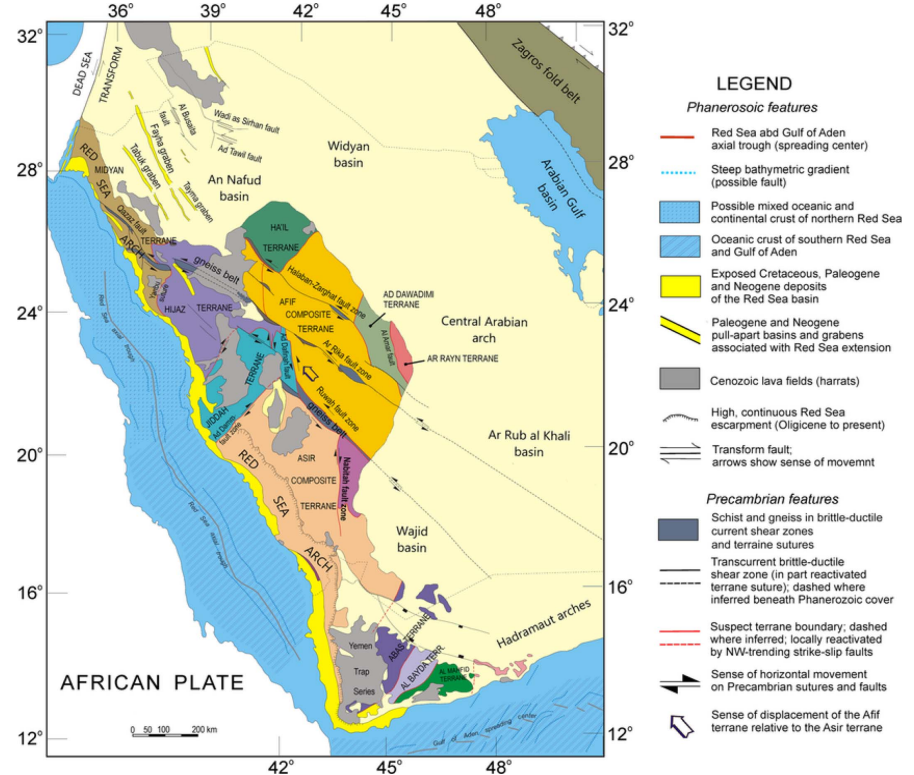


Figure 2. Tectonic map of Saudi Arabia highlighting seismic activity and fault distribution in the southern region [5].

Saudi Arabia's geographical location on the edge of the Arabian Plate, near tectonically active regions such as the Red Sea Rift and the Gulf of Aqaba Fault Zone, has made it the focus of several seismic studies. Previous research has mainly concentrated on understanding seismicity patterns and evaluating potential hazards across different regions of the Kingdom. For instance, studies have highlighted the increased seismic activity in the western and southwestern regions, attributed to the Red Sea Rift system [6] [7]. These studies used historical seismic records, probabilistic seismic hazard assessments (PSHA), and geotechnical investigations to identify areas of elevated seismic risk. Moreover, advanced modeling techniques have been employed to estimate ground motion parameters such as Peak Ground Acceleration (PGA) and Spectral Response Accelerations (SRA). Recent research has also incorporated GIS-based tools to map seismic hazards, providing a spatial analysis of risk distribution. These studies collectively emphasize the importance of localized hazard assessments, as ground motion can vary significantly based on fault proximity and local soil characteristics [8] [9].

The design of earthquake-resistant structures has significantly evolved over the past decades, with global standards such as the International Building Code (IBC) and Eurocode serving as benchmarks for seismic design. These standards emphasize the importance of incorporating seismic forces into the structural design process to mitigate the effects of ground shaking. Core principles include dynamic analysis of structures, ensuring ductility to absorb seismic energy, and reinforcing

structural components to prevent catastrophic failure [10].

In the Saudi context, adapting these global standards has been crucial to addressing the unique geotechnical and seismic conditions of the region. For instance, in the southern region, where soil properties range from soft sediments to rocky terrains, structural designs must account for potential amplification of ground motion. Seismic isolation techniques and advanced materials have also been recommended for critical infrastructure such as hospitals and schools to enhance resilience [11].

The Saudi Building Code (SBC) serves as the regulatory framework for construction across the Kingdom, providing comprehensive guidelines for structural safety, including seismic design. The SBC's seismic provisions are aligned with international standards but are tailored to local seismicity and geotechnical conditions. Key elements include:

- The division of the Kingdom into seismic zones, each with specific design criteria based on seismic hazard levels [12].
- Detailed requirements for dynamic analysis, including modal response spectrum analysis and time-history methods for critical structures.
- Minimum reinforcement ratios and ductility requirements to ensure that structures can withstand moderate to severe seismic events without significant damage [13].

The SBC also incorporates soil-structure interaction factors, recognizing the influence of local soil properties on seismic performance. Updates to the code have integrated findings from recent seismic hazard studies, emphasizing the importance of continuous refinement to reflect evolving scientific knowledge and engineering practices [14].

While previous studies have provided valuable insights into seismic hazards in various regions of Saudi Arabia, there is a notable gap in understanding the seismic risks specific to the southern region. Most studies have focused on areas such as Jeddah and Taif, leaving the southern region under-analyzed. Additionally, the impact of local soil properties on seismic performance has not been thoroughly studied, especially in areas with soft soils that may amplify ground motion.

This study aims to fill this gap by providing a comprehensive assessment of seismic hazards in the southern region of Saudi Arabia, with a focus on areas with increased seismic activity. It will also provide seismic design guidelines that consider the unique geotechnical properties of the region, contributing to improved seismic resilience for buildings and infrastructure in these areas.

2. Methodology

2.1. Seismic Data Collection

Seismic data were collected from sources such as the Saudi Geological Survey (SGS) [14], regional seismic monitoring networks, and international databases like USGS. The data included historical seismic records and information on soil and geological conditions in high-risk areas such as Jazan, Abha, and Najran.

2.2. Seismic Hazard Analysis

Seismic hazard analysis was conducted using probabilistic seismic hazard assessment (PSHA) techniques to estimate parameters such as Peak Ground Acceleration (PGA) and Spectral Response Acceleration (SRA) for different return periods [15]. The analysis considered regional trends and local factors, such as soil amplification effects, particularly in areas with soft soils, to evaluate the risks of future seismic events.

2.3. Development of Structural Design Guidelines

Based on the seismic hazard data, structural design guidelines were developed focusing on the resilience of buildings and infrastructure to earthquakes. Recommendations included using reinforced concrete, steel, and seismic isolation systems, with a focus on ensuring ductility to prevent catastrophic failure during seismic events. The guidelines were aligned with the Saudi Building Code (SBC) and international seismic design standards [16].

2.4. Analytical and Modeling Tools Used

The Crisis Program [17] was used for seismic hazard modeling to estimate PGA and SRA values.

3. Tectonic Setting

The southern region of Saudi Arabia is situated at the boundary between the Arabian Plate and the African Plate, a tectonic interaction that plays a significant role in shaping its seismic and tectonic characteristics. The seismicity of this region is primarily influenced by the Red Sea Rift and several fault systems, with the most prominent being the Jizan Fault. The Red Sea Rift, which runs parallel to the western coastline of Saudi Arabia, is an active divergent boundary where the Arabian Plate is moving away from the African Plate. This tectonic activity generates considerable shallow seismicity, particularly along the western edge of the country. The region experiences significant tectonic stress as a result of the continuous separation of these plates, leading to frequent faulting and seismic events [18]. Additionally, the Jizan Fault, located in the southwestern part of the region, also contributes to seismicity. This fault system is associated with tectonic movements that involve lateral displacement and have been responsible for moderate seismic events in the region [19]. The combination of these fault systems, particularly along the Red Sea Rift and the Jizan Fault, forms the primary sources of seismic activity in the southern region of Saudi Arabia, highlighting the importance of continuous monitoring and hazard assessment [20].

4. Seismicity of Southern Region of Saudi Arabia

The seismicity of the southern region of Saudi Arabia is shaped by its geological setting, particularly its proximity to active fault systems such as the Red Sea Rift and the Jizan Fault. The region has experienced moderate seismic activity, with

both shallow and deeper earthquakes occurring along these fault lines. Seismic events are predominantly concentrated near the tectonic plate boundaries where the Arabian Plate interacts with the African Plate, particularly along the Red Sea Rift (**Figure 3**).

4.1. Historical Seismic Activity (112-1963)

Historical seismic activity in the southern region includes significant events such as:

- A magnitude 5.8 earthquake in 1619 at 16.4° latitude and 44° longitude.
- A major event in 1881, with a magnitude 5.9 earthquake at 16.9° latitude and 43.8° longitude.
- The most notable earthquakes occurred in 1941, with magnitudes of 5.8 on February 4 and 5.9 on January 11, both centered near 16.4° latitude and 43.5° longitude.
- A smaller earthquake of magnitude 4.8 was recorded on October 17, 1955, at 17.2° latitude and 43.6° longitude.
- These events demonstrate the region's susceptibility to moderate seismic hazards, primarily concentrated near tectonic plate boundaries [2].

4.2. Instrumental Seismic Activity (1964-1985)

The availability of instrumental seismic monitoring from the 1960s provided more precise data on earthquake locations, depths, and magnitudes. Notable seismic activity during this period includes:

- A significant magnitude 6.1 earthquake in 1982 in the southern Red Sea region, causing localized damage.
- Frequent shallow earthquakes concentrated along the Red Sea Rift and the Jizan Fault.

Data from this period highlight the need for focused monitoring and the potential for significant ground shaking in the region [2].

4.3. Recent Seismic Activity (1986-2024)

From 1986 to 2024, improvements in seismic infrastructure have enhanced monitoring accuracy. Notable seismic events during this period include:

- A magnitude 6.4 earthquake in 1992 near Jazan, causing substantial ground shaking and localized damage.
- Moderate seismic events ranging from magnitudes 4.5 to 5.5 have been recorded, indicating ongoing seismic risks.

These events emphasize the importance of updated seismic assessments and the incorporation of risk-targeted mitigation strategies in engineering and construction practices [21].

The distribution of epicenters of shallow earthquakes (depth 10 - 30 km) and magnitudes ≥ 4.0 in the southern region of Saudi Arabia is shown in **Figure 3**. The data illustrate the clustering of seismic activity near major fault lines and tectonic boundaries, particularly along the Red Sea Rift and Jizan Fault.

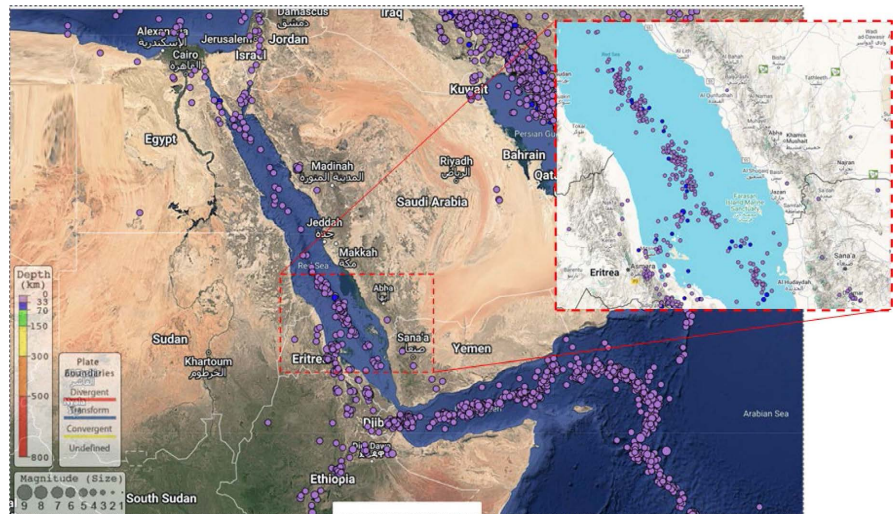


Figure 3. The data illustrate the clustering of seismic activity near major fault lines and tectonic boundaries, particularly along the Red Sea Rift and Jizan Fault (Source: Interactive Earthquake Browser—DS IRIS, <https://ds.iris.edu/ieb/>).

5. Input For PSHA in Southern Region of Saudi Arabia

The Probabilistic Seismic Hazard Analysis (PSHA) for the southern region involves gathering critical input data from various sources to estimate seismic risk. Key input data include earthquake catalogs, seismotectonic models, and recurrence relations, all of which form the foundation for hazard calculations.

5.1. Earthquake Catalogs and Tectonic Information

The earthquake catalog for the region is compiled from historical and instrumental sources, utilizing both local and global seismic networks. This data is crucial for understanding seismic distribution and identifying potential sources of seismic events in the region [22].

5.1.1. Nonduplication of Seismic Data

To ensure the accuracy of the earthquake catalog, data duplication is minimized by removing aftershocks and foreshocks, which can distort hazard assessments. Temporal window methods are applied to filter these secondary events, ensuring only primary seismic events are considered in hazard calculations [19].

5.1.2. Identification and Elimination of Clusters

To identify and eliminate earthquake clusters, clustering algorithms are used. These clusters consist of multiple events that occur after a main shock. The purpose of this process is to ensure that the recurrence relations used in the Probabilistic Seismic Hazard Analysis (PSHA) reflect only the primary seismic events, excluding aftershocks that have minimal impact on long-term seismic risk.

According to Gardner & Knopoff (1974) [22], time and distance windows are calculated using the following equations:

1) Time Equation (in days):

$$\text{Time (days)} = 0.0123 \times \text{Magnitude}^{5.903} \quad (1)$$

This equation calculates the time window based on the earthquake magnitude.

2) Distance Equation (in km):

$$\text{Distance (km)} = 11.786 \times \text{Magnitude} - 17.071 \quad (2)$$

The following **Table 1** and **Table 2** show the calculated time and distance windows for various levels of earthquake magnitudes based on Gardner & Knopoff's method:

Table 1. Time and distance windows according to Gardner & Knopoff (1974) [22].

Magnitude	Distance (km)	Time (days)
3.5	26	22
4.0	30	42
4.5	35	83
5.0	40	155
5.5	47	290
6.0	54	510
6.5	61	790

Table 2. Calculated time and distance windows from epicenter.

Magnitude	Distance (km)	Time (days)
3.6	25.4	23.6
3.7	26.5	27.8
3.8	27.7	32.5
3.9	28.9	37.9
4.0	30.1	44.0
4.1	31.3	50.9
4.2	32.4	58.7

5.1.3. Incompleteness Analysis

Seismic catalogs, particularly those from historical records and early instrumental data, often suffer from incompleteness due to the limitations of detection capabilities at the time. This issue is addressed by applying correction factors that account for the detection probability of earthquakes over time. These correction factors are used to adjust the data, ensuring that it accurately reflects the seismic activity in the region. By applying these correction factors, the seismic catalog becomes more complete, minimizing bias and providing a more accurate representation of the region's seismic history (**Table 3**).

These correction factors are essential for improving the reliability of the seismic data used in PSHA. The factors vary depending on the period of record and the magnitude of the seismic events. For example, earthquakes in the historical period

with a magnitude of 4.4 are assigned a correction factor of 3, while more recent events are given a factor of 1, indicating that they are fully detected.

Table 3. Incompleteness correction factors.

Magnitude	Historical Period	Instrumented Period	Recent Period
4.4	3	1.5	1
4.8	3	1.5	1
5.2	2	1	1
5.6	2	1	1
6	1.5	1	1
6.4	1.5	1	1
6.8	1.5	1	1
7.2	1	1	1

5.1.4. Missing Magnitudes

Statistical methods are used to estimate missing earthquake magnitudes in the catalog. These estimates are essential for ensuring that the PSHA accurately reflects the full spectrum of seismic activity, including events that were not recorded due to limitations in instrumentation.

5.2. Seismotectonic Source Models

Seismotectonic source models integrate geological, fault system, and historical earthquake data to identify seismic source zones and predict future seismic event characteristics like magnitude and frequency. For the southern region of Saudi Arabia, models focus on key fault systems such as the Red Sea Rift. These zones are categorized into area sources (associated with distributed seismicity and structural discontinuities) and fault sources (linked to transcurrent and normal fault systems).

Seismicity analysis and tectonic mapping are combined to estimate magnitude-frequency relationships and associate seismic events with geological structures. Area sources typically involve indirect or random seismic activity, while fault sources are directly tied to tectonic movements and extrusion processes like rifting and spreading. This framework helps assess seismic risks and guide infrastructure design to enhance resilience in the region.

Seismic Source Zones

Seismotectonic studies, epicenter clustering, and detailed seismicity analyses have been employed to delineate the seismic source zones for the southern region of Saudi Arabia. These zones, depicted in **Figure 4**, reflect a comprehensive model based on tectonic settings, observed seismicity, and insights from previous studies on the Arabian Peninsula. The unique tectonic and seismic features of each zone highlight the region's dynamic geophysical characteristics.

- The Yemen Highlands Zone (1): Moderate seismicity influenced by local fault

systems and volcanic activity.

- The Southern Red Sea Rift Zone (2): Shallow earthquakes dominate due to extensional tectonics.
- The Central Red Sea Rift Zone (3): Seismicity is associated with magma movement and tectonic extension.
- The Najran Seismic Zone (4): Crustal deformation leads to moderate seismic activity.
- The Jazan Coastal Zone (5): A mix of rift-related and local tectonic processes influences shallow seismicity.
- The Asir and Tihama Zone (6): Experiences intraplate deformation linked to the Red Sea Rift system.
- The Northern Red Sea Rift Zone (7): Frequent shallow seismic events occur due to divergent plate motions.

These delineated zones underscore the complex tectonic framework governing the southern region of Saudi Arabia. Incorporating detailed seismotectonic data from these zones is critical for seismic hazard assessments and risk mitigation efforts [20].

We will provide an example for a single area using the Logic Tree Diagram for the Najran Seismic Zone, which has been applied in the same context to all regions. The Logic Tree Diagram for the Najran Seismic Zone is a structured representation of the seismic source characteristics, highlighting fault types, probabilities, and key seismic parameters. The seismic sources in this region are divided into two main categories: Fault Source and Area Source.

1) Fault Source:

- **Strike Slip Fault:**

- Maximum magnitude (M_{\max}) is estimated at 6.5.
- Average seismic slip rate (ASSR) is 6.2 mm/year.
- Seismic moment release ($ASM_0 R$) is 2×10^{23} .

- **Normal Fault:**

- Fault lengths range from 12 to 25 km.
- Recurrence time ($Tr(M_{\max})$) is 600 years with a probability (Pr) of 15%.
- Maximum depth ($H(M_{\max})$) reaches 150 km.

2) Area Source:

- **Abrupt Seismic Events:**

- Maximum magnitude (M_{\max}) is estimated at 6.3.
- Dislocation is in the range of 0.05 - 0.25 m.
- Maximum depth ($H(M_{\max})$) is approximately 1000 km.

The fault sources dominate the seismic activity in the Najran Seismic Zone, with probabilities of 37% for fault-related events (divided equally between Strike Slip and Normal Faults). Area sources, representing abrupt events, account for 5% of the seismic activity, emphasizing the significance of localized crustal deformation in the zone. This logic tree structure aids in understanding seismic source contributions and supports probabilistic seismic hazard assessments (PSHA) for the region.

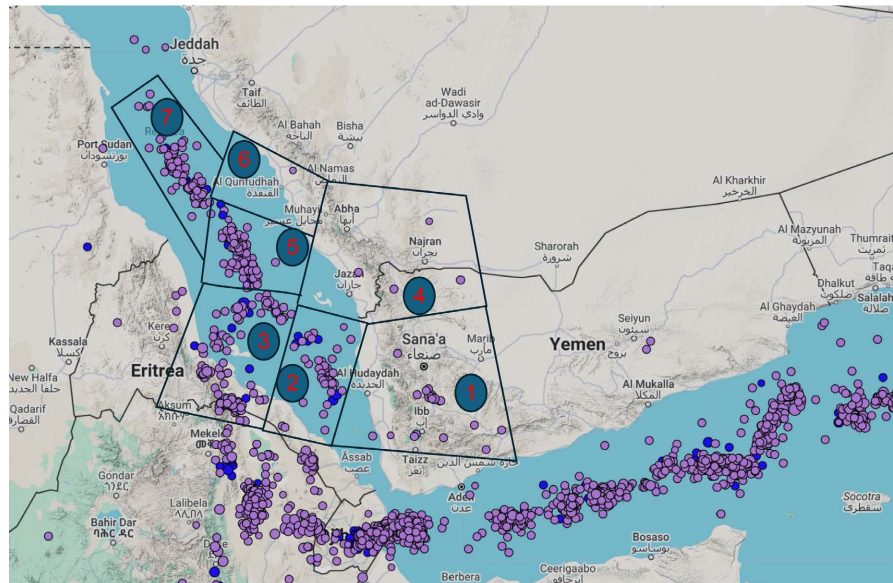


Figure 4. Seismic source zones in the southern region (Source: modification one Interactive Earthquake Browser—DS IRIS, <https://ds.iris.edu/ieb/>).

6. Recurrence Relations

Recurrence relations describe the frequency and magnitude distribution of earthquakes in each seismic source zone. These relations are critical for estimating the probability of seismic events over a specified time period.

6.1. Determination of β and λ Values

Statistical regression analysis was employed to determine the parameters β and λ , which are essential for defining the recurrence relationship of earthquakes in each seismic source zone (Table 4). The relationship follows the Gutenberg-Richter model [22], expressed as:

$$\log N(M) = a - b(M) \quad (3)$$

where $N(M)$ represents the number of earthquakes of magnitude M or greater per unit time, a is the activity level (intercept of the relationship at $M = 0$), and b is the slope parameter that indicates the relative frequency of small versus large earthquakes.

For zones with sufficient data, a truncated exponential recurrence model (Cornell and Vanmarcke, 1969 [23]) was applied:

$$N(\geq M) = \alpha \frac{\exp[-\beta(M - M_{\min})] - \exp[-\beta(M_{\max} - M_{\min})]}{1 - \exp[-\beta(M_{\max} - M_{\min})]}, \quad (4)$$

where:

- $\alpha = N(M_{\min})$ is the activity rate for the reference magnitude M_{\min} ;
- M_{\max} is the upper-bound magnitude;
- $\beta = b \ln(10)$ is derived from b .

The parameters for the recurrence relationships were estimated using the max-

imum likelihood method (Weichert, 1980 [21]). **Table 5** summarizes the parameters for all seismic source zones in the southern region of Saudi Arabia.

Table 4. Parameters of recurrence relationships for seismic source zones.

Zone No.	Zone Name	No. of events	a	β	λ	M_{\min}	M_{\max}	σM_{\max}	M_{\max} (obs)
1	Yemen Highlands Zone	87	11.02	2.11	3.55	4.0	6.5	0.25	6.3
2	Southern Red Sea Rift Zone	236	14.65	2.84	8.25	4.0	6.9	0.25	6.7
3	Central Red Sea Rift Zone	194	14.10	2.71	7.12	4.0	6.8	0.25	6.6
4	Najran Seismic Zone	13	10.45	2.19	1.62	4.0	5.6	0.25	5.4
5	Jazan Coastal Zone	92	12.73	2.50	3.98	4.0	6.4	0.25	6.2
6	Asir and Tihama Zone	58	11.35	2.22	2.45	4.0	6.3	0.25	6.1
7	Northern Red Sea Rift Zone	146	13.85	2.75	6.94	4.0	6.7	0.25	6.5

Table 5. Comparison of Risk-Targeted Maximum Considered Earthquake (MCER) parameters across selected locations in Southern Saudi Arabia.

Location	Current Study (MCER)			Saudi Code 2018 (MCER)		
	(PGA) 475-Year	SA 0.2 s (g) 2475-Year	SA 1 s (g) 2475-Year	(PGA) 475-Year	SA 0.2 s (g) 2475-Year	SA 1 s (g) 2475-Year
Najran	0.05	0.23	0.08	0.05	0.10	0.03
Jazan	0.10	0.45	0.11	0.17	0.45	0.09
Abo arish	0.19	0.56	0.15	0.25	0.55	0.11
Fifa	0.13	0.67	0.17	0.30	0.64	0.13
Abha	0.03	0.17	0.05	0.03	0.15	0.03
Khamis Mushayt	0.03	0.15	0.06	0.05	0.10	0.03
Al Baha	0.03	0.12	0.04	0.05	0.07	0.03
Baljurashi	0.03	0.10	0.05	0.05	0.07	0.03
Al-Namas	0.03	0.09	0.04	0.05	0.07	0.03
Muhayil Asir	0.04	0.12	0.06	0.06	0.07	0.03
Al-gunfudhah	0.03	0.13	0.04	0.05	0.07	0.03

Observations:

- **Southern Red Sea Rift and Central Red Sea Rift Zones:** These zones exhibit high seismic activity due to extensional tectonics and magmatic intrusions, with M_{\max} values close to 6.9.
- **Yemen Highlands and Najran Zones:** These zones have moderate activity levels with slightly lower M_{\max} values.
- **Jazan Coastal Zone:** This zone demonstrates intermediate seismic activity influenced by both local faults and the Red Sea Rift.

These results emphasize the variability in seismic activity across the region, necessitating tailored hazard assessments for each seismic source zone.

6.2. Cutoff Points

Cutoff points are used to exclude small earthquakes that do not significantly contribute to the overall seismic hazard. Earthquakes with magnitudes less than 4.0 are typically excluded from PSHA calculations as they are unlikely to have significant effects on structural design.

7. Attenuation Models

Attenuation models are critical components of Probabilistic Seismic Hazard Analysis (PSHA), as they estimate the reduction in ground motion intensity with increasing distance from the earthquake source. In the absence of region-specific attenuation relationships for the southern region of Saudi Arabia, existing ground motion prediction equations (GMPEs) from similar tectonic settings have been utilized. These models account for the unique tectonic framework of the region, which is characterized by interactions between the Arabian Plate and surrounding tectonic boundaries, including the Red Sea Rift and local fault systems.

Ground motion attenuation is influenced by several factors, including the seismic source mechanism, regional tectonic features, and local site conditions. For the southern region, GMPEs were selected based on their applicability to the region's tectonic setting, considering parameters such as crustal thickness, seismic wave propagation, and fault slip characteristics. These models predict the expected peak ground acceleration (PGA) and spectral acceleration (SA) at various distances and for different magnitudes.

The attenuation models adopted for this study include adjustments for regional variations in soil and rock properties, which play a significant role in modifying ground motion intensity. Specifically, attenuation relationships developed for regions with similar divergent and intraplate tectonic environments, such as the Red Sea Rift and other parts of the Arabian Peninsula, were incorporated. The selected models also account for local amplification effects due to soft soil layers prevalent in the Jazan Coastal Zone and the Najran Seismic Zone.

To ensure accuracy, the performance of these models was validated against available instrumental data from seismic events recorded in the southern region. The resulting attenuation curves exhibit a strong correlation between predicted and observed ground motions, particularly for shallow earthquakes common in the Red Sea Rift Zone and nearby fault systems.

8. Hazard Calculations and Results

8.1. Maximum Considered Earthquake (MCE)

The Maximum Considered Earthquake (MCE) represents the highest ground motion level with a 2% probability of exceedance in 50 years. It serves as a critical benchmark for designing earthquake-resistant structures, ensuring structural safety under extreme seismic events. MCE calculations are based on the Probabilistic Seismic Hazard Analysis (PSHA) methodology, which integrates diverse inputs to generate hazard maps and provide insights into seismic risks across the region.

This study utilizes a comprehensive Probabilistic Seismic Hazard Analysis (PSHA) framework to calculate Maximum Considered Earthquake (MCE) values for the southern region of Saudi Arabia. The methodology involves several key steps, beginning with the collection of seismic data from sources such as the Saudi Geological Survey (SGS), regional networks, and international databases like USGS. Earthquake catalogs were meticulously curated to include both historical and instrumental seismicity records. Seismotectonic modeling was then applied to account for the complex tectonic framework, incorporating area and fault source models that reflect the influence of the Red Sea Rift and local fault systems. Recurrence relationships, based on the Gutenberg-Richter law, were used to estimate the frequency-magnitude distribution of seismic events. Ground motion prediction equations (GMPEs) tailored to the Arabian tectonic environment were employed to estimate ground motion parameters, while site-specific factors, assuming Site Class B conditions in accordance with NEHRP standards, were incorporated. Numerical calculations were conducted using Crisis 2007 software to determine Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) values for short (0.2 seconds) and long (1 second) periods. Finally, MCE values PGA, S_s, and S₁ were generated for return periods of 475 and 2475 years (Table 6), consistent with international seismic design codes such as SBC 304, IBC and ASCE 7-16 as well as SBC304. This rigorous approach ensures accurate assessment and supports the development of robust seismic design guidelines.

Results and Comparison

The seismic hazard table for the southern region of Saudi Arabia based on the MCE (Maximum Considered Earthquake) analysis has been updated in (Table 6). The results include values for PGA (475-Year), SA 0.2 s (g) 2475-Year, and SA 1s (g) 2475-Year for key locations.

Table 6. Comparison of Maximum Considered Earthquake (MCE) parameters across selected locations in southern Saudi Arabia.

Location	Current Study (MCE)			Saudi Code 2007 (MCE)		
	(PGA) 475-Year	SA 0.2 s (g) 2475-Year	SA 1 s (g) 2475-Year	(PGA) 475-Year	SA 0.2 s (g) 2475-Year	SA 1 s (g) 2475-Year
Najran	0.07	0.29	0.11	0.06	0.27	0.9
Jazan	0.12	0.54	0.14	0.10	0.44	0.12
Abo arish	0.11	0.53	0.18	0.11	0.45	0.13
Fifa	0.16	0.64	0.20	0.14	0.62	0.18
Abha	0.04	0.23	0.07	0.03	0.21	0.06
Khamis Mushayt	0.04	0.21	0.22	0.04	0.19	0.06
Al Baha	0.04	0.17	0.27	0.03	0.16	0.05
Baljurashi	0.04	0.17	0.26	0.03	0.16	0.05
Al-Namas	0.04	0.17	0.23	0.03	0.16	0.05
Muhayil Asir	0.06	0.19	0.28	0.04	0.17	0.05
Al-gunfudhah	0.04	0.17	0.30	0.03	0.16	0.05

The seismic hazard assessment for the southern region of Saudi Arabia, as reflected in the provided table, highlights notable differences between the current study's Maximum Considered Earthquake (MCE) values and those presented in the Saudi Building Code 2007 (SBC 2007). For areas like Najran and Jazan, the current study indicates slightly higher Peak Ground Acceleration (PGA) values of 0.07 g and 0.12 g for a 475-year return period, compared to 0.06 g and 0.10 g in the SBC 2007. These differences may stem from updated seismic data and refined modeling approaches that consider recent tectonic activity. For regions such as Abo Arish and Fifa, which are closer to active tectonic boundaries, higher spectral acceleration (SA) values at 0.2 s and 1 s periods, particularly 0.53 g and 0.64 g for Fifa, reflect the significant influence of nearby fault systems like the Red Sea Rift. Conversely, interior regions like Abha and Khamis Mushayt demonstrate lower seismic activity, with PGA values of 0.04 g and 0.04 g, aligning closely with SBC 2007 and corroborating findings from earlier studies. Coastal areas such as Al-Gunfudhah and Muhayil Asir show relatively higher SA values, emphasizing the impact of tectonic proximity on seismic risks. These findings underscore the importance of updating seismic codes to incorporate localized hazard data and adopting robust design standards, particularly for high-risk zones like Jazan and Fifa, to enhance resilience against potential seismic events.

8.2. Risk-Targeted Maximum Considered Earthquake (MCER)

The Risk-Targeted Maximum Considered Earthquake (MCER) integrates both probabilistic seismic hazard analysis (PSHA) and structural performance considerations to reduce the risk of structural collapse to a defined level, typically 1% in 50 years. This methodology provides a comprehensive approach to assessing seismic risks by incorporating both hazard intensity and the vulnerability of structures.

Detailed Methodology

1) Seismic Hazard Data Collection and Analysis

The MCER calculation begins with defining the Maximum Considered Earthquake (MCE) values. These values are determined using the seismic hazard curves derived from PSHA, which represent the probability of exceedance of ground motion intensity over a given time period.

- **Seismic Hazard Curves:** Probability distributions were created for different ground motion levels, accounting for uncertainties in seismic source models, recurrence intervals, and attenuation relationships.
- **Input Parameters:** Key parameters included Peak Ground Acceleration (PGA), short-period spectral acceleration (SA 0.2 s), and long-period spectral acceleration (SA 1 s).

2) Application of Risk Coefficient (Cr)

The MCER values are obtained by adjusting the MCE values with a risk coefficient (Cr), which accounts for the probability of building collapse and structural performance.

Cr Definition:

The risk coefficient modifies the MCE values to achieve a target risk level. Cr is defined as:

$$Cr = \int_0^{\infty} H(a) \cdot f da \quad (5)$$

where:

- $H(a)$: Seismic hazard function representing the probability of ground motion exceeding level a .
- $F(a)$: Fragility function representing the probability of collapse at ground motion level a .

The integral combines the likelihood of seismic events with the structural vulnerability to determine the risk-adjusted ground motion.

3) MCER Calculation

The MCE_R for a site is calculated using the adjusted MCE values and the risk coefficient:

$$MCE_R = MCE \cdot Cr \quad (6)$$

where:

- MCE_R : Risk-targeted maximum considered earthquake.
- MCE : Maximum considered earthquake from PSHA.
- Cr : Risk coefficient derived from seismic hazard and fragility functions.

4) Soil Amplification Adjustments

Local soil conditions significantly influence ground motion characteristics. To account for these effects, site-specific amplification factors (F_a and F_v) are applied:

- For short-period accelerations (SA 0.2 s):

$$MCE_{R\text{adjusted}} = MCE \cdot F_a \quad (7)$$

- For long-period accelerations (SA 1 s):

$$MCE_{R\text{adjusted}} = MCE_R \cdot F_v \quad (8)$$

These factors, obtained from NEHRP or similar guidelines, adjust MCE_R values to reflect site-specific soil amplification effects.

5) Numerical Calculations

The calculations in this study utilized ASCE 7 - 16 provisions and seismic hazard modeling software (e.g., Crisis 2007). The following steps were performed:

- Define hazard curves for PGA, SA 0.2 s, and SA 1 s for each site.
- Apply Cr values based on ASCE guidelines and integrate fragility and hazard functions.
- Adjust the MCE_R values using F_a and F_v to account for local soil effects.

The observations highlight notable patterns in seismic hazard levels across the southern region of Saudi Arabia. For Najran, the PGA and SA 0.2 s values in the current study are slightly higher than those in the Saudi Code 2018, reflecting detailed local adjustments, while the SA 1 s values align well between the two datasets. In Jazan, a noticeable difference is observed in the PGA values, with the

current study reporting slightly lower levels compared to the Saudi Code, but the SA 0.2 s values remain consistent, confirming uniform seismic hazards in this zone.

Abo Arish and Fifa exhibit the highest SA 0.2 s values, especially in Fifa, due to its proximity to active seismic zones. The current study indicates slightly reduced SA 0.2 s values compared to the Saudi Code, suggesting a refined hazard assessment. In Abha and Khamis Mushayt, both regions display lower seismic hazard levels compared to coastal areas, with consistent values across the two datasets, showing minor variations from updated modeling techniques.

The mountainous regions of Al Baha, Baljurashi, and Al-Namas demonstrate uniform and low seismic hazard levels, with stable tectonic conditions reflected in consistent values between the studies. For Muhayil Asir, slightly higher values in the current study highlight localized soil and tectonic influences, while Al-Gunfudhah shows marginally higher SA 0.2 s and PGA values, indicating adjustments for soil amplification effects.

In conclusion, the comparison reveals general alignment between the current study and the Saudi Code 2018, with minor discrepancies due to localized adjustments and refined hazard modeling. Areas like Fifa and Abo Arish require greater focus for seismic risk mitigation due to their elevated hazard levels, whereas inland regions like Najran and Al Baha exhibit comparatively lower risks. These findings underscore the critical role of localized assessments in improving seismic resilience.

9. Structural Design Guidelines for the Southern Region of Saudi Arabia

The southern region of Saudi Arabia presents a unique seismic environment influenced by its proximity to active tectonic boundaries such as the Red Sea Rift and regional fault systems [24]. Developing effective structural design guidelines for this region necessitates a comprehensive understanding of seismic hazards, soil-structure interaction, and modern engineering practices [23]. This section provides a robust framework for designing earthquake-resilient structures, integrating data from Maximum Considered Earthquake (MCE) and Risk-Targeted Maximum Considered Earthquake (MCER) analyses [25].

Design Philosophy

The structural design in seismically active regions aims to minimize the risk of structural failure while maintaining cost-efficiency. The guidelines incorporate the following principles:

- **Performance-Based Design:** Structures are designed to ensure operational safety during moderate seismic events and prevent collapse during severe earthquakes.
- **Risk-Targeted Criteria:** Adjustments based on MCER values ensure that buildings meet safety benchmarks, such as a 1% collapse probability in 50 years.

- **Localized Adaptation:** Hazard assessments and soil characteristics specific to the southern region are integrated to reflect local seismic realities.

Seismic Hazard Integration

The design process relies on seismic parameters derived from detailed PSHA, including:

- **MCE Parameters:** Reflecting the maximum ground motion expected in the region with a 2% probability of exceedance in 50 years.
- **MCER Parameters:** Incorporating risk coefficients (CrC_rCr) to refine MCE values and enhance structural safety.

For example, in Jazan:

- **MCE SA 0.2 s = 0.54 g, MCER SA 0.2 s = 0.45 g.** This adjustment demonstrates the influence of risk-targeted criteria, reducing seismic demands by accounting for structural vulnerabilities.

Geotechnical Considerations

The geotechnical diversity of the southern region necessitates site-specific adjustments:

1) Site Classifications: Based on SBC 2018 provisions, Site Class B (moderate strength soils) is assumed for default calculations, while soft soils (e.g., coastal zones) require amplification factors (F_a and F_v).

2) Soil Amplification Effects: Soft soil layers prevalent in areas like Jazan and Fifa amplify seismic waves, necessitating adjusted spectral response factors.

Seismic Load Calculations

Seismic loads are calculated using advanced methodologies aligned with ASCE 7 - 16 and the Saudi Building Code (SBC):

1) Spectral Response Factors (S_{DS} , S_{DL}):

- Short-period (0.2s) and long-period (1s) spectral accelerations are adjusted for site conditions.
- Example for Jazan: $S_{DS} = S_{MCER} \times F_a = 0.45 \text{ g} \times 1.2 = 0.54 \text{ g} = 0.45 \text{ g} \times 1.2 = 0.54 \text{ g}$.

2) Base Shear (V):

- Determined using: $V = C_s \times W_v$.
Where $C_s = (S_{DS})/(R/I)$, R is the response modification factor, and I is the importance factor.

3) Ductility and Over-Strength: Design ensures structures can withstand seismic loads beyond elastic limits without catastrophic failure.

Structural Design Recommendations

1) Reinforced Concrete Frames:

- Emphasis on ductile detailing to absorb seismic energy.
- Use of confined zones at column-beam joints for enhanced performance.

2) Steel Structures:

- Adoption of moment-resisting and braced frames for lateral stability.
- Use of high-strength steel to accommodate dynamic loads.

3) Seismic Isolation Systems:

- Recommended for critical infrastructure (e.g., hospitals, schools).
- Isolation pads reduce ground motion transmission to the superstructure.

Risk-Targeted Adjustments

Integrating MCER ensures that designs reflect actual collapse risks:

- Coastal areas (e.g., Jazan, Abha): High seismic demands necessitate robust designs with advanced damping systems.
- Inland areas (e.g., Najran, Abha): Moderate seismic activity allows for simplified yet effective design approaches.

Sustainability and Resilience

1) Material Selection:

- Use of locally sourced, high-performance materials to reduce environmental impact.
- Incorporation of recycled content in concrete and steel to promote sustainability.

2) Energy Dissipation Devices:

- Implementation of energy-absorbing mechanisms to enhance structural resilience during earthquakes.

10. Conclusions

The seismic hazard evaluation and structural design guidelines for the southern region of Saudi Arabia presented in this study emphasize the critical need for localized assessments to address the region's diverse tectonic and soil conditions. Key findings include the identification of elevated seismic risks in coastal areas like Jazan and Abha, while inland regions such as Najran and Abha exhibit lower hazard levels. By leveraging MCE and MCER frameworks, this research provides nuanced insights into ground motion parameters, ensuring that design values reflect both seismic hazard and structural vulnerabilities.

The proposed structural design guidelines integrate modern seismic design principles, including site-specific adjustments, advanced response spectrum analysis, and reinforcement measures to enhance ductility and structural stability. These recommendations align with international standards such as ASCE 7-16 while addressing regional geological and geotechnical characteristics.

This study serves as a foundational resource for engineers, planners, and policymakers in advancing seismic resilience in the southern region. By bridging the gap between scientific evaluation and practical application, it underscores the importance of continuous research, updated codes, and collaborative efforts to safeguard communities and infrastructure from seismic risks.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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