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Seismic Hazard Analysis for Earthquake Risk Mitigation and Sustainable Natural Resource and Environmental Management in Afghanistan

Mohammad Jawad Rahimi[1], Abdulhai Kaiwaan[2], khalid Urfan[3], Sayed Javid Azimi[4], Abdullah Namdar[5]
[1,2,4] Department of structural Engineering, afghan international Islamic University, Kabul, Afghanistan
[3]Department of urban planning, parwan University, pawan, Afghanistan
[5]Department of civil engineering, abu dhabi university, UAE
Email: m.jawadrahimi@parwan.edu.af

Abstract

Afghanistan's complex geological and tectonic setting makes the country highly susceptible to natural hazards, particularly earthquakes. This study focuses on seismic hazard analysis to evaluate earthquake risks in Afghanistan's most vulnerable regions and to support effective risk mitigation strategies. The research aims to identify major seismic threats and assess their potential impacts on the sustainable management of natural resources and the environment. Given the significant damage earthquakes can cause across different regions, the study proposes strategic approaches to minimize their adverse environmental and resource-related consequences. Emphasis is placed on adopting holistic disaster risk management frameworks that take into account Afghanistan's socio-economic conditions and environmental constraints. Analytical models and hazard assessments demonstrate the critical role of government capacity-building and community-level training in disaster preparedness. The findings provide valuable guidance for policymakers and disaster managers, promoting informed decision-making through reliable seismic hazard data to enhance environmental sustainability and natural resource protection in earthquake-prone areas.

Keywords: Afghanistan; disaster management; earthquake risk; environmental sustainability; natural resource management; Seismic hazard analysis

تحلیل خطر زمین‌لرزه برای کاهش خطر زلزله و مدیریت پایدار منابع طبیعی و محیط‌زیست در افغانستان

محمد جواد رحیمی[۱]، عبدالحی کیوان[۲]، خالد عرفان[۳]، سید جاوید عظیمی[۴] و عبدالله نامدار[۵]
[۱،۲،۴]دیپارتمنت انجنیری ساختمانی، پوهنتون بین المللی افغان، کابل، افغانستان
[۳]دیپارتمنت پلانگذاری شهری، پوهنتون پروان، پروان، افغانستان
[۵]دیپارتمنت انجنیری عمومی، پوهنتون ابوظبی، دبی، امارات متحده
ایمیل: m.jawadrahimi@parwan.edu.af

چکیده

موقعیت جغرافیایی منحصربه‌فرد افغانستان این کشور را به‌شدت در برابر مخاطرات طبیعی، به‌ویژه زمین‌لرزه‌ها، آسیب‌پذیر ساخته است. تمرکز این تحقیق بر تحلیل خطر لرزه‌ای و به‌منظور ارزیابی و کاهش خطرات در آسیب‌پذیرترین مناطق کشور تمرکز دارد. هدف این تحقیق شناسایی تهدیدات لرزه‌ای و ارزیابی پیامدهای بالقوه آن‌ها بر مدیریت پایدار منابع طبیعی و محیط‌زیست است، زیرا زمین‌لرزه‌ها خطری جدی برای مناطق مختلف افغانستان محسوب می‌شوند. هدف اصلی این مطالعه ارائه راهبردهایی برای کاهش اثرات رویدادهای لرزه‌ای بر منابع طبیعی و پایداری محیط زیست افغانستان می‌باشد .تحقیق حاضر بر ضرورت به‌کارگیری رویکردهای جامع در مواجهه با سوانح مرتبط با زمین‌لرزه تأکید دارد و چالش‌های اجتماعی–اقتصادی و زیست‌محیطی افغانستان را به‌طور هم‌زمان مدنظر قرار می‌دهد. در این راستا، از مدل‌های تحلیلی و ارزیابی‌های خطر برای برجسته‌سازی اهمیت ظرفیت‌سازی دولتی و آموزش جوامع محلی در مدیریت سوانح استفاده شده است. نتایج تحقیق می‌تواند به مدیران بحران و سیاست‌گذاران در تدوین راهبردهای کارآمدتر پاسخ به بلایای طبیعی یاری رساند و با بهره‌گیری از داده‌های دقیق خطر لرزه‌ای، زمینه مدیریت پایدار محیط‌زیست و منابع طبیعی در مناطق زلزله‌خیز کشور را فراهم سازد.

کلید واژه‌ها: افغانستان؛ مدیریت سوانح؛ خطر زمین‌لرزه؛ پایداری محیط‌زیست؛ مدیریت منابع طبیعی؛ تحلیل خطر لرزه‌ای.

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Introduction

Afghanistan is situated in a highly seismically active region and has experienced numerous destructive earthquakes that have caused extensive damage to infrastructure, natural resources, and the environment (Ambraseys & Bilham, 2003). The country's unique geographical characteristics, including mountainous terrain and geologically unstable soils, further intensify seismic hazards and increase the severity of earthquake impacts (Boyd et al., 2007). These risks are particularly critical in the context of Afghanistan's limited disaster management capacity, highlighting the urgent need for effective strategies to reduce earthquake risk and enhance national resilience.

A major contributor to Afghanistan's seismic vulnerability is its location along several active fault systems, including the Hindu Kush, Chaman, and Herat faults (Rustami et al., 2017). Among these, the Hindu Kush fault system is one of the most seismically active regions in the world and has generated major earthquakes affecting both Afghanistan and neighboring countries (Shnizai et al., 2023). The complex tectonic setting of these fault zones represents a persistent source of seismic threat, particularly for densely populated and high-risk regions.

Despite the recognized presence of active fault systems, seismic hazard assessments in Afghanistan have not yet fully incorporated their detailed characteristics and potential impacts. Existing seismic hazard models often underestimate earthquake intensity and recurrence due to insufficient consideration of active fault behavior, leading to an incomplete evaluation of seismic risk across many regions of the country (Zare & Maleki, 2022).

To address this gap, the present study examines Afghanistan's active faults and their role in earthquake risk assessment using fault-line mapping, historical seismicity analysis, and probabilistic seismic hazard analysis (PSHA). Integrating these approaches enables the development of more realistic hazard models and supports the identification of targeted mitigation strategies aimed at reducing potential damage to infrastructure, natural resources, and local communities (Milad & M., 2018; Bakhshi et al., 2024).

Understanding seismic hazards in Afghanistan is essential given the country's ongoing socio-economic challenges and high vulnerability to natural disasters. Earthquakes can have severe short- and long-term consequences, including environmental degradation, damage to agricultural land, and disruption of critical natural resources (Ali, 2005). Consequently, sustainable management of natural resources in earthquake-prone areas must be closely linked to seismic risk reduction strategies.

By applying seismic hazard analysis, this study seeks to provide actionable insights for policymakers, disaster managers, and local communities to improve disaster preparedness, strengthen response planning, and enhance resilience against future seismic events (Ali, 2005).

This study aims to evaluate seismic hazards in Afghanistan's most vulnerable regions, identify key areas of risk, and assess their potential impacts on sustainable resource management and environmental stability. The goal is to propose effective mitigation strategies that will not only help reduce the immediate impacts of earthquakes but also support the long-term sustainability of natural resources and environmental health.

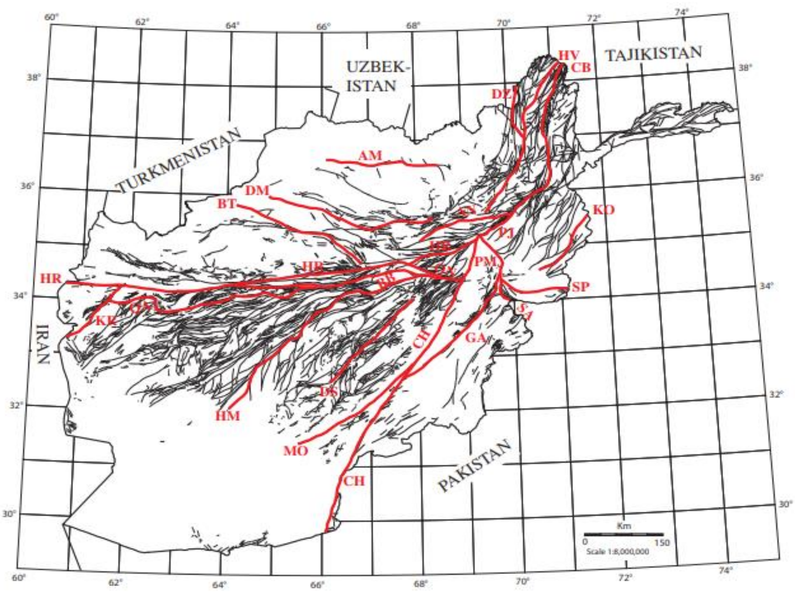


Fig. 1. *Tectonic map of Afghanistan)*

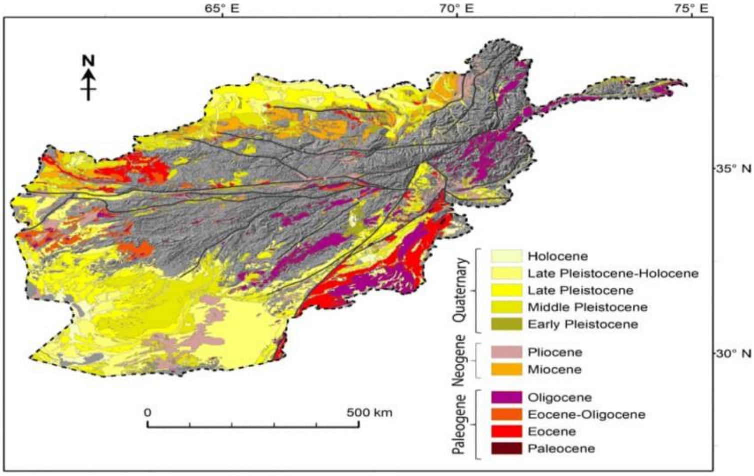


Fig. 2. *Geological map of Afghanistan*

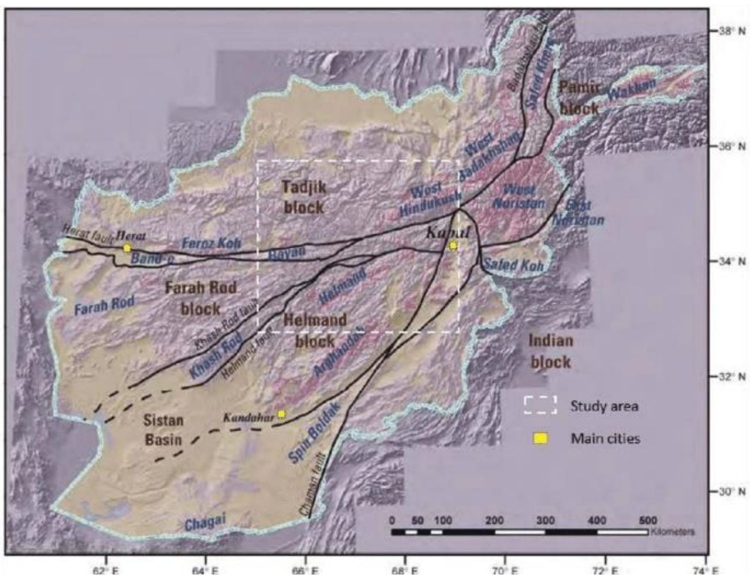


***Fig. 3**. Seismic map of Afghanistan*

Literature Review

Numerous studies have investigated seismic hazard assessment using deterministic and probabilistic approaches in different tectonic settings. Previous research has focused on estimating ground motion parameters, identifying active fault systems, and evaluating seismic risks to infrastructure and urban environments. In Afghanistan and neighboring regions, limited but growing research has highlighted the critical role of active faults, local geological conditions, and appropriate attenuation models in seismic hazard analysis. To provide a clear overview of existing research and methodologies relevant to this study, a summary of key literature is presented in Table 1.

Table 1. *Summary of previous studies on seismic hazard analysis*

Study	Region	Methodology	Key Findings
Bakhshi et al. (2025)	Kunduz, Afghanistan	Deterministic and probabilistic methods (SeisRisk software)	Estimated base acceleration of 0.427 g; emphasized the need for updated building codes.
Yucemen (2013)	Turkey	Probabilistic insurance risk analysis	Demonstrated integration of seismic risk into insurance calculations.
Bai et al. (2024)	Luding, China	Site investigation	Evaluated the effectiveness of seismic isolation systems.
Shnizai et al. (2023)	Kabul Basin, Afghanistan	Fieldwork and remote sensing	Identified active faults with estimated magnitude potential of Mw 7.3–7.8.
Hosseini Varzandeh et al. (2024)	Kermanshah, Iran	Post-earthquake damage assessment	Identified major structural vulnerabilities following a Mw 7.3 earthquake.
Field (2005)	Global	Probabilistic seismic hazard analysis (PSHA)	Emphasized integration of attenuation models with fault characterization.
Ahmadi and Kajita (2017)	Kabul, Afghanistan	Urban seismic evaluation	Assessed the impact of seismic risk on urban land development.
Alina et al. (2019)	Russia	Grid-characteristic numerical method	Evaluated seismic stability of high-rise buildings.
Keshavarz and Morteza (2017)	Bushehr, Iran	PSHA	Developed uniform hazard spectra for Bushehr Province.
Bambang et al. (2019)	Tasikmalaya, Indonesia	PSHA	Re-evaluated seismic hazards considering local faults and megathrust zones.
Alizadeh and Pourzeynali (2018)	Amol, Iran	PSHA	Produced zoned peak ground acceleration maps using updated magnitude relations.
Ghodrati Amiri et al. (2015)	Kerman, Iran	Seismic hazard analysis	Developed seismic hazard maps and uniform hazard spectra.
Fahimi Farzam et al. (2018)	Iran	PSHA and DSHA	Provided an overview of seismic hazard assessment methodologies.

Zare et al. (2022)	Khark Island, Iran	PSHA	Developed acceleration zoning maps highlighting seismic risk.
Dastjerdi et al. (2018)	Bushehr, Iran	Deterministic and probabilistic methods	Assessed seismic hazards associated with major regional faults.
NEA (2019)	Global	Comparative PSHA	Compared seismic hazard levels for nuclear facilities in different regions.
Penarubia et al. (2020)	Philippines	Probabilistic seismic analysis	Developed a seismic hazard model incorporating fault motion and ground motion parameters.
ShamsAldane et al. (2018)	Iran	PSHA	Estimated seismic accelerations for major Iranian faults.
Bakhshi and Rezaie (2021)	Iran	Deterministic and probabilistic methods	Showed higher peak acceleration near faults; vertical acceleration reached 0.5–0.6 of horizontal acceleration.
Boyd et al. (2007)	United States	Probabilistic ground motion analysis	Estimated probabilistic ground motion levels for major Afghan cities.

Research Methodology

This study adopts a multifaceted methodological framework to assess seismic hazards in vulnerable regions of Afghanistan and to evaluate their potential impacts on sustainable natural resource and environmental management. A bibliographic research approach is employed, integrating existing seismic hazard studies with contemporary seismic modeling techniques. This approach enables a systematic evaluation of seismic risk by combining established scientific methods with region-specific data (Bakhshi et al., 2024).

Seismic Hazard Assessment

Seismic hazard assessment in this study is conducted using both deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA), which are widely applied methods for evaluating earthquake risk. These approaches are used to estimate key seismic parameters, including peak ground acceleration (PGA), ground shaking intensity, and earthquake magnitude across different regions of Afghanistan (Bakhshi et al., 2024).

The deterministic approach focuses on worst-case earthquake scenarios by estimating the maximum credible earthquake that may occur along major active fault systems. This method provides conservative hazard estimates based on fault geometry and potential rupture characteristics, which are particularly important in tectonically complex regions (Shnizai et al., 2023).

In contrast, the probabilistic approach evaluates the likelihood of earthquake occurrence and associated ground motion over a specified time period. PSHA accounts for uncertainties in earthquake magnitude, recurrence intervals, and ground motion prediction, allowing for a comprehensive assessment of seismic risk under varying probability levels (Bakhshi et al., 2024). The integration of DSHA and PSHA offers a robust framework for seismic hazard assessment in Afghanistan, where multiple active fault systems, including the Hindu Kush and Chaman faults, contribute to significant seismic risk (Shnizai et al., 2023).

$$M_s = 1.25 + 1.244 \log L\, ;\; L(m) \qquad (1)$$

The proposed Ambraseys and Melville model (Equation 3) and the four Wells and Coopersmith equations (Equations 4 to 7) can also be used to determine the controlling earthquake (Table 1).

Ambraseys- Melville equation (Hossein bakhshi).

$$M_s = 5.4 + \log L\, ; L(km) \qquad (2)$$

Wells-Cooper Smith equations (Amin Keshavarz, 2017)

Table 2: *Wells-Cooper Smith equations (Amin Keshavarz, 2017)*

Fault type	**Magnitude span**	**Estimated equation**	**Equation number**
Slip fault	5.8-6.1	$M_s = 5.16 + 1.12 \log L\, ; (km)$	(3)
Reverse fault	5.7-4.4	$M_s = 5 + 1.12 \log L\, ; (km)$	(4)
Normal fault	5.7-2.3	$M_s = 4.86 + 1.32 \log L\, ; (km)$	(5)
All faults	5.8-2.1	$M_s = 5.08 + 1.16 \log L\, ; (km)$	(6)

***Table**3. displays the suggested Solmaz model (relationships 7-9). (Milad D, 2018). Solmaz equations*

Fault type	Estimated equation	Equation number
Slip fault	$M_s = 1.404 + 1.16 \log L\,; (km)$	(7)
Reverse fault	$M_s = 2.021 + 1.142 \log L\,; (km)$	(8)
Normal fault	$M_s = 0.809 + 1.341 \log L\,; (km)$	(9)

Zareh's proposed model is given in relation (Mehdi Zare,. 2017).
Zareh Equation (1993) (Mehdi Zare, 2022).

$$M_s = 0.91 \ln L_R + 3.66 \qquad (10)$$

The rupture length of the fault, or LR, is expressed in terms of meters in the Nowrooz relation and kilometers in the aforementioned relations.

2.2. Calculating the supervisor earthquake for deterministic hazard assessment

Following the faults' classification based on mechanism and the use of the Nowrooz, Ambersis-Melville experimental relations to calculate the rupture length, which in this study is 0.37 for faults over 100 km and 0.5 times for faults under 100 km. The Sulmaz connection and Wells-Coopersmith were used to estimate the magnitude of the controlling earthquake. The ideal load-bearing coefficient was used to calculate the magnitude, and Table .3 shows the results for each defect.

***Table 4:** Earthquak controller for faults located less than 200 kilometers from Kunduz city*

Row	Fault name	Method	Fault length	Rupture length	Estimated magnitude by experimental equations				Ms=Mw
					Nowroozi	Ambraseys	Wells	Solmaz	
			Km	Km	0.25	0.25	0.25	0.25	
F1	Darafshan	Normal	215.851	79.87	7.36	7.30	7.07	7.38	7.28
F2	Central Badakhshan	Normal	203.833	75.425	7.33	7.28	7.04	7.35	7.25
F4	Hari rod	Normal	17.257	17.257	6.53	6.64	6.29	6.49	6.49
F5	Chaman	Normal	64.9	32.45	6.87	6.91	6.61	6.86	6.81

Choose Attenuation Formulas

Attenuation equations are empirical relationships derived from recorded earthquake data to describe the variation of ground motion with distance, magnitude, and local site conditions (Penarubia et al., 2020). In seismic hazard analysis, it is essential to determine the maximum horizontal and vertical components of ground acceleration for different soil types, as soil properties significantly influence ground motion characteristics (Penarubia et al., 2020). These parameters must be established prior to applying attenuation relationships to ensure reliable and consistent seismic hazard assessments.

Ramazi- Schenk equation 1994

$a = a_1(a_2 + d + H)^{a_5} exp(a_6 M_s); \quad H = |d - a_3|^{a_4} \quad ; a = {cm}/{s^2}$ (11)

This model is in the general form of Equation (12), and the proposed coefficients are presented in Table 4.

Table 5: *Proposed Ramazi-Schenk connection coefficients (Behrooz Alizadaeh, 2018)*

Acceleration component		a1	a2	a3	a4	a5	a6
ah	Soil	4000	20	16	0.63	-2.02	0.8
	Rock	4000	20	16	0.63	-2.11	0.79
av	Soil	4000	20	16	0.48	-1.75	0.53
	Rock	4000	20	16	0.48	-1.75	0.53

Campbell- Bozorgnia attenuation equation 2000:

$$ln\,Y = c_1 + c_2 M_w + c_3(8.5 - Mw)^2 + c_4\, ln(\{{R_s}^2 + [(c_5 + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10}F_{SS} + c_{11}F_{RV} + c_{12}F_{TH} + c_{13}S_{HS} + c_{14}S_{PS} + c_{15}S_{SR} + c_{16}S_{HR}; Y = g \qquad (12)$$

The model used in this relationship is generally Equation (13), and the model's coefficients are shown in the Table. (٥).(Gholamreza Ghodrati Amiri, 2015).

Table 6: *Bozorgnia attenuation equations 2000: Suggested constants and coefficients*

Uncorrected horizontal component of acceleration	C1=-2.896	C2=0.812	C3=0	C4=-1.318	C5=0.187	C6=-0.029
	C7=-0.064	C8=0.616	C9=0	C10=0	C11=0.179	C12=0.307

	C13=0	C14=-0.062	C15=-0.195	C17=-0.320	σ =0.509	
Uncorrected vertical component of acceleration	C1=-2.807	C2=0.756	C3=0	C4=-1.391	C5=0.191	C6=0.044
	C7=-0.014	C8=0.544	C9=0	C10=0	C11=0.091	C12=0.223
	C13=0	C14=-0.096	C15=-0.212	C17=-0.199	σ =0.548	

The classification of soil type in the Campbell-magnitude reduction relationship is shown in Table ۷.

Table7: *Division of soil types in the Bozorgnia attenuation equation*

Holocene Soil (HS)	VS30=290m/s	SHS=1	SPS=0	SSR=0	SHR=0
Pleistocene Soil (PS)	VS30=370m/s	SHS =0	SPS =0	SSR =1	SHR=0
Soft Rock (SR)	VS30=420m/s	SHS =0	SPS =0	SSR =1	SHR=0
Hard Rock (HR)	VS30=800m/s	SHS =0	SPS =0	SSR =0	SHR=1

The classification of the fault mechanism in the Campbell-magnitude reduction relationship is as described in Table 7.

Table 8: *Division faulting mechanism*

Strike Slip	FTH=0	FSS=1	FRV=0
Reverse	FTH=0	FSS=0	FRV=1
Thrust	FTH=1	FSS=0	FRV=0

Khademi attenuation equation 2002:

$$Y = C_1 \, exp(C_2 M_W)((R + C_3 \, exp(C_4 M_W))^{C_5}) + C_6 S; \; Y = g \quad (13)$$

In this case, the model can be used in the general form of relation (14), and the proposed coefficients are shown in Table 8 (Bakhshi H, 2021).

Table 9: *The suggested coefficients for the Khademi attenuation equations in 2002*

acceleration component		C1	C2	C3	C4	C5	C6	S
Horizontal component	Soil	0.040311	0.417342	0.001	0.65	-0.035852	-0.035852	1
	Rock	0.040311	0.417342	0.001	0.65	-0.035852	-0.035852	0
Horizontal component	Soil	0.0015	0.8548	0.001	0.4	-0.4	-0.463	1

	Rock	0.0015	0.8548	0.001	0.4	-0.4	-0.463	0

Nowroozi attenuation equation 2005

The model applied in this section is presented in Equation (15), and the corresponding coefficients are listed in Table 9 (ShamsAldane et al., 2018).

$$ln(A) = c_1 + c_2(M_W - 6) + c_3 \, ln\left(\sqrt{EPD^2 + h^2}\right) + c_4 S; \; A = cm/s^2 \qquad (14)$$

Table 10: *Suggested coefficients for Nowroozi attenuation equations 2005*

Acceleration component		C1	C2	C3	C4	H	σ	S
Horizontal component	Gravel & sand	7.969	1.220	-1.131	0.212	10	0.825	1
	Rock & Alluvial	7.969	1.220	-1.131	0.212	10	0.825	0
Horizontal component	Gravel & sand	7.262	1.214	-1.094	0.103	10	0.773	1
	Rock &Alluvial	7.262	1.214	-1.094	0.103	10	0.773	0

Mahdavian attenuation equation 2006:

In this case, the model presented in Equation (16) is applied, and the corresponding coefficients are provided in Table 10 (Ghodrati Amiri et al., 2015).

$$Log\,(y) = a + bM_S + c\,log(R) + dR; \; y = cm/s^2 \qquad (15)$$

Table 11*: Suggested coefficients for the Mahdavian attenuation equations 2006*

	floor	Earthquake parameters	A	B	C	D	Σ
Alborz and Central Iran	of stone	PGAH	2.058	0.243	-1.02	-0.000875	0.219
		PGAV	1.864	0.232	-1.049	-0.000372	0.253
	of soil	PGAH	1.912	0.201	-0.79	-0.00253	0.204

PGAV	1.76	0.232	-1.013	-0.000551	0.229

Ghodrati attenuation equation 2007:

In this case, the model used is the general form of Equation (17) (Ghodrati, 2007), and its proposed coefficients are specified in Table 11 (Iman, 2015).

$$Lny = C_1 + C_2 M_S + C_3 L_n(R + C_4 exp[M_S]) + C_5 R;\ y = cm/s^2 \quad (16)$$

Table 12: *Suggested constant coefficients for the Ghodrati attenuation equation 2007*

	Floor	Earthquake parameters	C1	C2	C3	C4	C5	Σ
Alborz and Central Iran	of stone	PGAH	4.15	0.623	-0.96	-	-	0.478
		PGAV	3.46	0.635	-0.996	-	-	0.49
	of soil	PGAH	3.65	0.678	-0.95	-	-	0.496
		PGAV	3.03	0.732	-1.03	-	-	0.53

Table 13: *Results of determinant risk analysis in Kunduz*

Row	Fault name	Closest distance	Estimated magnitude	Acceleration component			
				II و I soil type		IV و III soil type	
		Km	Ms=Mw	Horizontal	Vertical	Horizontal	Vertical
F1	Darafshan	91.633	7.28	0.3	0.25	0.31	0.3
F2	Central Badakhshan	167.925	7.25	0.15	0.37	0.4	0.3
F4	Hari rod	183.451	6.49	0.19	0.31	0.37	0.3
F5	Chaman	183.5	6.81	0.4	0.41	0.35	0.38

1. In type 1 soil, the Chaman fault is associated with the maximum ground acceleration, which ranges from 0.4 to 0.41.

2. In type II soil, the Central Badakhshan fault is associated with the maximum ground acceleration, which ranges from 0.4 to 0.3.

Probabilistic Seismic Hazard Analysis

Using "SeisRisk III" software and seismic springs, good seismic parameters, attenuation equations, and Khademi, Nowroozi, and Mahdavian relations—all of which have weight coefficients of 0.10, 0.14, 0.17, 0/19, 0.20, and 0.20, respectively—are used in this method to determine the maximum horizontal and vertical acceleration curves for the region. These curves are based on two soil types: types I and II, and types III and IV of the standard No 2800, respectively (Figures 3 to 6). It should be mentioned that Bandar and Perkins wrote the SeisRisk III program for probabilistic risk analysis. (M. Fahimi Farzam, 2018).

This software can optimize ground movement parameters in the area by accounting for design levels, appropriate levels of danger, and the probabilities and uncertainties to calculate the magnitude of the region and the earthquake rate. This is done after defining seismic sources and determining the diminution equation, such as the coefficients obtained by the ijko method (Briassoulis, 2019).

To perform fast and accurate hazard analysis, Design parameters (base acceleration, spectral acceleration, plot spectrum) and parameters associated with seismic sources, seismicity, and reduction connection are calculated for each risk level via a probabilistic conjunction, and the evaluation is based on the TR return period or the probability of an annual occurrence (Equation 18).

$$P = \frac{1}{T_R} \qquad (17)$$

TR = The average time of occurrence of seismic activity within the target range of a particular magnitude. P = Reversal of the return period corresponding to the annual seismic probability (Kuehn NM, 2020).

Equations (19) and (20) can be used to calculate the chance of an earthquake (q) occurring during the structure's useful life (n years), yielding the period of return or the probability of an annual earthquake. (Shnizai et al., 2023; Rustami et al., 2017; Boyd et al., 2007)

$$T_R = \frac{1}{1-(1-q)^{1/n}} \qquad (18)$$

$$P = 1 - (1 - q)^{1/n} \qquad (19)$$

In this study, the Seismic design levels with return periods of 72, 225, 475, and 2475 years have been examined in accordance with the Improvement Instruction for Existing Buildings (2002). These stages are: 1. Selective Hazard Levels 1: This risk level is calculated on a 72-year return time (a 50% chance of an event occurring in 50 years).

2. Selective Hazard Level 2: Based on a 20% probability of recurrence in 50 years, or a 225-year return period, this category of risk is determined.

3 . Risk level 1: Given a 10% chance of an occurrence occurring in 50 years, or a 475-year return time frame, this risk level is established. The Iranian Standard 2800 Regulation refers to earthquakes as having a hazard level of 1 (DBE).

4. Risk Level 2: Based on a 2% possibility of an occurrence occurring in 50 years, or a 2475-year return time frame, this risk level is established. Standard 2800 refers to earthquake hazard level two as MPE.

Geographical and Fault Line Data

Afghanistan's seismic hazard analysis relies heavily on data on its active fault lines and seismic activity. Active fault lines, identified through geological studies such as those by Shnizai et al. (2023), provide essential data for determining the potential magnitude and frequency of earthquakes across different regions. (Shnizai et al., 2023)

Data from remote sensing, field surveys, and geological mapping are used to update and refine the knowledge of fault zones. These fault lines, including the Hindu Kush, known for frequent seismic activity, and the Chaman Fault, contribute to much of Afghanistan's seismic risk. The study also incorporates data from neighboring regions to improve hazard estimates and assess broader seismic risks affecting cross-border areas. (Shnizai et al., 2023; Rustami et al., 2017; Boyd et al., 2007)

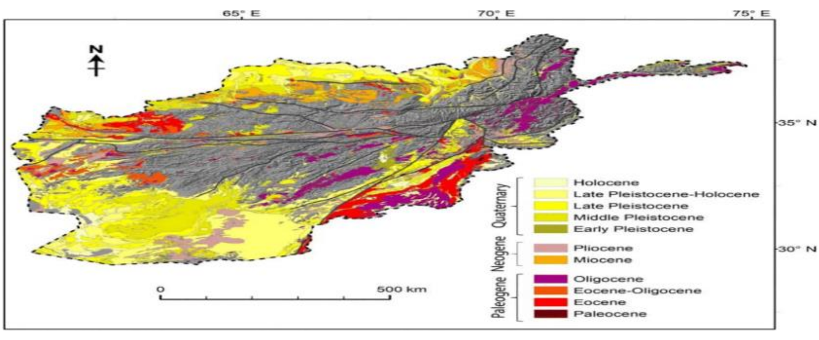
Environmental Impact Evaluation

In addition to the seismic hazard analysis, this research evaluates the environmental impacts of earthquakes, focusing on how they could affect Afghanistan's natural resources and environmental sustainability. Afghanistan's agriculture, water resources, forests, and ecosystems are especially vulnerable to seismic activity, particularly in regions with weak infrastructure and limited disaster resilience. Earthquakes can trigger landslides, soil liquefaction, and the destruction of agricultural land, severely impacting food security and water availability. The study analyzes the ecosystem services provided by Afghanistan's natural resources, including how seismic events could disrupt these. For example, disruption to water supply systems due to infrastructure damage or changes in river courses, as well as the loss of vegetation due to landslides, are identified as significant environmental risks. These impacts are assessed through the literature review of case studies from earthquake-prone regions such as Indonesia and Japan, where similar environmental issues have been documented. (Ahmadi & Kajita, 2017; Ali, 2005; Fahimi Farzam et al., 2018)

Fig. 4. *Geological map of Afghanistan*

Risk Mitigation and Adaptation Strategies

The research also aims to propose feasible mitigation strategies to reduce the impact of earthquakes on both the population and the environment. These strategies focus on disaster risk management and sustainable environmental practices that can help Afghanistan's government and local communities prepare for and respond to seismic threats. (Fahimi Farzam et al., 2018)



Mitigation Approaches Include:

- Strengthening building codes and infrastructure to withstand seismic shaking.
- Developing early warning systems for seismic events to alert vulnerable communities in real-time.
- Promoting soil stabilization techniques and land-use planning to minimize landslide risks.

- Community training and capacity-building to improve disaster preparedness at the local level, particularly in rural and isolated areas. Furthermore, this research stresses the importance of sustainable land use and ecosystem-based approaches for disaster risk reduction. This could include efforts to preserve wetlands for flood control and reforestation to reduce soil erosion. (Ahmadi & Kajita, 2017)

Analytical Tools and Software

Advanced seismic hazard software tools, such as Seisrisk and other earthquake modeling platforms, are used to conduct the probabilistic and deterministic seismic hazard assessments. These tools enable detailed seismic hazard mapping, helping identify high-risk areas and prioritize them for risk-reduction measures. The software also supports integrating geological data, seismic event history, and climatic conditions to create robust models of earthquake occurrence and impacts. (Bakhshi et al., 2024)

Data Collection and Synthesis

Data for this study is collected from multiple sources, including:

- Historical earthquake data from global and regional seismic databases.
- Geological surveys and remote-sensing imagery to map fault lines and assess geological vulnerabilities.
- Government and local authorities need to understand ongoing disaster response measures and vulnerabilities.
- Global case studies and best practices in seismic hazard and environmental risk assessment. (Shnizai et al., 2023; Rustami et al., 2017)

By synthesizing diverse data sources, this research aims to develop a comprehensive seismic hazard model for Afghanistan that not only identifies the most vulnerable regions but also examines the broader environmental implications of these risks. The ultimate goal is to provide a framework for sustainable disaster management that prioritizes the preservation of Afghanistan's natural resources and environment alongside human safety. (Prada et al., 2018)

Findings

Seismic Hazard Assessment in Afghanistan: Critical Challenges and Pathways to Resilience

A comprehensive seismic hazard assessment for Afghanistan underscores a series of urgent and interconnected challenges that threaten the nation's safety and development.

High Seismic Hazard Posed by Active Tectonic Structures

Afghanistan is located within a region of intense and ongoing tectonic activity, straddling the complex convergence zone of the Eurasian and Indian plates. Major active fault systems—including the Herat, Chaman, Badakhshan, and the deeply seismic Hindu Kush region—present a continuous and severe seismic threat. Historical and instrumental records confirm that these structures are capable of generating high-magnitude, destructive earthquakes, posing a persistent danger to population centers across the country.

Severe Vulnerability of the Built Environment

The physical vulnerability of Afghanistan's building stock and infrastructure represents a critical risk multiplier. A predominant share of structures, including public buildings, residential housing, and critical facilities, is constructed without adherence to earthquake-resistant design principles. This is attributable to the lack of a mandatory, nationally enforced building code, limited technical capacity, and widespread use of non-engineered construction methods. Consequently, even moderate seismic events have the potential to cause disproportionate levels of damage, collapse, and loss of life.

Necessity for Advanced, Localized Hazard and Risk Modeling

Effective risk management requires moving beyond generalized hazard maps. The application of both Probabilistic Seismic Hazard Analysis

(PSHA), to define long-term ground motion exceedance probabilities, and Deterministic Seismic Hazard Analysis (DSHA), for scenario-based assessment of maximum credible earthquakes, is essential. Crucially, these analyses must be informed by site-specific geotechnical and microzonation studies to account for local soil conditions, basin effects, liquefaction susceptibility, and slope instability, which dramatically influence shaking intensity and damage patterns.

Fundamental Gap in Public Awareness and Institutional Preparedness

Social and institutional vulnerability compounds the physical risk. Public knowledge of earthquake hazards and protective measures is generally low, while national and local disaster management frameworks often lack the resources, plans, and capacity for effective response. **Strategic** priorities must therefore include: (1) deploying and modernizing seismic monitoring networks and early warning systems; (2) implementing nationwide public education and community drills; and (3) developing robust emergency response and recovery plans (Ahmadi & Kajita, 2017; Ali, 2005).

Conclusion

The convergence of high seismic hazard, acute physical vulnerability, and significant socio-institutional exposure places Afghanistan at severe risk from earthquakes. Mitigating this risk requires a sustained, multi-sectoral commitment to building resilience. The following strategic interventions are proposed as foundational pillars for a national risk reduction agenda:

Code Development, Enforcement, and Retrofitting

- Develop and legislate a mandatory, nationally applicable building code based on modern seismic provisions.
- Launch large-scale programs to assess, prioritize, and retrofit critical public infrastructure (e.g., hospitals, schools, emergency centers) and vulnerable housing.
- Build capacity within the engineering community, construction sector, and regulatory bodies for code compliance and quality assurance.
- Enhanced Monitoring and Data-Driven Decision Making:

- Expand and technologically upgrade the national seismic network to improve earthquake detection, location, and characterization.
- Integrate seismic data with geological and geotechnical databases to create dynamic hazard and risk models that support land-use planning and emergency management.

Investment in Preparedness and Public Education

- Institutionalize earthquake safety education in school curricula and through public awareness campaigns.
- Conduct regular, multi-agency emergency exercises at all administrative levels to test and refine response plans.
- Empower local communities through community-based disaster risk management programs.

Fostering Collaborative Governance

- Establish a coordinated, multi-stakeholder platform involving government ministries, academia, the private sector, and international partners.
- Align national policies and development investments with the goal of seismic risk reduction, ensuring it is mainstreamed across sectors (Yucemen, 2013).

By adopting this comprehensive and proactive framework, Afghanistan can systematically reduce its seismic risk, protect its citizens and economic assets, and lay the foundation for safer, more sustainable development in the face of an inevitable seismic future (Yucemen, 2013).

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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