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Application of Probabilistic Seismic Hazard Assessment for Earthquake Hazard: Case Study of Karachi City, Pakistan

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Abstract

In this study, we analyzed a thorough examination of seismic hazard assessment for Karachi city, with the aim of ensuring the construction of safe and sustainable buildings and structures. Karachi, being the largest city and an economic hub of Pakistan, serves as the focal point for this study. The study begins by assessing the potential danger posed by an earthquake resulting from tectonic activity in the area. To accomplish this, the region, which spans approximately a radius of 200 km, is divided into eight distinct seismic zones. The study incorporates ground motion prediction equations that are compatible with the seismotectonic environment of the study area. The resulting ground motions are determined by the peak horizontal ground acceleration and the 5% damped spectral acceleration (SA). The seismic activity in the study area is primarily characterized by small to moderate earthquakes, as indicated by recorded data. Based on the historical earthquake data, it has been observed that significant earthquakes with high magnitudes have taken place within a radius of approximately 200 km from Karachi, such as the Bhuj earthquake in 2001. The primary active tectonic features in the region include the Pab Fault, Kirthat Fault, Hab Fault, Jhimpir Fault, Surjan Fault, Ornach-Nal Fault, and Rann of Kutch Faults. In order to ensure the safe and sustainable seismic design of building structures in Karachi, it is advised to adhere to the recommended seismic design parameters. These parameters include a peak ground acceleration (PGA) of 0.19g and 0.33g, with a shear wave velocity (Vs30) of 750m/sec for foundation conditions. The return period for these parameters is determined based on the nature of the structures, with a value of 475 years for one set of parameters and 2,475 years for the other.

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1. Introduction

Pakistan exhibits extensive areas of moderate to high seismic activity, primarily caused by the collision of the Indo-Pak and Eurasian tectonic plates. Due to this collisional tectonics, great Himalayas and associated mountains formed in the northern Pakistan. The geographical region of Pakistan consists of a cohesive network of active seismotectonic features with regional scope. These features primarily consist of different types of active faults that are typically found in mountain ranges formed by tectonic collision. The northern region of Pakistan is situated in close proximity to the subduction contact zone where the Indian plate and the Eurasian plate meet (Ahmad et al., 2023, Rehman et al., 2023). The region encompassed by the Himalayas has consistently experienced moderate to large earthquakes, such as the Kangra earthquake in 1905, the Bihar-Nepal earthquake in 1934, and the Assam earthquake in 1897. These seismic events have significantly impacted the historical record. The western regions of Pakistan are situated along a transform boundary where two tectonic plates meet. This boundary is characterized by the movement of the Indian plate towards the north. This zone has been the source of numerous moderate to large earthquakes, such as the Mach earthquake in 1931 and the Quetta earthquake in 1935, both of which caused significant destruction. The study area in Southern Pakistan includes the Makran area, where the subduction zone of the Arabian plate beneath the Eurasian plate is located. This subduction zone was responsible for the Pasni earthquake in 1945, which resulted in significant destruction.

Pakistan, a South Asian country, exhibits susceptibility to a range of natural calamities. Over the past few decades, the country has encountered recurrent instances of floods, earthquakes, landslides, and tsunamis (Sajjad et al., 2014). Following the occurrence of the Kashmir earthquake in 2005, the Building Code of Pakistan (BCP) underwent revisions by esteemed scientists and prominent government institutions. Seismic precautions were implemented for the infrastructure, accompanied by the development of macrozonation maps that consider the ground as a uniformly leveled rock (MonaLisa et al., 2007). After considering the seismic vulnerability of the country, the subsequent task involved the development of surface ground motion maps for Pakistan, ranging from tehsil to city levels. The majority of seismic hazard assessment studies conducted in Pakistan focus on the regional scope (MonaLisa et al., 2007; Khan et al. 2018; Khaliq et al., 2019; Waseem et al., 2020; Khan et al., 2020; Rahman et al., 2021). Unfortunately, a few studies city or district-wise have been completed (Qadri et al. 2015 a,b; Khan et al. 2016; Qadri et al. 2018; Khaliq et al., 2019; Maqsoom et al. 2021; Younis et al., 2021; Shah et al. 2022; Qadri and Mirza 2023) and there is still a lot of scopes to work on such detail hazard assessment studies highlighting the seismic vulnerability at tehsil and district levels in Pakistan. The motivation to conduct the present research on Karachi city, located in a seismically active zone of the country, was provided. The primary aim of this study is to evaluate the seismic hazard that Karachi city faces. This will be achieved by creating an enhanced seismotectonic model and determining ground motion parameters.

Based on the latest available earthquake data, total hazard curve and response spectra is generated for (i- return period= 475 years and ii-return period= 2475 years). The purpose of this research is to provide essential information for the master planning of safe seismic design for future developments in Karachi city. Karachi is the most populous city in Pakistan and is characterized by the presence of high-rise buildings and structures. Therefore, ensuring sustainable development in the face of earthquake hazards is a mandatory requirement for the city.

2. Geological Settings

Karachi is situated in the southern region of the Kirthar fold-and-thrust belt (figure 1). This belt spans approximately 50 to 70 kilometers in width and stretches for about 380 kilometers in a north-south direction. It is a folded zone that extends between Quetta and Karachi. The sediment composition primarily consists of Oligocene and Neogene sediments, specifically marine terrigenous and calcareous terrigenous deposits. A trough refers to a geographical feature characterized by a low-lying area or depression located between hills. This formation occurs as a result of the rim of tectonic plates. The study area is located between the southwestern corner of Karachi, extending through the Pub and Kirthar Ranges. The geological formations present in the area consist of the Nari and Gaj formations, which belong to the Oligocene and Miocene epochs, respectively. The Khirthar formation of the Eocene epoch is also found in the northwestern region.

The formations extending from the western coast of Karachi to northern Sindh are consistently exposed. The geological process in the southwest region results in the creation of a sequence of asymmetrical folds and anticlines. The formations are composed of shale, limestone, and sandstones, along with a small amount of weathered material from the surrounding older terrain.

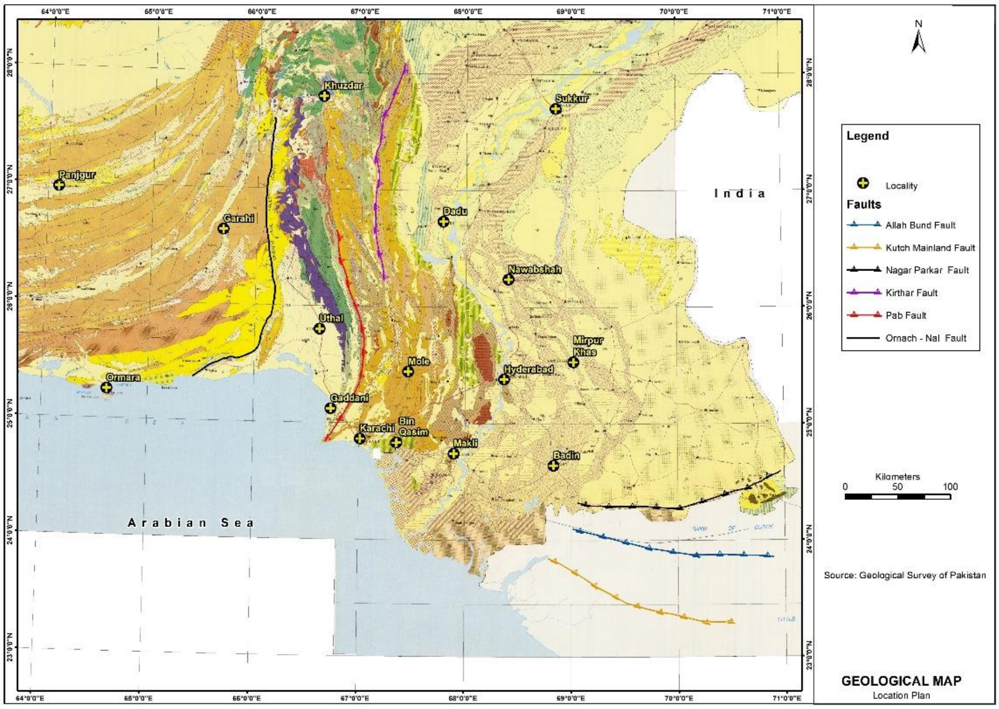

Fig. 1. General Geological Map of Karachi and Surrounding (Modified from GSP Map).

3. Probabilistic Seismic Hazard Analysis (PSHA)

Probabilistic Seismic Hazard Analysis (PSHA), which forms the fundamental basis for many modern earthquake design code provisions and practices for public safety by safe structural design. PSHA aims to produce an explicit description of the distribution of future shaking that may occur at a site. The objective of probabilistic seismic hazard analysis (PSHA) is to quantitatively assess the likelihood (or probability) of surpassing different levels of ground motion at a specific location (or a collection of locations) considering all potential earthquakes. The flowchart depicted in figure 2 illustrates the overall process for conducting a Probabilistic Seismic Hazard Analysis (PSHA) using the methodologies proposed by Cornell (1968) and McGuire (1976). The PSHA study encompasses several notable features:

a) Reliable earthquake catalogue
b) Seismotectonic model
c) Ground-Motion Prediction Equations (GMPEs)

Flowchart gives the understanding about the overall process of PSHA. From figure 2, we can easily understand that what the mandatory input data/parameters are required to use them in PSHA process and ultimately to achieve the target/goals i.e. PGA, Total Hazard Curve/Response Spectra etc.

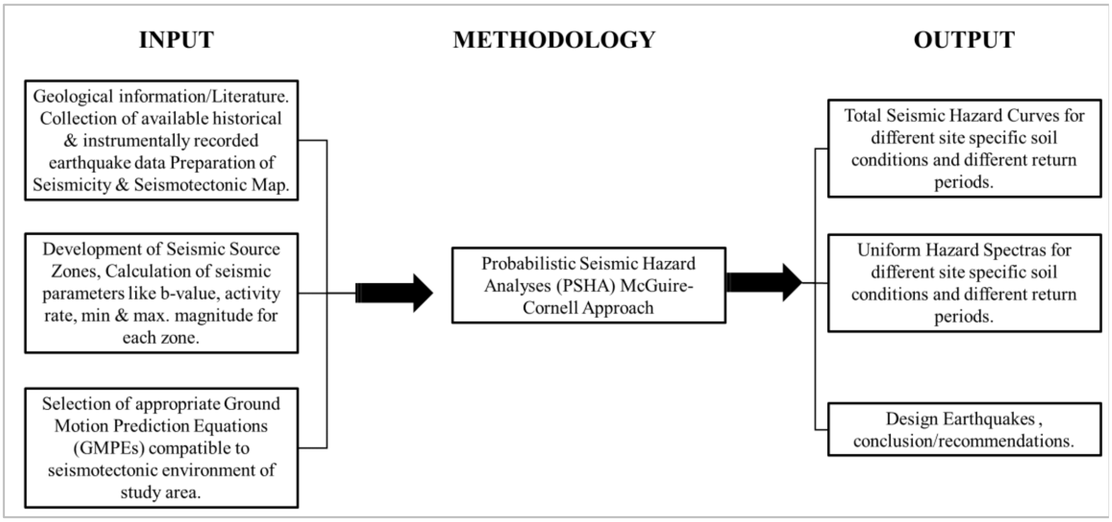

Fig. 2. General Flow Chart for Current study of PSHA.

3.1 Composite earthquake catalogue compilation

The probabilistic hazard assessment method requires comprehensive datasets of the earthquake history in the region being studied in order to conduct a thorough seismic hazard assessment. The initial phase in seismic hazard assessments involves the development of an earthquake catalogue. This catalogue serves the purpose of identifying seismic sources and establishing the recurrence patterns for these sources. The instrumental record is obtained from various sources, including both local and global networks such as the National Earthquake Information Centre (NEIC), Pakistan Meteorological Division (PMD), and International Seismological Centre (ISC), among others. The collection of historical data is derived from publicly available articles (e.g. Oldham, 1883; Quittmeyer and Jacob, 1979; Ambraseys and Bilham, 2003; Ambraseys and Bilham, 2014). The earthquake catalogue utilized in the present research encompasses both historical and instrumental seismicity data, encompassing a radius of 200 km around the study area. Based on the pre-instrumental and instrumental record, it can be determined that the region exhibits seismic activity and primarily experiences low to moderate magnitude seismic events. A total of 1646 earthquake events, ranging from magnitude 3.0 to 8.3 Mw, have been chosen for the purpose of constructing the earthquake catalogue. These events span from the present time until December 2022 (figure 3).

During the design process of the earthquake catalogue, the removal of identical seismic events from multiple sources was carried out based on the incident times and epicenters. The earthquake catalogue employed various magnitude types, such as body waves and surface waves, which were subsequently standardized to a unified magnitude Mw. This standardization process was achieved by applying attenuation relations proposed by Scordilis (2006), Idriss (1985), Ambraseys & Bommer (1990) and Ambrayseys & Bilham (2003). The seismicity map of the study area is depicted in figure 4.

Figure 5 displays a seismotectonic map, which illustrates the seismic activity and the faults in the specified area. The subsequent procedure involves declustering the dependent events, namely foreshocks and aftershocks, utilizing the methodology proposed by Gardner and Knopoff (1974). This process effectively eliminated a total of 459 dependent events from the dataset. The provided maps is a comprehensive base map that displays various Seismotectonic details essential for conducting seismic hazard and risk studies. It encompasses information on geology, rock types, fault orientations (including their respective lengths), lineaments (also with lengths), and seismic earthquake events. This map serves as a fundamental resource for analyzing and assessing seismic hazards and risks.

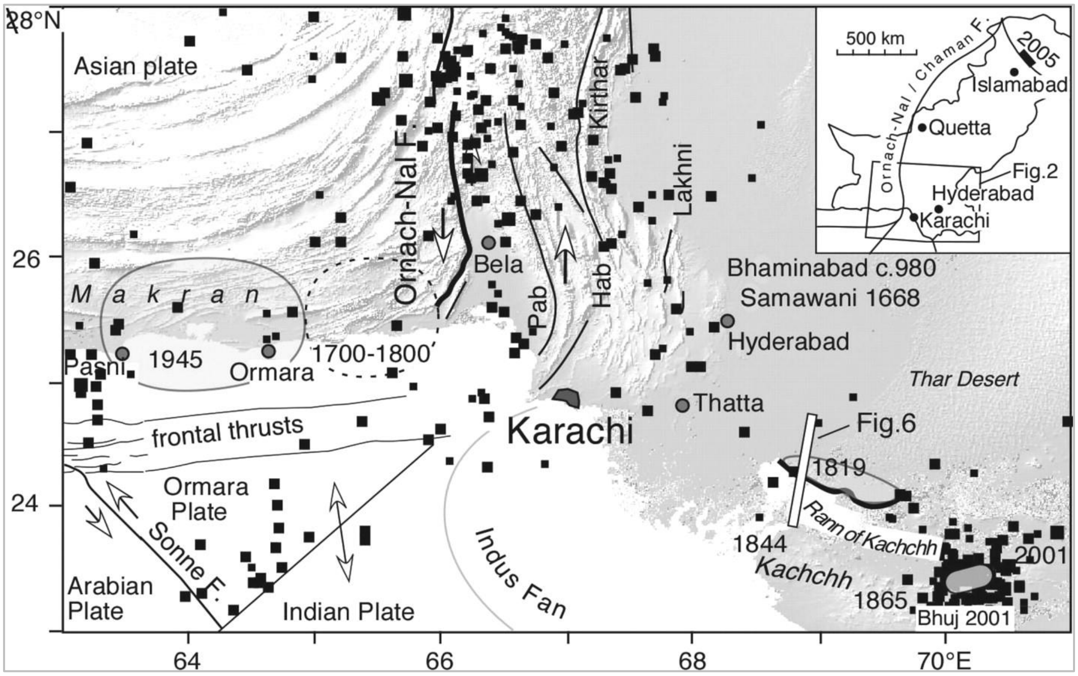

Fig. 3. Location of active faults, seismicity and dated historical earthquakes (Reproduced from Bilham et al. 2007).

3.2 Seismotectonic Modelling

The term "seismotectonics" is commonly used to refer to the investigation of earthquake occurrence and characteristics, as well as its correlation with the tectonics of a specific area and the broader dynamics of the Earth's crust. The utilization of tectonic and seismic data from the region aids in the formulation of concepts pertaining to the seismotectonic environment of Karachi city. The identification of the prominent seismogenic features that are responsible for seismic hazards is for Karachi a crucial aspect of understanding and mitigating these hazards:

- Pab Fault, Hab Fault, Jhimpir Fault, Surjan Fault and,
- Kirthar Fault
- Ornach-Nal Fault

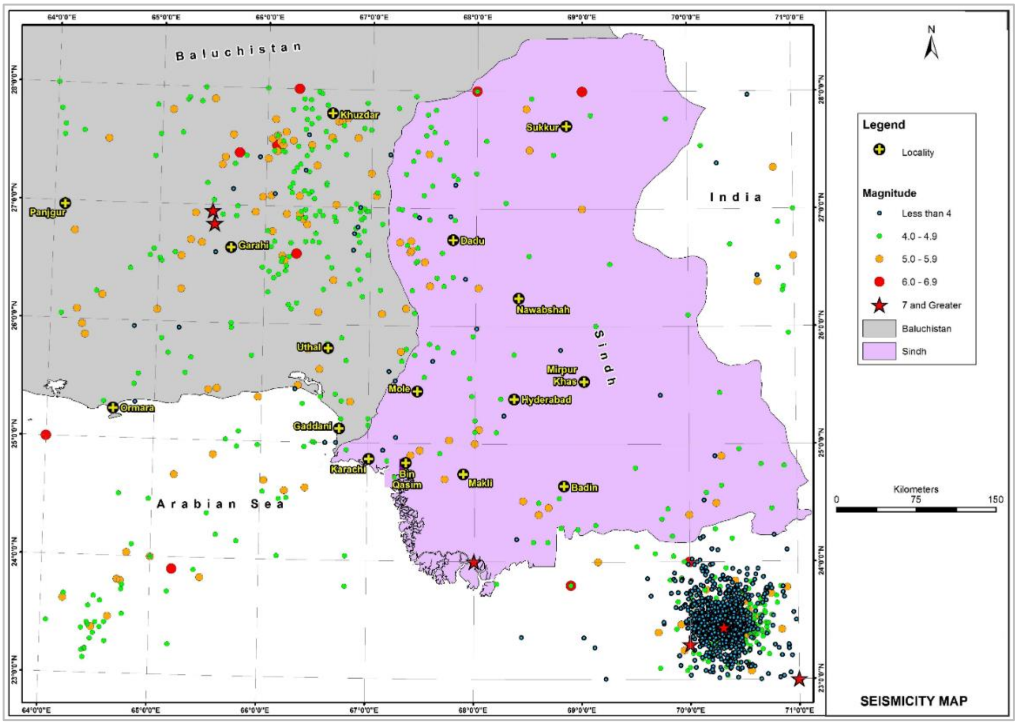

Fig. 4. Seismicity map of Karachi and surrounding region.

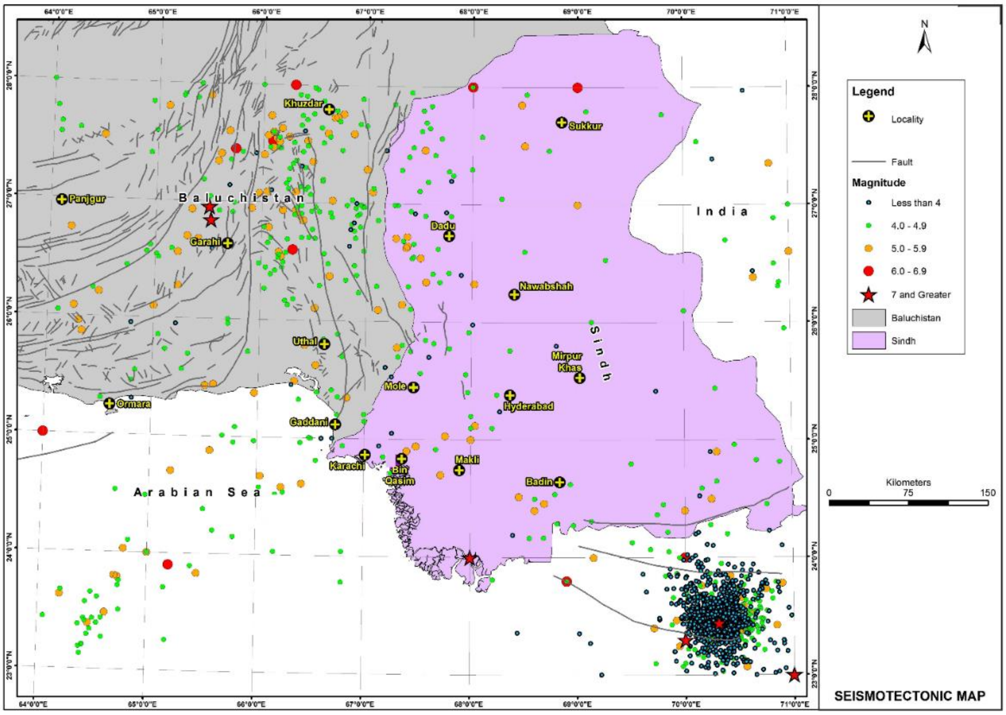

Fig. 5. Seismotectonic map of Karachi and surrounding region.

The presence of these seismogenic features suggests that the region is primarily characterized by thrust faulting, with some occurrence of strike-slip faulting as well. The faults are classified as active based on the seismic activity they are associated with. Figure 5 displays a seismotectonic map of the study region, illustrating the seismic activity associated with the tectonic characteristics.

The analysis relies on a source model that utilizes area sources due to the lack of dense instrumentation in Pakistan, which poses challenges for monitoring seismic activity from a specific fault. The characterization of seismic sources is widely recognized as a crucial step in the process of assessing seismic hazards. The region surrounding Karachi city, with a radius of approximately 200 km, is divided into eight area source zones. These zones, as depicted in figure 6, share similar seismotectonic characteristics. A magnitude-frequency curve, as depicted in figure 7, is constructed by segregating earthquakes that occur in each zone from the overall composite catalogue. Reliable earthquake catalogues, seismotectonic models, and Ground-Motion Prediction Equations (GMPEs) play a vital role in a PSHA study to overcome uncertainties and to meet the realistic seismic design parameters.

Based on the seismicity and tectonic behaviour, an updated seismotectonic model (consist eight seismic area source zones) of study area, around 200 km radius of Karachi city, has been developed for the current study. The following each zone, as depicted in figure 6, share similar seismotectonic characteristics:

Indus Platform

The Indus Platform zone defined as a separate zone based on its relatively stable tectonic setting and have dispersed low to moderate seismicity. The maximum magnitude of this zone is taken as Mw 6.0.

Thar

This zone comprises of entirely different seismoteconic setup. The Thar Desert is one of the significant geologic and geomorphic features of Pakistan located along its eastern borders. It extends beyond the international border into India. This zone has relatively low to moderate level of seismicity. The maximum magnitude of this zone is taken as Mw 5.8.

Rann Kuch

This zone has been marked by enclosing the areas of EW Fault System i.e. Allah Band Fault, Nagar Parkar Fault and Kachch Mainland Fault. The sense of slip is reverse with east-west rupture strike. This seismotectonic zone has also been marked based on the distribution and higher frequency of seismicity as compared to northward Thar and Indus Platform seismic zones. The maximum magnitude of this zone is taken as Mw 8.3.

Kirthar Pab

This zone has been constituted by coalescing the Kirthar, Pab, Khude, Mor Ranges and Karachi Arc, which collectively represent southern fold and thrust belt of Pakistan along the western boundary of Indian Plate. Pab and Kirthar faults are associated to this zone. This Kirthar-Pab seismic zone has been marked because of similarities of major compressional and transpressional tectonics and associated seismicity which are markedly different from the west ward Chaman seismic zone. The maximum magnitude of this zone is taken as Mw 6.4.

Chaman

This zone mainly comprises the seismotectonic setup of Chaman Fault System and Ornach Fault System, which represents the western margin of the Indian Plate. This seismoteconic zone has been formed as a separate zone due to its transpressional tectonic environment marking transform plate boundary as compared to the western and eastern bounding zones with mainly compressional structures. The maximum magnitude of this zone is taken as Mw 7.7.

Makran

The east west trending Makran Subduction Zone being an active plate boundary between subducting Arabian Plate beneath Eurasian Plate. This seismotectonic zone has been demarcated based on its EW subduction tectonic setup. The maximum magnitude of this zone is taken as Mw 8.2.

Murray Ridges

The Murray Ridges is a long NE trending seismogenic source which is marked by strike slip and normal faulting. These faults are of limited extent and collectively constitute the ridge. This zone has entirely different seismotectonic setting i.e. the Indian-Arabian plate boundary terminates at a triple junction located southwest of Karachi. This zone is differentiated from the westward-southwest Makran Subduction Zone due to its oblique extension and capability to generate moderate shallow depth earthquakes. The maximum magnitude of this zone is taken as Mw 8.2.

Chahgai

Chaghi magmatic arc is one of the most important tectonic zones of the country. It is an east west trending, arcuate, south verging magmatic belt. This zone has different seismotectonic setup as compared to its eastward Chaman Zone and southward Makran Zone. The maximum magnitude of this zone is taken as Mw 7.0.

3.3 Modelling Earthquake Recurrence

The determination of the standard annual exceedance rate for various magnitudes of seismic events within a specific time frame is accomplished through the application of the Gutenberg-Richter Law. The plot in figure 7 displays the relationship between the magnitude 'm' and the aggregate of earthquakes in a given year 'Nc' for each source area. The study area encompasses various zones, namely Chagai zone, Chaman Fault zone, Indus platform zone, Kirthar zone, Makran zone, Murray Ridges zone, Rann Kuch zone, and Thar zone. The utilization of this plot facilitates the establishment of a recurrence relation, similar to the Richter equation. The coefficients 'a' and 'b' in the Richter equation are determined through a least square linear regression analysis of the dataset. This analysis is performed up to the minimum magnitude threshold, beyond which the seismic record is considered comprehensive. The seismic parameters obtained through computation at this stage are presented in table 1.

The procedure focuses around dividing the analyzed region into distinct fundamental zones, also referred to as seismic sources. It involves determining the probability of occurrence for one or more seismic events of a specific magnitude within a designated zone, all within a specified time frame. In our analysis, we consider the potential occurrence of earthquakes of varying magnitudes and the attenuation of ground motion to assess the likelihood of different levels of ground motion exceeding certain thresholds at a specific location. The cumulative effect of various sources is then utilized to assess the overall hazard by estimating the annual frequency of ground motion occurrences across the studied region.

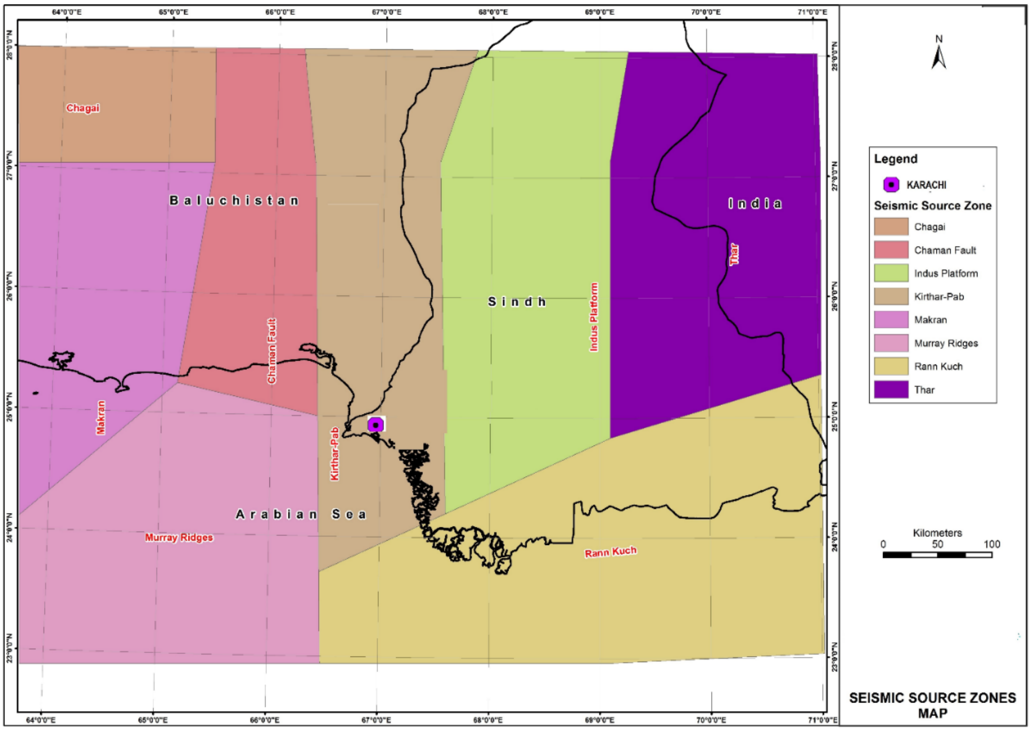

Fig. 6. The Seismic Source Zones Map displays different formations represented by colors, as indicated in the legend.

Table 1. Area source parameters for probabilistic analysis.

Zone No.	Seismic Source Zone	No. of Earthquakes above Min. Magnitude	Minimum Magnitude (Mw)	Activity Rate /Year	b-Value	Maximum Magnitude (Mw)
1	Indus Platform	35	4.2	0.565	1.21	6
2	Kirthar-Pab	118	4.3	1.903	1.36	6.4
3	Chaman	85	4.1	1.370	0.60	7.7
4	Makran	27	4.4	0.435	0.98	8.2
5	Murray Ridges	61	4.2	0.983	0.91	8.2
6	Thar	15	4.2	0.242	0.70	5.8
7	Chahgai	14	4.3	0.225	0.81	7
8	Rann Kuch	95	4.0	1.530	0.80	8.3

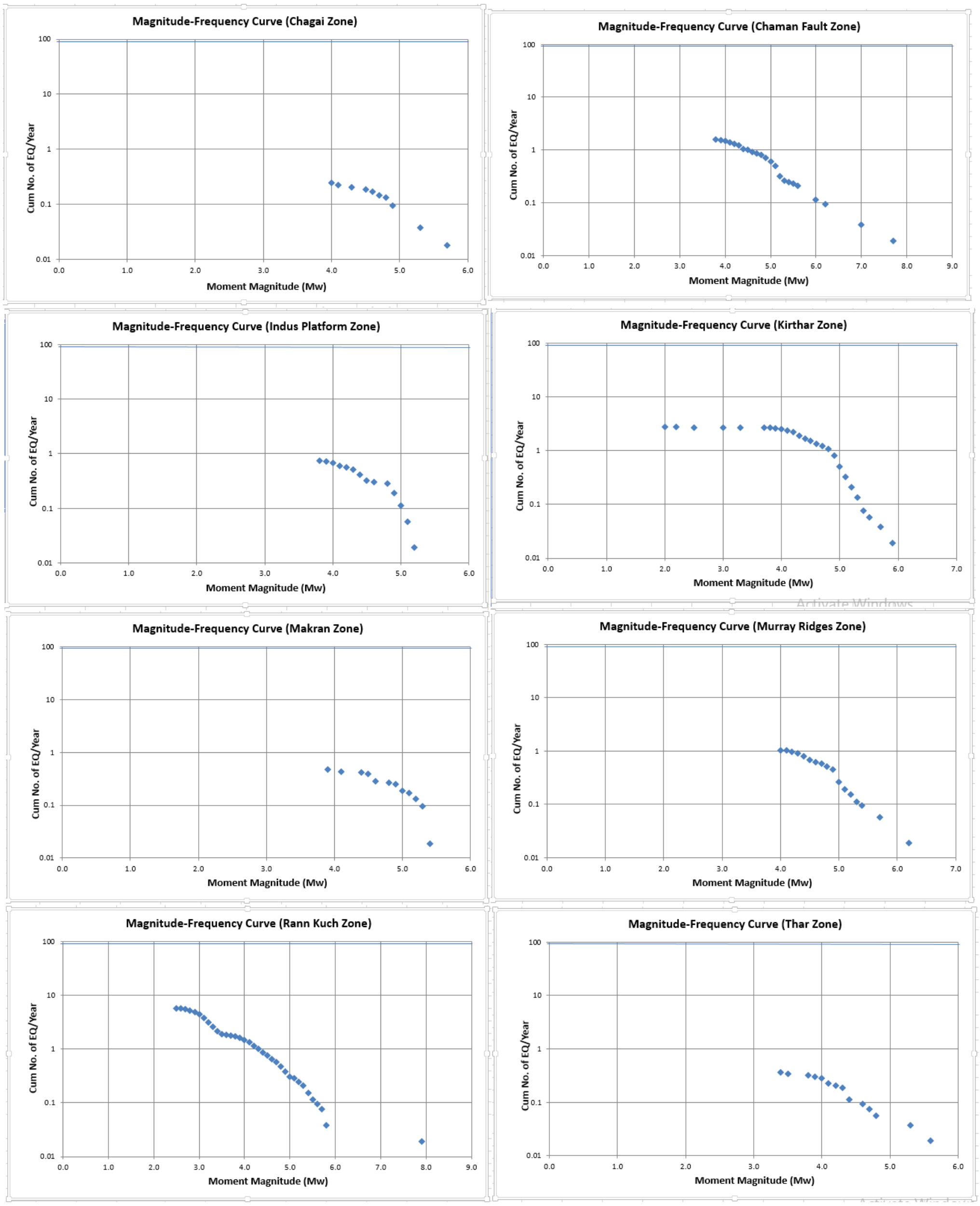

Fig. 7. Magnitude frequency curves of Chagai zone, chaman fault zone, Indus platform zone, Kirthar zone, Makran zone, Murray Ridges zone, Rann Kuch zone, and Thar zone.

3.4 Ground Motion Prediction Equations (GMPE)

The Ground Motion Parameter Estimation (GMPE) is a statistical model utilized for the calculation of various ground motion parameters, including Peak Ground Acceleration (PGA) and Spectral Acceleration, within a designated study area. Local ground motion prediction equations (GMPEs) are not accessible due to a lack of sufficient local strong motion data. As a result, the Next Generation Attenuation (NGA) equations were employed for Probabilistic Seismic Hazard Analysis (PSHA). These equations, developed by Abrahamson et al. (2014), Boore et al. (2014), and Campbell & Bozorgnia (2014) under the Pacific Earthquake Engineering Research (PEER) Centre, are specifically designed to be compatible with the seismotectonic characteristics of the study area. It is worth noting that these equations are applicable to regions with active tectonic activity and shallow crustal faulting worldwide. The equations proposed by Bommer et al. (2010) are suggested for use in NGA. The equation utilized for the intermediate/deep earthquake zone of the Makran Subduction Zone was derived from BCHydro (2012) and USGS (2014). This equation is specifically designed for subduction zones. Each equation was assigned equal weightage. The analysis utilized the site foundation condition with a VS30 value of 750 m/sec. The probabilistic approach, initially developed by Cornell in 1968 and subsequently modified by various researchers, was employed to estimate the return period at multiple stages of the ground motion. The Probabilistic Seismic Hazard Analysis (PSHA) was performed using the advanced EZ-FRISK software, which was developed by FUGRO Consultants, USA.

4. Results and Discussion

The probabilistic hazard assessment method is employed to calculate Ground Motion Parameters, such as PGA (Peak Ground Acceleration) and g-values, at various return periods. The technical description of Ground Motion Parameters includes Total Hazard Curves and Response Spectra (refer to figure 8 and 9). Each type of soil profile has its own site-specific total hazard curves and response spectra. The presence of varying PGA/g-values for different soil profile types indicates that each soil profile exhibits distinct ground shaking behavior during an earthquake. As per practice adopted in national/international building codes, the soil profile type “SB” is used as foundation condition i.e. Vs30=750 m/sec, as one of the input parameters of PSHA for calculation of Peak Ground Acceleration (PGA). The same globally adopted practice is used in the current study. Hence, it is imperative for any building or proposed structures to be designed with careful consideration of the site-specific soil profile and corresponding ground motion parameters. The calculated ground motions have the potential to inform future master planning and facilitate the safe seismic design of potential or proposed future developments within the City.

The hazard curve pertains to the likelihood of surpassing a specific level of ground shaking or ground motion across various return periods, which are the inverses of the Annual Frequency of exceedance. The Uniform Hazard Spectra (figure 9) illustrates the average probabilistic ground motions at various return periods. This encompasses the PGA (reciprocal of Annual Frequency of exceedance). Using the ‘Total Hazard Curve + Response Spectra’, one could determine each ground motion’s annual probability of occurrence. Then, one could decide whether that corresponding probability is acceptable, as earthquake ground shaking could differ from site to site (Qadri and Mirza 2023). The ground motions for the study area were calculated for the average horizontal PGAs and response spectral acceleration (figures 8 and 9). The total hazard curves represent the peak ground acceleration at 0.01 periods. Ground motions are utilized by calculating them through Probabilistic Seismic Hazard Analysis (PSHA), which combines the Total Hazard Curve and Response Spectra.

The peak ground acceleration (PGA) values for the soil profile type "SB" have been determined to be 0.19 g and 0.33 g for return periods of 475 and 2475 years, respectively. The present study is of great importance to land use planners who are striving to mitigate seismic vulnerability resulting from unstable soils and proximity to fault lines. The current study has the potential to contribute to the microzonation of the study area by considering the proximity of active faults near Karachi city and the thickness of loose sediments.

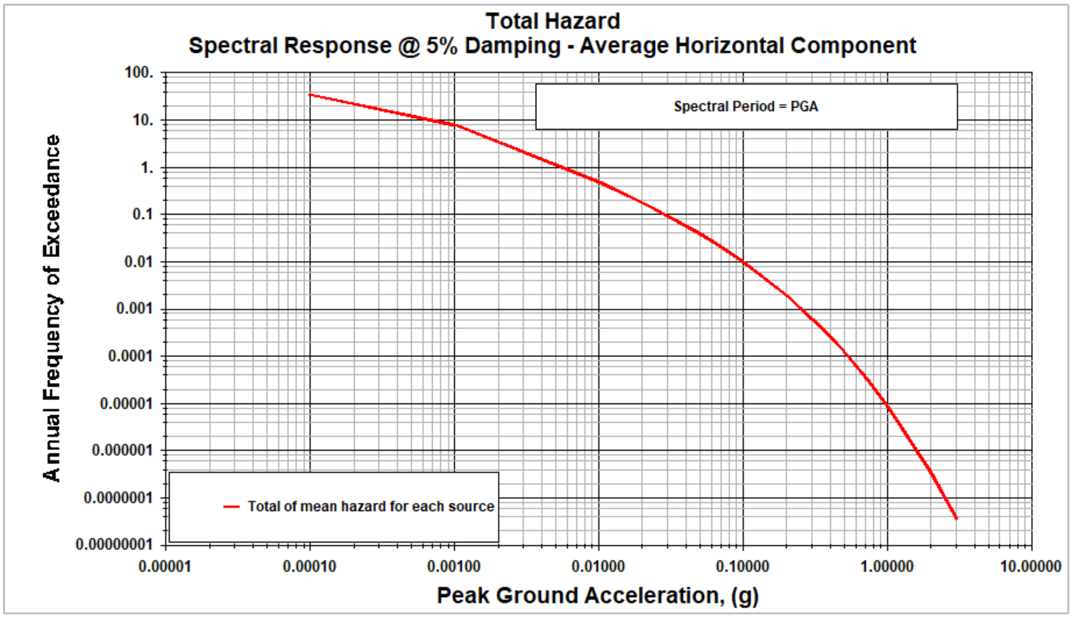

Fig. 8. Total hazard curve, the spectral response of 5% damping the average horizontal component.

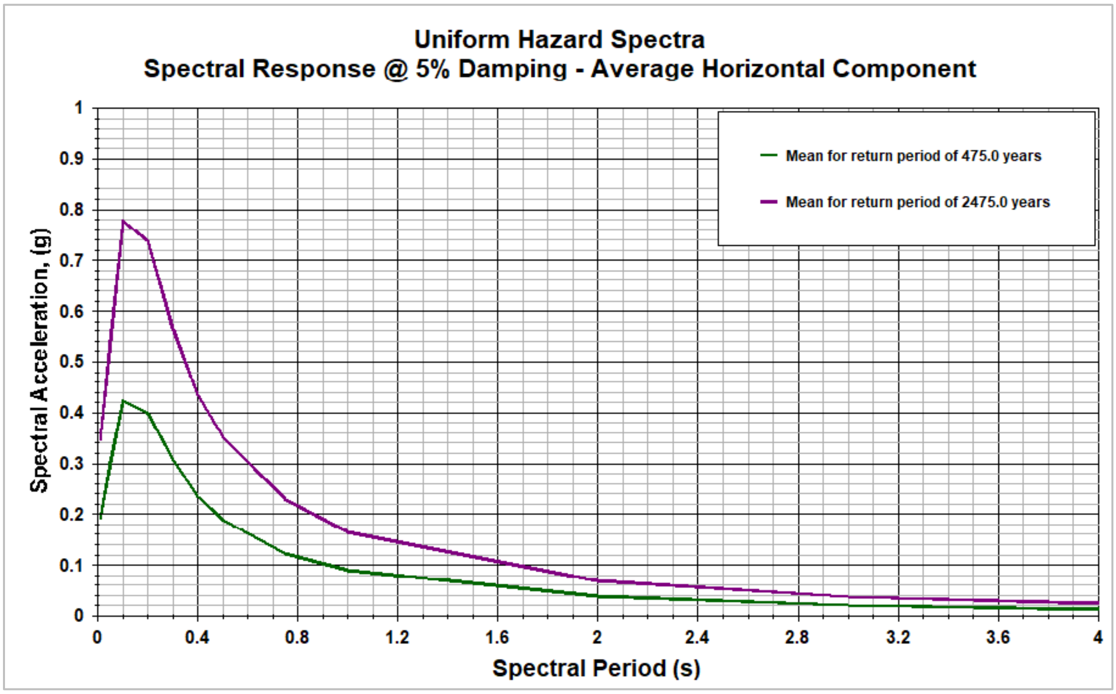

Fig. 9. Uniform total hazard curve spectral response of 5% damping the average horizontal components.

5. Conclusions

The seismic hazard assessment study conducted on Karachi city reveals the existence of several seismogenic sources in close proximity, indicating the area's susceptibility to earthquakes. Furthermore, the implementation of building codes remains a significant concern within the study area, as it has the potential to result in loss of life and structural damage, depending on the intensity of the event. Despite evidence of the seismic vulnerability of Karachi city, the current infrastructure development are not synchronized with the site specific uniform hazard response spectra. Thus this study will be instrumental in pre-disaster mitigation strategies for urban planners and policymakers for future master planning.. The current study can serve as a foundation for a large-scale project aimed at conducting comprehensive research to assess seismic hazards and risks in and around the city of Karachi. In order to facilitate the neighboring regions of Karachi City, it is necessary to update the existing data set with specific information pertaining to the area. This will enable more comprehensive and detailed investigations to be conducted.

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Conflict of Interest

The authors affirm that they have no financial or personal relationships with any individuals or organizations that could have potentially influenced the work presented in this paper.

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