Earthquake Risks and Lack of Disaster Management in Afghanistan

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Key Points:

- Afghanistan is in a tectonically active region of the Indian, Eurasian, and Arabian plate boundaries.
- A database of active geological faults and seismic regions is important in earthquake disaster risk reduction in the country.
- Infrastructure codes, design, and earthquake disaster management are possible solutions for disaster mitigation.

Abstract

Afghanistan is in a seismically active area and is historically hit by destructive earthquakes. It is located on the edge of the Eurasian tectonic plate, bordered by the northern boundary of the Indian plate, and with the collisional Arabian plate into the South. The Hindukush and Pamir Mountains within Afghanistan are the western extension of the Himalayan orogeny uplifted and sheared by Indian and Eurasian plate convergence. These tectonic activities have created several active deep faults across the country and in the Hindukush-Himalayan region, where high-magnitude earthquakes have historically occurred. Earthquakes in Afghanistan are primarily driven by the relative northward movements of the Arabian plate past western Afghanistan and the Indian plate past eastern Afghanistan as both plates subduct under the Eurasian plate. These tectonic movements caused ground shaking from high to moderate and low from the northeast through the southwest of the country. On June 22, 2022, the southeastern part of Afghanistan was hit by a destructive Mw6.2 earthquake. The purpose of this study is to develop an ArcGIS Pro database of compiled geologic faults and regions of heightened seismicity for spatial analyses of earthquake disaster severity across Afghanistan. These spatial analyses place better constraints on the placement of active and historic seismicity along mapped and known active faults for progress in earthquake disaster management. Furthermore, we define current hazards associated with building and infrastructural design and competency given the recurrent and eminent seismicity within Afghanistan and describe possible directions and solutions to mitigate the threat to life and property[1].

1 Introduction

Tectonic earthquakes in the Himalayan region resulted from the subduction of the Indian continent under the Eurasian plate (Guo et al., 2017; Verma et al., 1980). Hindukush Mountains are part of the Himalayan active tectonic region, which happened from the Northeast to the southeast of Afghanistan and extended to the surrounding region (Chouhan, 1970; Verma et al., 1980). The region underwent intensive folding, thrusting, and faulting in the Mesozoic and Cenozoic eras. The folding and faulting in the Himalayan region trend northwest-southeast and east-west directions (Joshi & Hayashi, 2010). Northward underthrusting of the Indian crust beneath Eurasia generates many earthquakes and makes this area one of the most seismically hazardous regions on Earth (Bilham, 2019; Hinsbergen, 2022). This region is presently where the

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most distractive earthquakes occur, propagating seismic waves throughout Afghanistan and the surrounding regions (Kufner et al., 2021; Rehman et al., 2017a). Therefore, the northeastern region of Afghanistan is the center of high-hazard earthquakes.

From ancient times, Afghanistan has been affected by destructive seismic activities that centered in the northeastern region (Rehman et al., 2017b). Each year, Afghanistan is struck by moderate to strong earthquakes, causing damage, economic losses, and fatalities (Boyd et al., 2007a). During the last 30 years, earthquakes have caused over 10,000 fatalities (World Bank, 2017). Strong earthquakes occur every few years in and around Afghanistan, there have been about 100 damaging earthquakes since 1900 (Daniell et al., 2011). Recently, there has been a frequency in the recurrence of earthquakes around epicenters and along the main faults in Afghanistan. In 2019, an earthquake with M_w6.1 magnitude occurred in Badakhshan province, and an M_w5.1 earthquake in 2021 in Kabul with no fatalities and less damage (Risklayer, 2023). In 2015, the M_w7.5 earthquake in the Hindukush Mountains caused 117 fatalities and destroyed over 7,000 houses (IFRC, 2015). In June 2022 a M_w6.2 earthquake struck the southeastern region of Afghanistan, causing over 1,163 fatalities, 3,600 injured, and about 1,000 houses destroyed (Qiu et al., 2023a). A M_w6.5 earthquake Shaked Jurm of Badakhshan on the 21st of March 2023 with no fatalities. All the earthquakes were followed by aftershocks and recurrence in and around the mainshock centers.

The impact and vulnerability of earthquake hazards in Afghanistan are mainly due to the distribution of active faults across the country; settlement in disaster-prone areas, unreinforced construction against earthquake shaking; lack of disaster management system, including but not limited to poverty, conflict, and instability in the country (SESRIC, 2016). To this end, earthquake disaster management is important for earthquake risk and vulnerability reduction, and it is the basis for the country's sustainability. Over the past two decades, Afghanistan's disaster risk management focused on response and recovery (UNDRR, 2020). However, the Government of the Islamic Republic of Afghanistan (GoIRA) worked with development partners, including the World Bank, United Nations organizations, and relevant international NGOs, to develop Disaster Risk Management (DRM) systems and mainstreaming Disaster Risk Reduction (DRR) in the development process (World Bank, 2018). GoIRA structured the DRM and DRR in the national development strategy (GoIRA, 2013, 2021). Based on that number of policies and plans developed in the framework of DRM and DRR but remained in the draft (ANDMA, 2011). In addition, the protracted war and conflict exacerbate Afghanistan's vulnerability to natural disasters (Peters, 2021a). Insecurity and conflict cause state fragility, which leads to socioeconomic vulnerability from one side on the other hand, natural disasters result in frequent loss of lives, livelihoods, and properties and cause migration and displacement (International Alert, 2015). All these causes and effects intensify disaster impacts, whereas Afghanistan has a wealthy natural potential for disaster risk reduction. In conclusion, this study focused on studying earthquake disasters in Afghanistan and approaches for earthquake disaster risk reduction. The seismic risk analysis is based on major historical records and modeling earthquake faults and tectonic zones using ArcGIS Pro. Risk assessment is created by combining hazard, exposure, and vulnerability. Data from USGS, Risklayer, and other databases were analyzed using ArcGIS Pro. The paper concluded with some constructive recommendations on earthquake risk mitigation which is a missing part that greatly assists risk reduction.

2 Methodology

In this study, we compile and use all currently cataloged and recorded earthquake databases and historical records for Afghanistan and the surrounding region to investigate earthquake disasters and related socioeconomic exposure and vulnerability. Afghanistan and the surrounding countries are within the convergent Himalayan tectonic region, as the Eurasian and Indian plates collide. This zone is a special focus of geological studies. Therefore, there are some papers on Afghanistan and surrounding countries' tectonic settings, active faults, and earthquake disasters. Recently, the United States Geological Survey (USGS) investigated seismic activities in Afghanistan (Dewey, 2006). USGS investigated geological faults, seismic zones, and created earthquake hazard maps including a historical earthquake database (Dewey, 2006; USGS, 2023). Some historical and recent earthquake records were used from Risklayer online database (Risklayer, 2023). The updated main geological faults crossed Afghanistan and connected with surrounding regions including plate boundaries are derived from the ArcGIS REST Services Directory (ArcGIS, 2023; Bird, 2003). In this study, USGS reports and databases are reviewed, and recent earthquakes were added to the existing database. Tectonic settings, active faults, and seismic regions of Afghanistan were digitized and mapped with the updated data using ArcGIS Pro. Also, earthquake hazard maps and historical databases updated with recent earthquakes were created. Based on the available data a simple approach for earthquake Disaster Risk

Reduction (DRR) was proposed for Afghanistan. Some of this paper's raw materials are drawn from the author's own experience.

Due to the protracted war and conflict in Afghanistan, most data recording and research infrastructure have been destroyed (Rubin, 2011). Our research investigations have been challenging due to the lack of accurate data. Therefore, a national-level DRM is hampered by a lack of consistent data on hazard risk and vulnerability nationally. The approaches that can be used to assess earthquake-related hazards and risks are limited by the lack of data and security issues preventing field observation and data collection. There is a long gap in the available data between 1980 to 2002, and later due to war and conflict in Afghanistan. In the past couple of decades, the State Ministry for Disaster Management and Humanitarian Affairs (DMHA), with national and international partners, set up a national-level disaster information management system, and it started its initial recording system. Since the Taliban occupied and took control of Afghanistan, the system has been inoperable. Now, advanced remote sensing technology enables quantitative risk assessment in data-scarce areas (Cremen et al., 2022; Ward et al., 2015).

ArcGIS Pro was used for creating maps, data reanalyzing, and visualizing (Esri, 2023). Topographical and hydrological mapping, remote-sensing data, and satellite images were used from National Geographic, Esri, USGS, the Food and Agriculture Organization (FAO) of the UN, and the National Oceanic and Atmospheric Administration (NOAA).

3 Results and Discussions

In Afghanistan within the public population, there is a common perspective that earthquakes are natural disasters that can occur anywhere, with no predictability or government-led hazard investigations or mitigation, such as building codes. However, earthquakes in Afghanistan occur due to direct tectonic processes associated with movements between the Indian, Eurasian, and Arabian plates (Abdullah et al., 2008; Ruleman, 2011; Ruleman et al., 2007). The boundaries between these plates consist of coalesced, continental stresses merged into a concentrated deformed zone or plane, or a fault, where episodic, large, brittle crustal movements deform or rupture the surface (Abdullah et al., 2008; Ruleman, 2011; Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005; Wheeler & Rukstales, 2007)and showing recurrent movement through the geologic past. Faults with movement within the Quaternary Period, or Pleistocene, over the last 2.58 Ma, are considered active by the Nuclear Regulatory Committee

(Mcginnis et al., 2016). Faults are distributed through different regions in Afghanistan (Ruleman et al., 2007). Strong earth-shaking and infrastructure destruction have been well documented around major historical earthquakes and located epicenters. These have been primarily recorded, located, and documented along the major plate boundaries between Afghanistan, Pakistan, and Asia (Dewey, 2006). The Badakhshan province in northern Afghanistan is the center of major earthquake concentrations. Seismic source zones and some faults extend beyond the national boundary (Fig. 3) (Ruleman, 2011) The historical record shows that many large earthquakes located in surrounding countries have created vigorous shaking and caused damage within Afghanistan (Fig. 2). Ruleman and others (2007) extend the seismic hazard for Afghanistan to any seismic source zone within 100 km of the country's political boundary. To the most extent, earthquakes cannot be predicted nor managed, but earthquake hazards can be defined, mitigated, and decreased by reducing risk, vulnerability, and exposure to Afghanistan's infrastructure and population. The following sections explain the tectonic structure, historic earthquake disaster record after Hopper et al (Hopper et al., 2006), infrastructural and population vulnerability, and conclude with earthquake risk management solutions for Afghanistan.

3.1 Tectonic Structure of Afghanistan and the Surrounding Region

Afghanistan is located on the perimeter of the Eurasian plate in the complex active tectonic region of the Alpine-Himalaya orogenic belt, constructed during the collision between the Indian, Arabian, and Eurasian plates beginning in the Late Paleogene and continued to the present (Abdullah et al., 2008; Mahmood & Gloaguen, 2012a). Afghanistan has hundreds of kilometers long active plate boundaries from the west, south, and east. In the west, the Arabian plate moves northward relative to Eurasia at about 31 mm/y (Vernant et al., 2004) that is the active plate boundary trends northwestward through the Zagros region of southwestern Iran (Ambraseys & Bilham, 2003) (Fig. 1). This plate motion has deformed the region within and surrounding Iran, forming major structures including north-south-trending, right-lateral strike-slip fault systems on its eastern boundary with Afghanistan, and a series of east-west-trending reverse and strike-slip faults discontinuously distributed throughout the country (Boyd et al., 2007b).

Along the eastern margin of Afghanistan, the Indian plate moves northward relative to Eurasia at an average rate of about 34.4 mm/y (Valdiya & Sanwal, 2017b). Eurasian plate motion and collision with the Indian plate occur at a rate at various measured rates averaging ~13 mm/y (Bird, 2003; Ruleman et al., 2007; Sella et al., 2002; Vernant et al., 2004). This movement has formed a broad, transpressional plate boundary zone, trending southwestward from the Hindukush in northeastern Afghanistan, through Kabul, and along the country's eastern side (Wheeler, Bufe, Johnson, Dart, et al., 2005). Deformation had formed the belt of major, north-northeast-trending, left-lateral strike-slip faults and continues with abundant historic and contemporary seismicity.

The seismicity intensifies within northeastern Afghanistan along a prominent zone of deep earthquakes associated with northward subduction of the Indian plate beneath Eurasia, extending beneath the Hindukush and Pamir Mountains (Boyd et al., 2007b; Perry et al., 2019). In the Pamir and Hindukush, the seismogenic zone starts from 50 km, reaches approximately 250 km depth, and has several subduction features, such as crustal and thrust faults and a local seismicity zone with high speeds (Sippl, Schurr, Tympel, et al., 2013; Sippl, Schurr, Yuan, et al., 2013).

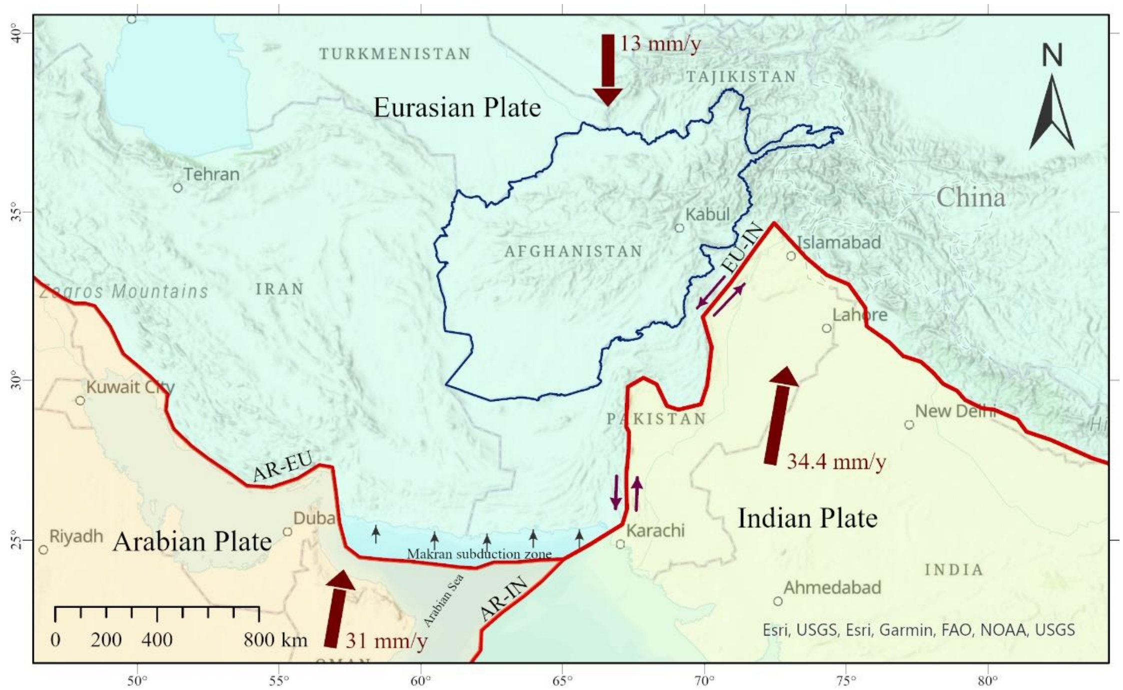

Figure 1. Tectonic setting of Afghanistan and the surrounding regions. The bold arrows show the relative direction and velocities of the Eurasian (EU), Arabian (AR), and Indian (IN) plates. The small arrows show EU and IN transform boundaries labeled in red.

Some faults are active because of the historical record, recent significant earthquake occurrences along the faults, and the appearance of surface rupture. Earthquakes in Afghanistan and the surrounding region caused and will likely cause severe damage from strong ground shaking, faults rupturing the ground surface, liquefaction, and extensive landslides. As we witnessed, the devastating M_w6.2 earthquake struck the southeastern region of Afghanistan on 22nd June 2022 (Qiu et al., 2023b; Shnizai, 2020). Figure 1 shows Afghanistan's location on the Eurasian plate, including the Indian and Arabian plate boundaries.

The Makran subduction zone is formed between the overriding Eurasian plate and the subducting Arabian plate (Fig. 1). It is due to the northward subduction of the oceanic part of the Arabian Plate beneath the Lut and Afghan blocks in the northwestern Indian Ocean (Mokhtari et al., 2019; Nemati, 2019). It has a complicated tectonic setting as it is located at a triple junction with the Indian Plate. Southwestern Pakistan, southeastern Iran, and southernmost Afghanistan comprise a broad transpressional fold and thrust belt comprised of south-southeast-verging, north-dipping thrust faults, and associated east-northeast-trending folds (Priestley et al., 2022; Shareq, 1981). It is a seismically active region, producing frequent large-magnitude earthquakes with the most recent magnitude Mw7.7 earthquake occurred in September 2013 in Balochistan Province (Mokhtari et al., 2019).

3.2 Regional Tectonic Framework and Associated Fault Systems

Hindukush and Pamir Mountains in Afghanistan are part of the Himalayan orogeny uplifted by the collision between the Indian and Eurasian plates. This tectonic event and associated movements have created several active deep faults in the Hindukush-Himalayan region and crossing Afghanistan (James, 1989; Mahmood & Gloaguen, 2012b) as shown in Figure 2. The boundary of the Himalayan tectonic region reaches the foothills of the Sulaiman Mountains in the west, the Indo-Burmese Arc in the east, and the Himalaya Front in the north of India (Tsapanos et al., 2016). Earthquakes are an episodic release of building region tectonic strain and stress and motion, or slip, between crustal blocks causing major damaging shaking in this region (Kearse & Kaneko, 2020). Also, the relative motion between the two plates in the west and south of the Himalayan front is oblique, resulting in strike-slip, reverse-slip, and oblique-slip earthquakes and associated displacement along faults and fault zones (Ruleman, 2011; Ruleman et al., 2007; Valdiya & Sanwal, 2017a). As depicted in Figure 2, Afghanistan and the surrounding countries are in the same tectonic region and have a similar tectonic structure. The fault systems crossing Afghanistan extend into the surrounding countries. Ruleman et al.

(2007) considered any fault within 100 km of the Afghanistan political border to be a potential threat to Afghanistan's population and infrastructure. The main active fault systems are the Chaman, Hari Rud, Central Badakhshan, and Darvaz, with many subsidiary smaller faults and fault zones accommodating motion between these major faults (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005; Wheeler & Rukstales, 2007), with high-magnitude shallow and deep crustal earthquakes. Figure 2 shows earthquakes from 1964 to 2004 in the region. Recently, high-magnitude earthquakes occurred around these fault systems affecting Afghanistan and the surrounding regions (Bilham, 2019; Kufner et al., 2023). In the western part of the country earthquake shaking from the Arabian plate caused deadly earthquakes in eastern Iran (Nemati, 2019).

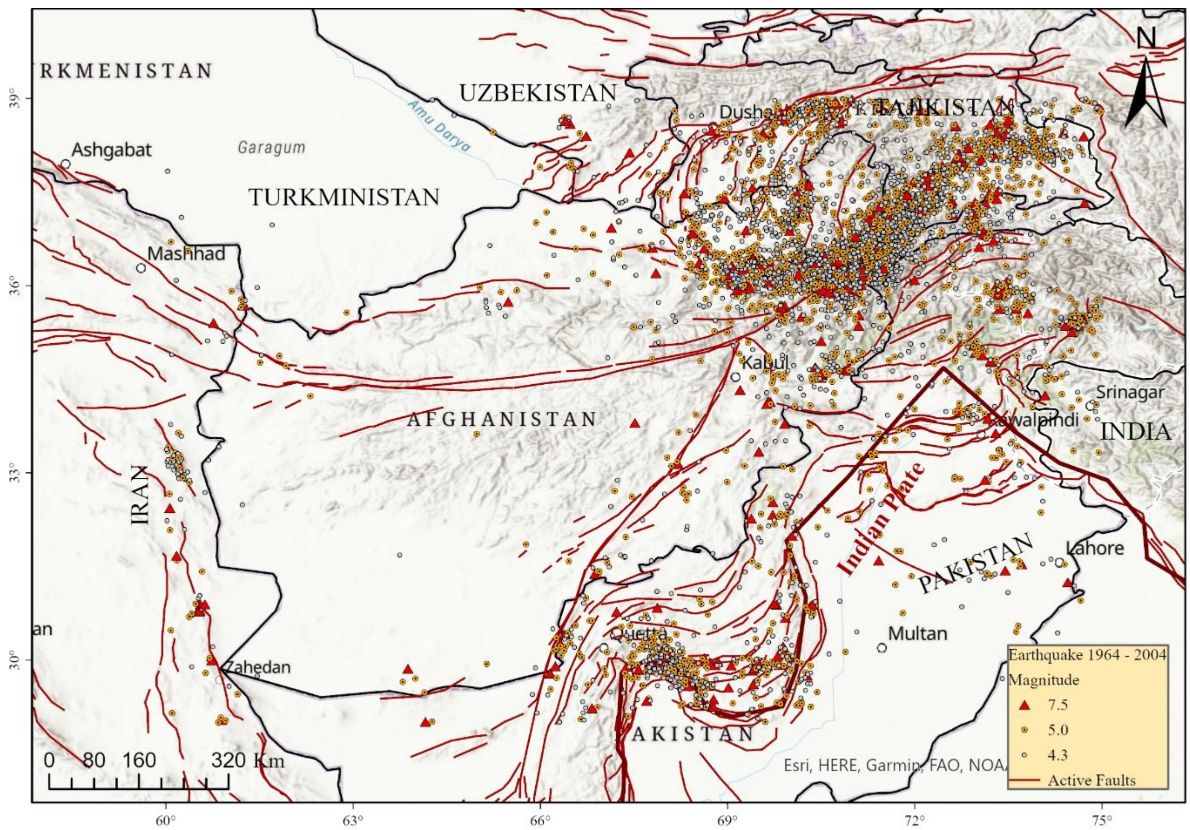

Figure 2: Historical earthquakes in Afghanistan and surrounding regions between 1964 – 2004. The historical earthquakes are modified from the USGS database (Ambraseys & Bilham, 2003.

3.3 Tectonic Zones of Afghanistan

Afghanistan is an assemblage of different crustal and oceanic blocks composing several unique terranes welded onto the southern margin of the Eurasian plate during a series of successive accretionary events beginning in the Paleozoic and continuing to present (Bohannon, 2010; Doebrich & Wahl, 2006; Ruleman et al., 2007; Sinfield & Shroder, 2016). The geological structure of Afghanistan is dominated by the Mesozoic (Cimmeride) and Tertiary (Himalayan) orogenic episodes that have created and continue to create mountainous regions and the dramatic landscape of Afghanistan (Tapponnier et al., 1981a; Whitney, 2006). Afghanistan has been classified as four distinct seismotectonic regions with different geologic histories and structures (Bohannon, 2010; Shareq, 2011; Shroder et al., 2022; Wheeler, Bufe, Johnson, & Dart, 2005; Wheeler & Rukstales, 2007) as outlined in Figure 3.

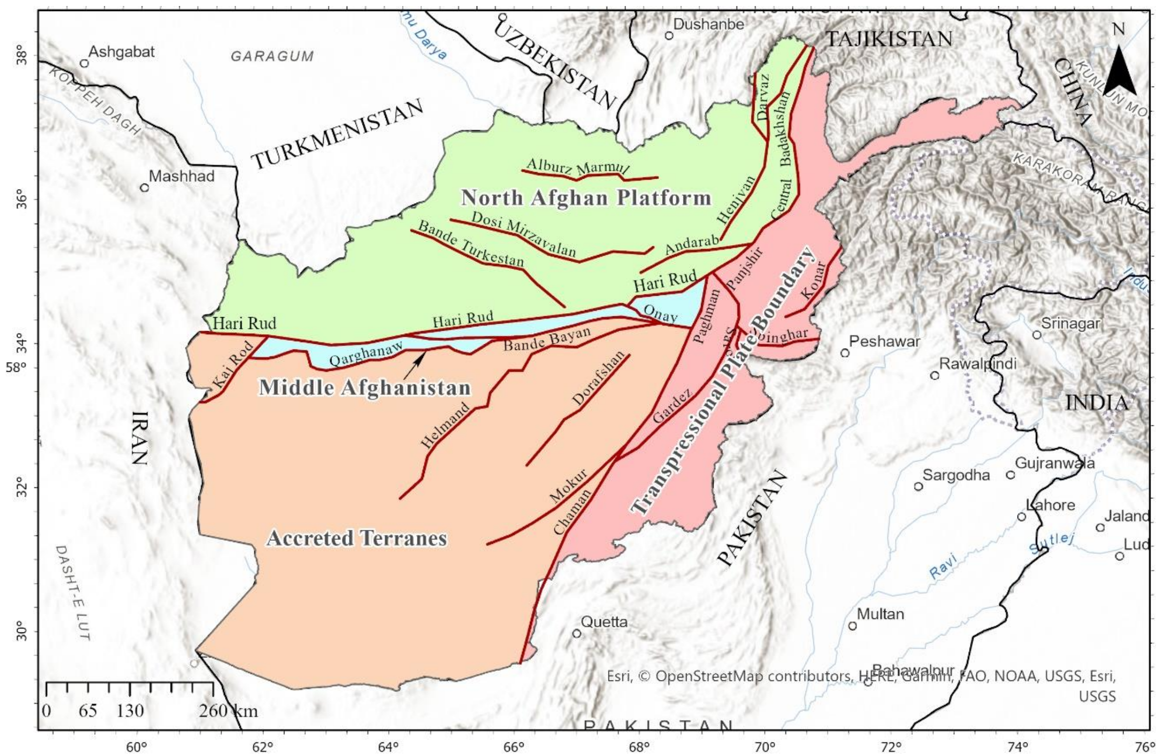

Figure 3. Tectonic zones and major fault systems of Afghanistan (red lines) (modified from Wheeler et al., 2005). The green region is the North Afghan Platform, the light pink region is the Transpressional Plate Boundary, the blue region is the Middle Afghanistan, and the orange region is the Accreted Terranes zone.

The Transpressional Plate Boundary region is the boundary between the Eurasian and the Indian plates caused by continental collision and moving northward at a rate of about 39 mm/y (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). The plate is located south and east of the Afghan Block, including the eastern portion of the Hindu Kush, Pamir Mountain ranges, and the Sulaiman fold and thrust belt of southern Afghanistan (Fig.3). The western and northern boundaries of this zone are defined by the left lateral Chaman and Central Badakhshan fault systems, respectively, with the exotic Kabul crustal block (Bohannon, 2010; Ruleman et al., 2007), where the Chaman fault shows greater tectonic activity and more recent earthquakes. This is the most active seismic zone in Afghanistan, with the local exception of the eastern part of the North Afghan Platform (Figure 3).

The North Afghan Platform region lies north of the Hari Rud fault zone and west of the Central Badakhshan fault systems, and includes the Tajik basin (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005)(Fig. 3). The Darvaz is a more active fault in the Platform. This zone formed the southern margin of the Eurasian continental plate, and it is relatively stable tectonically. It comprises deformed metamorphic and igneous rocks basement and was created during the Carboniferous-Permian and Hercynian Orogeny (Shnizai, 2020). The eastern part of the North Afghan Platform is more seismically active than the rest it might be incorporating the Darvaz fault in this part.

The Middle Afghanistan Geosuture Zone is a narrow zone occurred immediately south of the North Afghan Platform and is part of the current right-lateral Hari Rud fault zone (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). It forms the boundary between the North Afghan Platform and the Afghan Block, including other terranes to the south (Sinfield & Shroder, 2016). The Hari Rud River flows along the major downfaulted graben within the geosuture south of the Paropamisus Mountains.

The Accreted Terranes region is located south of the Geosuture and includes numerous external folded, faulted, partially metamorphosed, and deformed blocks that comprise the mountains and plains of the Farah, Helmand, and Arghandab areas formed during the Mesozoic Cimmerian Orogeny and that involved closing of the Paleo-Tethys Ocean (Banks, 2014; Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005) (Fig. 3). The accreted Terranes is a seismically calm, or quiescent, region.

Identification of these tectonic zones, after Wheeler et al. (2005) and Ruleman et al. (2007), will allow us the capability to assign the distribution of earthquake magnitudes over different faults and regions of Afghanistan. In general, the tectonic activities, earthquakes, and deformation in Afghanistan and the surrounding region are driven by the collision between the northward-moving Indian and Eurasian plates (Prevot et al., 1980; Ruleman et al., 2007). This movement has formed active Quaternary faults across the country, showing modern tectonic activity such as moderate to high magnitude and potentially damaging earthquakes. The Earth's crust in Afghanistan is divided by a complex network of faults with different ages and directions of movement, as delineated in Figure 2. Ancient Earthquakes along the myriad of faults within Afghanistan (Figure 2) have caused different amounts of slip during earthquakes in the geologic past. Due to the temporospatial migrations of stress and strain within the region, some faults are active causing recent destructive earthquakes, while other faults are dormant, or quiescent in historical times (Lawrence et al., 1981; Mahmood & Gloaguen, 2011; Quittmeyer & Jacob K.H., 1979). Figure 3 demonstrates major geologic regions and fault systems extending across Afghanistan. Some faults have moved repeatedly and frequently during the Quaternary Period, showing continuous movement into the recent Holocene epoch, but have no historical evidence for movement. Identification of repetitive movement through the geologic past without historic movement is indicative of a seismic hazard. Thus, investigating active faults is in the foundation for these seismic hazard assessments. They allow either estimation of the locations, size, and dates of large historical earthquakes or estimating the rate of fault slip averaged over several earthquake cycles. Most recent details studies of these faults are conducted by USGS using satellite image analysis (Ruleman, 2011; Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). However, field studies were not conducted, and detailed investigations of the fault activities, slip rates, and more geologic characteristics are needed. Ruleman et al. (2007) subdivided Afghanistan into eight tectonic domains, each having distinct physiographic, geomorphic, and associated neotectonics qualities of Quaternary deformation (Ruleman et al., 2007).

3.4 Major Active Faults in Afghanistan

Within this study, previously mapped and identified faults and fault zones are investigated in Afghanistan, and 10 large seismically active faults are suggested through these investigations. The most prominent four active faults are the Chaman, Hari Rud, Central Badakhshan, and Darvaz, which are explained in detail below (Boyd et al., 2007a; Lawrence et al., 1981; Wheeler, Bufe, Johnson, Dart, et al., 2005).

Chaman Fault: The Chaman fault is a system of several faults that forms the western edge of the transpressional plate boundary between the Eurasian and Indian plates (Fig. 3). The 650-km long Chaman fault is a left-lateral strike-slip faults system seismically very active in southeastern

Afghanistan. The fault slip rates are reported to differ between 19-35 mm/y(Lawrence et al., 1981; Ruleman et al., 2007; Tapponnier et al., 1981b), being the most active fault within Afghanistan (Ruleman et al., 2007). The Chaman fault system has been subdivided into four to five main faults: Chaman, Mokur, Gardiz, and Paghman (Ruleman et al., 2007; Shroder et al., 2022) (Fig. 2 and 3). Earthquakes and recurrent movement along the fault have created many complex surface ruptures along the fault trace (Ruleman et al., 2007). There are numerous historical accounts of major large, damaging earthquakes throughout Afghanistan and the surrounding regions. A few of the major historic earthquake accounts include 1) an earthquake in July 1505 with an estimated magnitude of M_s 7.3 produced 60 km of surface rupture and several meters of vertical offset near Kabul; 2) an earthquake on December 20, 1892, near 31°N, created a 60 km surface rupture that produced 60-75 cm of left-lateral slip and dropped the west wall of the fault down 20-30 cm (Barnhart, 2017; Quittmeyer & Jacob K.H., 1979); and 3) an earthquake in 1975 with a magnitude of Mw 6.4 near 30°N produced 5 km of surface rupture and 4 cm of left-lateral offset with a small eastside down slip (Boyd et al., 2007a). Recently, a M_w6.2 earthquake occurred on June 22, 2022, created a 0-8 km long surface rupture with a maximum slip of about 2m at a depth of 2 km (Qiu et al., 2023b).

Hari Rud Fault: The Hari Rud fault system, also called the Herat fault, is a right-lateral strike-slip fault trending nearly east to west; it separates the Northern Afghan Platform from Central Afghanistan (Fig. 3) (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). The fault extends 730 km to the west across Iran's border, from its intersection with the Chaman fault north of Kabul (Boyd et al., 2007b; Ruleman et al., 2007). The fault is a major continental-scale suture that coincides with the boundary between the relatively stable, gently deformed Eurasian content to the north and extensively deformed accreted terrains to the south (Tapponnier et al., 1981a), which has been a major tectonic boundary since the early Mesozoic (Tapponnier et al., 1981b). Previous studies indicate that the area along this suture zone originated as a north-dipping structure, developing into a right-lateral strike-slip fault in Tertiary time. Recent studies indicate a continuation of Quaternary tectonic activities along the fault (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). Few earthquakes and little background seismicity do occur along the Hari Rud fault, but the fault demonstrates less tectonic activity than Chaman, Darvaz, Central Badakhshan, and the Konar fault (Boyd et al., 2007b; Dewey, 2006; Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005).

Central Badakhshan Fault: The Central Badakhshan fault is a left-lateral oblique thrust fault extending from the Panjshir fault's eastern end to the Tajikistan border (Fig. 3) (Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005). It is a north-northeast trending fault associated with active oblique-thrust faults (Ruleman, 2011; Ruleman et al., 2007; Shnizai, 2020). Thrust faults, along with left-lateral and right-lateral fault zones show evidence of probable recurrent Quaternary tectonic activity, indicating a complex interplay between faults in this transpressional region (Ruleman, 2011; Ruleman et al., 2007).

Darvaz Fault: Located in northeastern Afghanistan and extending northward into Tajikistan, the Darvaz fault is a 380-km long, left-lateral fault, trending parallel to the Central Badakhshan fault (Ruleman, 2011; Ruleman et al., 2007; Wheeler, Bufe, Johnson, & Dart, 2005) (Fig. 3). The Darvaz fault is in a seismically active region with continued Quaternary tectonism, where Holocene and late Pleistocene deposits are laterally offset by 20 to 0 meters and 300 meters, respectively (Dewey, 2006; Ruleman et al., 2007; Trifonov, 1978). The Andarab, Darafshan, Sarobi, Konar, Alburz Marmul, and Panjshir faults all demonstrate Quaternary tectonic activity; however, previous investigations and other datasets are limited for these faults. These faults and fault zones and characterizing the active tectonic signature of them should be a focus of future research related to seismic hazards within Afghanistan and the surrounding region.

3.5 Historical Earthquakes in Afghanistan

Historical records of earthquakes over hundreds to thousands of years give us a first-order approximation of the hazards (Bilham, 2019; Dewey, 2006). Afghanistan is in an active tectonic region; thus, a historic earthquake database is essential for disaster risk management. Recently, the population has increased by an order of magnitude, so the vulnerability of dwellings subjected to seismic shaking has increased. The protracted war and conflict in Afghanistan destroyed research organizations, and databases, and disturbed the data collection process, resulting in large data gaps. Recently, the USGS conducted unique investigations on the country's tectonic and earthquake disaster vulnerability mapping and initiated a historic earthquake record database (Ambraseys & Bilham, 2003; Dewey, 2006). World Bank prepared the Afghanistan disaster risk profile (e.g., World Bank, 2017); the United Nations Environmental Program (UNEP) founded the basis for environmental sciences, scientific studies, and conducted basic work on environmental disasters (e.g., Noori & Sherzad, 2020; Unep, 2003; UNEP, 2016).

The USGS database shows that the history of deadly earthquakes in Afghanistan returns thousands of years as shown in Figure 4. The catalog records more than 1300 earthquakes, and the history of the first earthquakes in the record returned to A.D. 734 to the present (Ambraseys & Bilham, 2003). The earliest documented earthquake occurred in A.D. 819 in the north of the country with an M_s7.4 estimated magnitude. This earthquake caused heavy damage and many casualties within villages more than 10 kilometers from the epicenter (Boyd et al., 2007b).

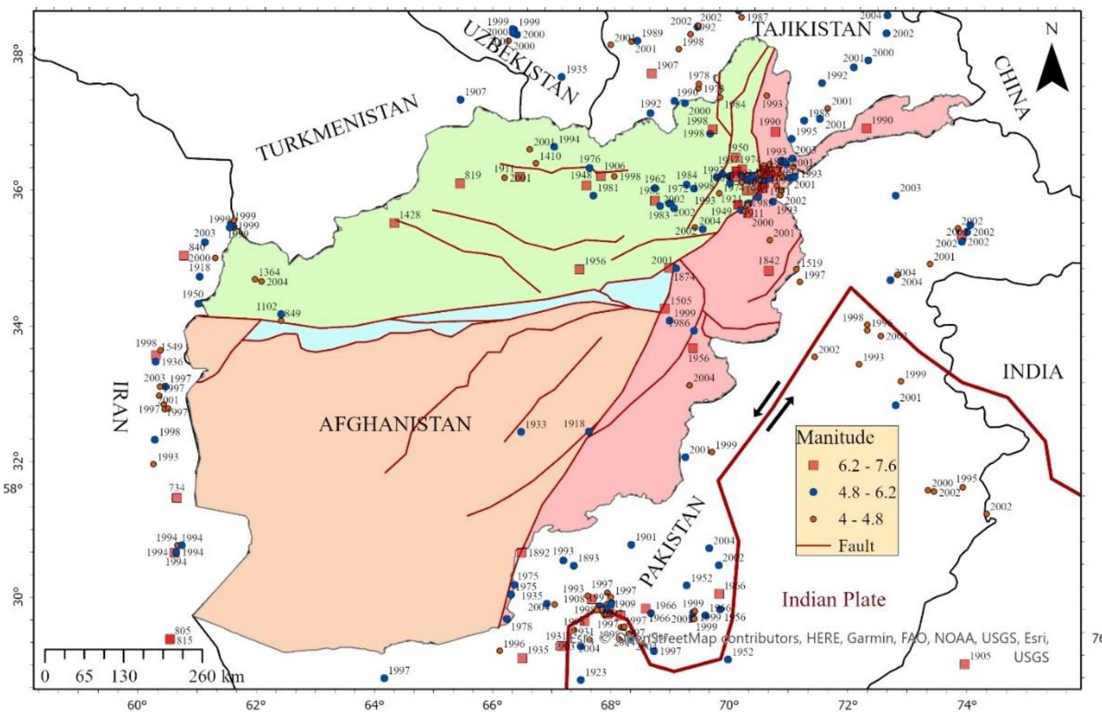

Figure 4: Historical earthquakes and their magnitudes and main tectonic zones and fault systems in Afghanistan. Modified from Wheeler et al. (2005) and Dewey et al. (2006)

Figure 5 shows the historic earthquake location, magnitude, and focal depth inside Afghanistan territories and surrounding regions. Earthquakes with focal depths between 0 and 70 are considered shallow earthquakes; between 70 and 300 km are intermediate-depth earthquakes, and deep-focus earthquakes are 300 to 700 km (Hammed et al., 2013). Intermediate-depth earthquakes represent deformation within the subducted lithosphere beneath the Eurasian Plate, rather than shallow plate interfaces between subducting and overriding tectonic plates. They typically cause less damage on the ground surface above their foci than similar-magnitude shallow-focus earthquakes. Still, large, intermediate-depth earthquakes may be felt at great distances from their epicenters. Occasional deep-focus earthquakes, greater than 300 km, occur beneath northeastern Afghanistan as well (USGS, 2015).

The Transpressional Boundary region is the most tectonically active region in Afghanistan as shown in Figure 3. It is home to the Hindukush deep seismic zone, where deep earthquakes with high magnitudes occur, while the country's central and western parts have remained seismically inactive. Also, the active, left-lateral, strike-slip Chaman fault is the fastest-moving fault in the southeastern region. For instance, in 1505, a segment of the Chaman fault near Kabul, Afghanistan, ruptured, causing widespread destruction. The M7.6 earthquake on 30 May 1935 in Quetta occurred in the Sulaiman Range and killed 30,000 civilians while affecting 60,000 others outside the Afghanistan territories. In Afghanistan, earthquakes of moderate magnitude 5.0-5.9 have been destructive and have caused fatalities. Therefore, the catalog presented here covers all earthquakes greater than a magnitude M5 event.

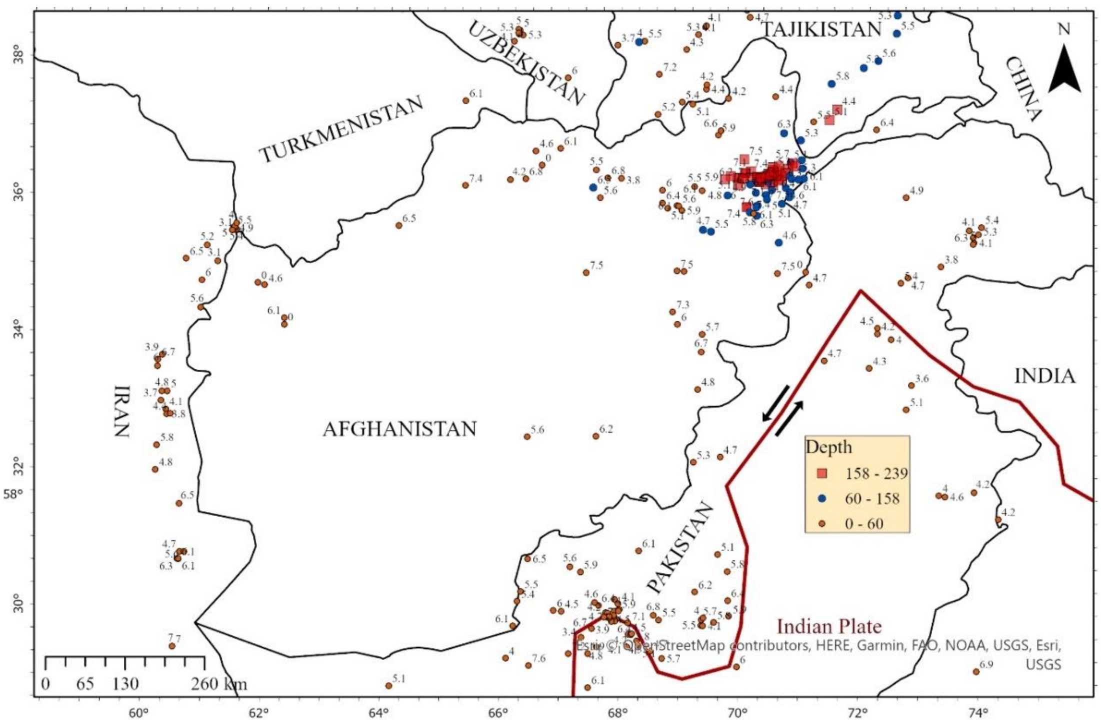

Figure 5: Historical earthquakes with their magnitudes and focus depths.

3.6 Recent Seismicity and Earthquakes in Afghanistan

Figure 6 shows Afghanistan and the surrounding vicinity's seismotectonic map with the recent earthquakes from 1990 to 2004. Many earthquakes were occurring during this period. A few most recent destructive are summarized below:

On June 21, 2022, an M_s6 magnitude earthquake with a 40-km deep epicenter struck near Khost province of Afghanistan (Fig. 6). The earthquake had 1150 casualties, 3,000 injured, and

10,000 homes damaged in Khost and Paktika provinces (USGS, 2022). The most affected districts in Khost were Sperah and Barmal, Nikeh, Ster Giyan, and the Ziruk area in Paktika. The earthquake caused a landslide in Khost killed 10 people and injured 25. Technically, the pattern of elastic waves that were radiated by the June 21, 2022, earthquake indicates the event was predominantly strike-slip faulting, either a left-lateral slip on a northeast-striking fault or a right-lateral slip on a northwest-striking fault (Kufner et al., 2023; USGS, 2022), and modeled regionally by Ruleman et al. (2007) and Ruleman (2011).

On October 26, 2015, a M_s7.5 magnitude earthquake occurred southwest of Jurm in Badakhshan province near the Hindukush region (Fig. 6). The earthquake happened due to reverse faulting at an intermediate depth, approximately 210 km below the Hindukush Range in northeastern Afghanistan (Hayes et al., 2016). Focal mechanism solutions indicate that rupture occurred on either a steep, south-dipping reverse fault or a shallow, north-dipping thrust fault.

Several M_s7 magnitude earthquakes were recorded in northern Afghanistan in the Hindukush region during the second half of the past century (Fig. 6). In March 2002, a M_s7.4 earthquake occurred just 20 km west of the October 26, 2015, event, with a similar depth and thrust fault orientation. The 2002 event caused over 150 fatalities and either damaged or destroyed over 400 houses in a seismogenic landslide. In December 1983 an M_s7.4 earthquake occurred at a similar depth just 8 km south of the October 26, 2015, event; the earthquake resulted in 26 fatalities, hundreds of injuries, and extensive infrastructural damage in the region. In October 2005 the deadliest earthquake hit the Kashmir region of Pakistan proximal to the eastern border of Afghanistan (Mulvey et al., 2008).

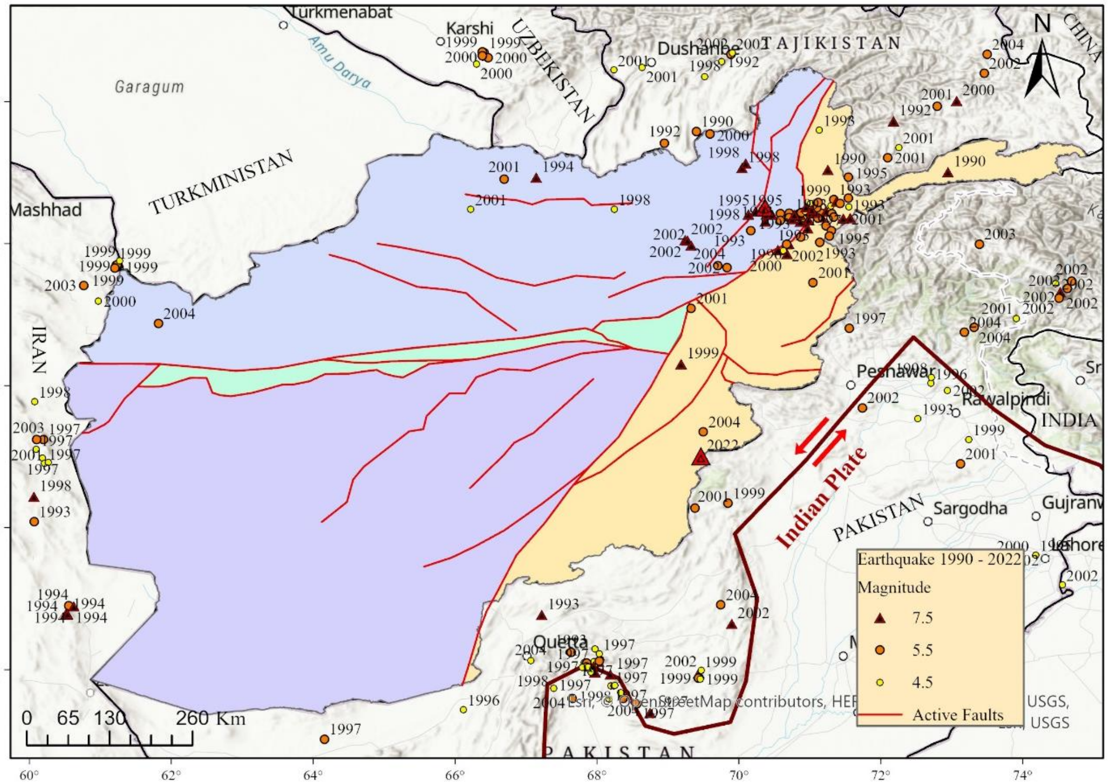

Figure 6: Recent earthquakes from 1990 – 2022 in Afghanistan.

In general, Afghanistan is in need of a proper disaster database and a regular national disaster management system, involving the mapping of tectonic structures and active faults, and interactive earthquake hazard maps. By using available national data with global geospatial data, we can begin to understand the extent of earthquake vulnerable regions and areas prone to higher impact earthquake risk disasters. Several worldwide historical earthquake databases provide useful information, such as seismological information, building damage, social losses (deaths, injuries, home-less and affected), and economic losses. Also, this information is essential in understanding global economic and social losses, and it has a profound impact on Gross Domestic Production (GDP) and Human Development Index (HDI) worldwide (Daniell et al., 2011). In this study, with the support of the available national and geospatial data, more accurate and current seismotectonic maps, earthquake hazard maps, and a historical earthquake database have been created. As Afghanistan is in a tectonically active region, future destructive earthquakes will occur proximal to population centers, most likely causing numerous casualties and massive damage. In order to reduce the risk of earthquake disasters in the country, a seismic hazards protection plan must be considered in all development plans; construction code must be applied in all urban, public, and private buildings, and contingency plans must be developed for the most vulnerable areas of high seismic hazard.

3.7 Earthquake Hazard Map of Afghanistan

Figure 7 depicts the Afghanistan earthquake hazard map divided into 6 seismic regions based on earthquake shaking intensity from low to high, light blue to red, respectively. The hazard map was first initiated by USGS (Boyd et al., 2007a). The region proximal to the Central Badakhshan, Darvaz, and Chaman faults, has experienced the highest shaking and most destruction historic earthquakes, shows the most geomorphic evidence for continuous tectonism (Ruleman, 2011; Ruleman et al., 2007), and thus defined on this map as the highest seismic hazard. The second highest seismic hazard exists in the dispersed region associated with these main fault zones as predictable shaking as major events along the faults resonate and attenuate throughout the region. In general, the transpressional plate boundary area from the Darvaz-Badakhshan fault system in the east to the North Afghan Platform in central-western Afghanistan are the most seismically active regions.

The region with the pink color is the third seismically active area (the area around the Hari Rud fault), in the western of the country, it is influenced by the Arabian fault and transtensional strike-slip faulting along the Iran-Afghanistan border (Austermann & Iaffaldano, 2013; Ezati et al., 2022; Walker & Jackson, 2004) The rest is a seismic calm area mostly covering the Accreted Terrans. The details of the seismic region are explained in the legend on the right side of Figure 7.

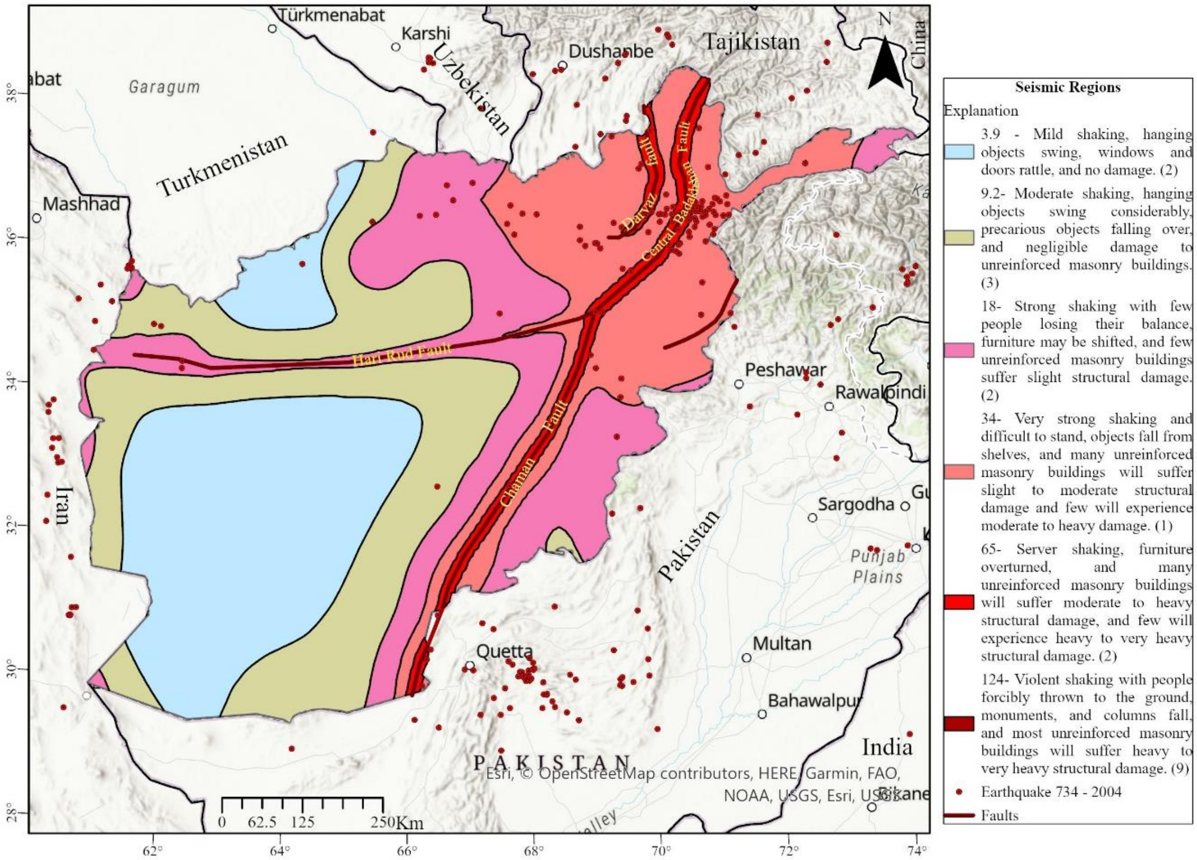

Figure 7: Earthquake hazard map of Afghanistan with seismic regions defined on the right inset map unit list (modified after Boyd et al., 2007).

3.8 Socioeconomic and Environmental Vulnerability to Earthquakes in Afghanistan

More than four decades of war and conflict in Afghanistan have killed millions, forced millions to flee their homes, and destroyed the country's infrastructure and environment (Oxfam, 2009; Price, 2019). This condition kept the country away from socioeconomic development and exacerbated the natural disaster vulnerability (Peters, 2021b; Přívara & Přívarová, 2019). In addition, climate change has deeply affected natural resources, especially water and agriculture (Mihran, 2011). The combined effects of man-made and natural disasters put the country in extreme poverty, and the HDI is at its lowest level. About 97% of the population was below the poverty line in 2021 (Clayton Thomas, 2021; UNDP, 2021). Vulnerability is increasing around disaster-prone areas due to increasing population density along with a lack of technical information for proper disaster management. Ultimately, this is due to a lack of stable and responsible leadership in the country.

The population distribution between urban and rural areas is quite large. With a total estimated population of 32.9 million, about 23.4 million live in rural areas 8 million in urban areas, and 1.5 million nomads (NSIA, 2021). Most of the earthquake vulnerable areas are rural. During the GoIRA, GDP was exceptionally high, and life standards and livelihood were improved well. GDP was $20.14 billion in 2020 (IMF, 2023), despite earthquake disasters having a profound impact on the economy, lives, and livelihoods of people in Afghanistan. Destructive earthquakes have been known in Afghanistan for over four millennia (Shroder, 2014). Since 1990, 355 documented low and high-magnitude earthquakes have caused huge losses to resources and infrastructure (UNDRR, 2020). The estimated GDP value of assets decreases when high-magnitude earthquakes occur (World Bank, 2018). However, earthquake disaster risk management is absent in Afghanistan. The country will reach socioeconomic and environmental sustainability when proper disaster management is conducted through extensively available natural solutions, land use management, construction code application, and relocation of the vulnerable population from disaster-prone areas. These are essential tools to reduce vulnerability and reliance on international aid in disaster response and will result in poverty reduction (Mead, 2022). Peacebuilding and political stability are a prerequisite for sustainable development in Afghanistan. As of June 22, 2022, the earthquake in Khost and Paktiya provinces lacked a legitimate and responsible government. The poor presence of relief organizations, insecurity, and access to the harsh terrain result in a low response. In addition, the earthquake disaster was already exacerbated by the preceding flood and drought, which led to reduced pastureland, water shortages, food insecurity, economic degradation, land degradation, and internal displacement in Afghanistan.

3.9 Unstandardized Construction

From ancient times people in Afghanistan have been living around disaster-prone areas. People believe that the will of God cause natural disasters due to the evil deeds of humans, making approaches to mitigate disaster risk seem impossible. People constructed houses on steep slope areas prone to landslides and avalanches. Many houses are built from mud, masonry, and bricks, and RCC (Reinforced Cement Concrete), is the modern construction in Afghanistan. Strong shaking earthquakes destroy mostly unreinforced buildings constructed from mud, brick, and masonry increasing casualties (Lang et al., 2018). Improved construction standards and techniques supplied by scientific seismic hazard estimation could significantly reduce the loss of life and properties. The variety of destructive and deadly hazards associated with earthquakes poses a real threat to reconstruction efforts and the economic growth of Afghanistan. Boyd and others developed a model built on historical earthquake records and the current tectonic environment to predict the strength of ground shaking in future earthquakes (Boyd et al., 2007b). Therefore, it is essential to efficiently identify buildings' vulnerability to ground shaking to reduce construction failure and avoid losses during earthquakes by retrofitting the constructions. Haziq and Kiyotaka investigated building codes for sustainable and resilient structures (Haziq & Kiyotaka, 2017). Construction is generally based on the availability of materials and equipment in Afghanistan due to a lack of disaster vulnerability awareness and low economic conditions. Most of the buildings follow the traditional methods of construction without considering building codes and earthquake reinforcement. Lang and others defined 29 building typologies in Central and South Asia. According to their classifications, the standard building types in Afghanistan's suburban and urban centers are constructed from burnt clay brick masonry, concrete block masonry walls, and Reinforced Concrete (RC) buildings, regularly observed in the south-central and western cities. Building types dominate rural Afghanistan from stone masonry walls, mud (adobe) walls, and load-bearing timber frames. Most building typologies are vulnerable to earthquake shocks (Lang et al., 2018). GoIRA approved the building code in 2012 to measure construction sustainability (ANSA, 2012). Recently, there have been promising improvements in public and private buildings. However, most facilities still ignore building codes not considered in construction which susceptible buildings to earthquake shocks.

3.10 Earthquake Disaster Risk Reduction Measures

Over the past two decades security was the focus and main challenge for the GoIRA and that covered more than 50 percent of the national budget (GoIRA, 1390). However, some disaster management activities were conducted with financial and technical support from donors. World Bank, UN organizations, and relevant international NGOs worked on developing DRM systems and mainstreamed DRR in the development process (World Bank, 2018). GoIRA structured the DRM and DRR in the national development strategy (GoIRA, 2013, 2021). Based on the number of policies and plans developed in the framework of DRM, DRR remained in the draft (ANDMA, 2011). Disaster risk management focus was on response and recovery (UNDRR, 2020). Disaster management must be collaborative and multi-discipline, carried out before and after a natural disaster to mitigate the risks of the disaster. A cycle of five interconnected processes, such as 1) Mitigation and Control, 2) Preparedness, 3) Disaster Inducing, 4) Response, and 5) Recovery (Chaudhary & Piracha, 2021; Yu et al., 2018). The first step in managing and reducing the risk of natural disasters covers all possible mitigation and control measures. If the disaster progresses, preparedness should be considered to leave the area exposed to disaster risks. The response is immediately after the disaster, and the recovery is a longer process after emergency management. Figure 8 Shows the disaster management cycle.

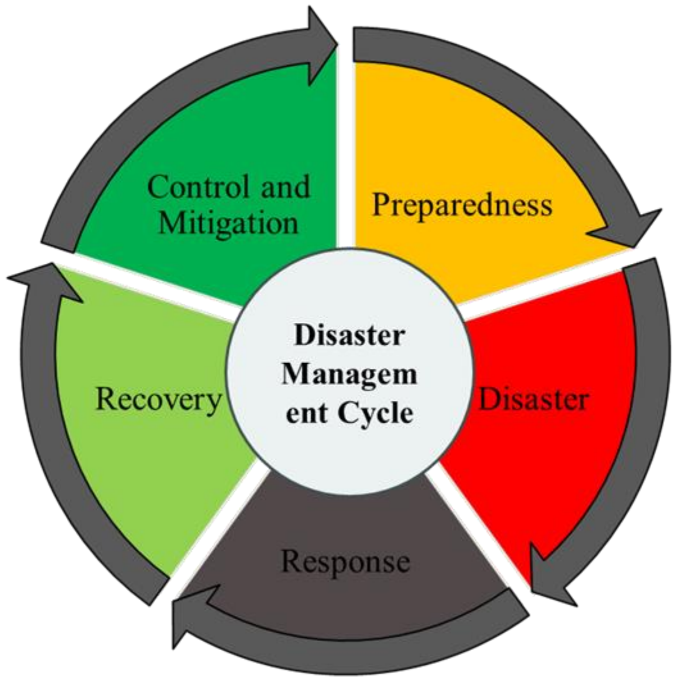

Figure 8: Disaster management cycle.

The earthquake disaster risk management framework has several engineering and soft managerial measures. Main engineering measures included 1) mapping the vulnerability and designing construction and building codes based on the seismic assessment map of the area. 2) Applying building codes on private and public buildings with required reinforcement to reduce vulnerability. 3) Identifying a seismically calm area to relocate the vulnerable population. 4) Diverging stream flow from across active geological faults and earthquake-prone areas because of blockage of a stream after earthquake shaking. The leading soft management measures include 1) Geological investigation that provides basic information about the area's geological structure, including geological formations, bedrocks, and sedimentation depths over the bedrocks. 2) Tectonic structure and geological faults in and around the area. 3) information about earthquake hazards, risks, vulnerability, and history of earthquakes in and around the region. 4) Public awareness about disaster vulnerability, protection, and emergency drills are integral to disaster management.

The above-mentioned measures are essential for earthquake disaster management in Afghanistan. Some initial steps are being taken on both engineering and soft-measure aspects of disaster management in the country. Initial information about the tectonic setting, seismic zones, earthquake database, and initial earthquake hazards map including initial disaster risk management framework exists. Few studies have been conducted on the construction code of Afghanistan. This information is essential as initial steps toward the earthquake DRR and its founding basis for earthquake disaster and risk management investigations. For urgent measures on earthquake risk management and response planning, the hazard map is essential for understanding the vulnerable area, scope, and level of seismic hazard for various parts of the country (Fig. 7). Also, this type of assessment is an essential source of information for engineers to increase safety and resilience against strong earthquakes in the design of critical facilities such as power plants, dams, pipelines, and major roads.

4 Conclusions and Recommendations

Afghanistan is in a tectonically active region and is highly vulnerable to destructive earthquake hazards. Chaman, Hari Rud, Central Badakhshan, and Darvaz are active geological faults in Afghanistan. Regions around these faults have been identified and characterized as seismically active. All the regions have experienced historic destructive earthquakes, leaving most places exposed to earthquake hazards.

Most of the earthquake vulnerability in Afghanistan is due to the high numbers of inhabitants within these earthquake-prone areas. Additionally, poverty, and a lack of political stability, security, disaster management plans and preparedness, and public service contribute to the absence of humanitarian support to civilians during natural disasters. Decades of conflict and instability have undermined the country's coping mechanism and protective capacity. This increases the likelihood that hazard events become disasters with significant humanitarian and economic consequences. While natural hazards and tragedies do not necessarily cause conflict, natural disasters can exacerbate the challenges people already face in fragile states, create new risks, and stress an already weakened governance system.

This study proposes earthquake disaster risk mitigation, reducing the exposed population's vulnerability through disaster management, and empowering the local community and awareness program. Seismic risk mitigation measures should be taken to minimize seismic risk and losses in earthquake disaster-prone areas, as shown in the earthquake hazard map (Fig. 7). It is noteworthy that disaster management is an essential step toward the sustainable development of the country. Finally, this study ends with the following recommendations for disaster managers, planners, and urban policymakers to facilitate a reasonable evaluation of the current seismic risk state in the country and prepare for the future possible earthquake DRR.

- Preparing a comprehensive earthquake hazard map based on further scientific investigations. Interactive hazard maps should be prepared to contain all active faults crossing the specific regions, vulnerable regions, vulnerable populations, and properties, including earthquake calm places for relocation.

- Establishing a Disaster Management System (DMS) consisting of all five processes (Mitigation, Control, Preparedness, Response, and Recovery). A qualified team is needed for quality management. Capacity building and mobilization of the management team is required. The team should have full access to all the national and international online databases, GIS maps, analysis skills, and research capabilities. The team should proceed with any management process based on their investigation results. They should have the support of relevant national agencies and international organizations. In the current context of Afghanistan, DMS with high technical mobilization and huge financial backing is difficult. Therefore, a DMS with a national context, community base, and possible international support is working, and it is essential for earthquake vulnerability reduction.

- Public Awareness is critical; the disaster management team can lead outreach objectives with relevant organizations. Public awareness is essential for vulnerable communities to construct resilient buildings using locally available materials and construction techniques. Informing the most exposed population to earthquake disasters is at the forefront, with voluntary relocation and assistance an option for exposed inhabitants.

- Establishing a historic and contemporary earthquake database and catalog, with the installation of seismographs and Early Warning Systems (EWS). USGS already established a database with historical records, it should be updated with the new data and must be enriched with interactive online maps. The existing unoperated seismograph network? currently within Afghanistan should be updated, and others should be installed in appropriate places for a complete seismic record. Possibly, an emplacement of a locally available EWS is needed for disaster prediction, emergency management, relocation, and response-related information.

- Creating a national context construction code for government, public, local, and private buildings, including masonry and mud buildings. Assisting and supporting poor communities on the construction code application.

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Open Research

This study did not use new field data, models, computer codes, or new software. Most of the data in the study were used from the available sources that were all referenced. Main earthquake data, such as geological faults, seismic zones, and earthquake hazard maps including a historical earthquake database were used from the United States Geological Survey (USGS) (Bilham, 2019; Dewey, 2006; USGS, 2015, 2022; Wheeler et al., 2005). In this study, we used USGS earthquake databases (Dewey, 2006; USGS, 2023). Recent earthquakes were added to the existing USGS database and used as new information in this paper (USGS, 2015b, 2022). Some historical and recent earthquake records were used from Risklayer online database (Risklayer, 2023). The updated main geological faults crossed Afghanistan and connected with surrounding regions including plate boundaries are derived from the ArcGIS Global Earthquake Archive (ArcGIS, 2023; Bird, 2003). Finally, Afghanistan's tectonic settings, active faults, and seismic regions were digitized and mapped with the updated data using ArcGIS Pro (Esri, 2023). Also in this study, the earthquake hazard map from (Boyd et al., 2007) was modified, and historical databases updated with recent earthquakes were used (Ambraseys & Bilham, 2003; Dewey, 2006). Therefore, most of this study is prepared from previously published sources mentioned above and all the citation are listed below. All the data including PDF, websites and database have direct links to access.

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