ORIGINAL PAPER

Evaluation of seismicity of Karachi city in the context of modern building codes

Abbas Haider[1] · Zia ur Rehman[1]

Abstract
Spectral acceleration is representative of seismic hazard in modern building codes as well as an important parameter used in seismic design these days. Karachi, an economic artery of Pakistan, is located in the vicinity of an active tectonic setting, i.e., triple junction, with uncertain seismicity. Keeping in view the modern seismic design practices, efforts are required to evaluate the seismic hazard of Karachi city in terms of spectral acceleration. This study is focused on the estimation of seismic hazard for the metropolitan city of Karachi in the context of modern building codes. The seismic potential of around 800–900-km circle was considered a threat for the city, and 13 seismic zones (A-1 to A-13) were identified as seismic sources. A seismicity model based on Gutenberg-Richter law was developed, identifying A-1 and A-11 as zones of high seismicity. The ground attenuation model recommended for the Middle East region proposed by Akkar and Bommer was utilized for the computation of different ground motion scenarios. Short-period, S_S, and 1-s, S_1, spectral acceleration values for considered region were calculated as 1.37 m/s^2 and 0.41 m/s^2, respectively. In addition, peak ground acceleration (PGA) values for Karachi city were observed to be in a range of 0.7–0.77 m/s^2. The results of this study provide bases for the preparation of seismic risk maps, the estimation of earthquake insurance premiums, seismic zonation for region lying on Arabian and Indian plates, and the preliminary site evaluation of critical facilities.

Keywords Probabilistic seismic hazard analysis · Seismicity · Makran subduction zone · Spectral acceleration · Seismic design

Introduction

Pakistan has experienced several large earthquakes within the past 100 years. Karachi, the financial capital of the country, is considered to be vulnerable to earthquake hazard. The argument that existing seismic potential in a circle of 800–900 km around Karachi city can produce a disaster in no time is alarming, because of the strategic location of the city and its economic importance for the country. Literature suggests that the seismicity of the Metropolitan City of Karachi is marred with uncertainty (Bilham et al. 2007).

Seismic hazard analysis, often termed seismic hazard assessment (SHA), is a vital tool to predict the ground motion during the earthquake and to develop seismic hazard maps. Different techniques are adopted by different researchers for SHA. The probabilistic method for SHA is one of the most credible practices today. The probabilistic seismic hazard analysis, occasionally named as probabilistic seismic hazard assessment (PSHA), is mainly based on Cornell's work (Cornell 1968). Based on the methods proposed by Cornell latterly, different programs for estimating seismic hazard were published by (Bender and Perkins 1987; McGuire 1976). Literature suggests that the "PSHA" term started in the 1970s' decade. A comprehensive tutorial to conduct PSHA was given by Hanks and Cornell (Hanks and Cornell 1994). The PSHA approach is modified by different researchers over time, such as by Atkinson and Goda (2011) and Petersen et al. (2008). The modern PSHA approach can consider the implementation of data of active sources and has improved relative to the traditional approach in prediction (Hassan et al. 2017). Currently, PSHA is extensively used as a standard part of the "due diligence" for designing and constructing the critical

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structure and prediction of earthquakes for different regions (Hanks and Cornell 1994; Mulargia et al. 2017; Solomos et al. 2008).

Many researchers have carried out studies to account for the seismic hazard of different regions. In the context of the Indian plate, using the ground motion prediction (GMP) equations, Algermissen and Perkins (1976) and Khattri et al. (1984) established a map showing peak horizontal acceleration distribution of India for a probability of exceedance around 10% in a period of 50 years. Furthermore, Bhatia et al. (1999) conducted the PSHA to develop the seismic hazard map (SHM) for India and some regions of Pakistan. Under the Global SHA Program, an SHM of India was generated using the GMP equation given by Joyner and Boore (1979). Khattri et al. (1984) and Bhatia et al. (1999) also used a similar GMP equation to generate SHM for different specific regions of India. Parvez et al. (2003) developed the SHM for India using the deterministic hazard assessment (DSHA) technique. Das et al. (2006) developed an SHM for the northeast region of India by conducting PSHA. Jaiswal and Sinha (2007) conducted a PSHA of peninsular India using nine areal source zones. Similarly, Mahajan et al. (2010) conducted PSHA to develop a modified SHM for the sub-continent. Nath and Thingbaijam (2012) used a modified approach of logic tree framework for the SHA of India. Several recent efforts have also been made by various other researchers to estimate the seismic hazard for different isolated geological regions on the Indian plate and established SHM, which endorse the need of carrying out special and individual studies to assess the seismicity of a specific region (Chingtham et al. 2019; Choudhury et al. 2018; Cortés-Aranda et al. 2017; Lindholm et al. 2016; Maiti et al. 2017; Puri and Jain 2019; Putti et al. 2019; Ramkrishnan et al. 2019; Shreyasvi et al. 2019). In the context of Arabian and African plates, SHA was conducted by different researchers considering the geological settings of the different regions, such as by Aldama-Bustos et al. (2009); Almadani et al. (2015); Deif et al. (2013); Hamlaoui et al. (2017); Mohamed et al. (2012); Mouloud and Badreddine (2017); Rehman et al. (2017); and Zahran et al. (2019). SHA was also conducted by different researchers for various locations on the Eurasian plate and other regions using either PSHA or DSHA technique and established SHM, e.g., by Erdik et al. (1985); Ince and Kurnaz (2018); Kartal et al. (2014); Meletti et al. (2008); Meletti et al. (2016); and Vilanova and Fonseca (2007). Besides, various researchers have estimated spectral acceleration for various locations in Pakistan utilizing different SHA techniques and have also established SHM for different parts of Pakistan (Bilham et al. 2001; Bilham et al. 2007; Cortés-Aranda et al. 2017; Mahmood et al. 2016; Monalisa et al. 2007; Parvez et al. 2003; Sarwar et al. 2016; Shah et al. 2019). Such a rich literature highlights the importance of carrying out area-specific SHA studies. However, there is still literature scarcity on SHA

of many regions on the Indian and Arabian plate, for example, the coastal region of Pakistan.

In addition, seismic provisions were included in the Building Code of Pakistan (BCP 2007) after the 2005 Muzaffarabad Earthquake. Presently, BCP defines seismic loading in terms of peak ground acceleration (PGA), which makes this value significant for structural analysis (BCP 2007). Most modern codes like International Building Code (IBC-06/09) and the building code by the American Society for Civil Engineers (ASCE 7-05) define seismic loading in terms of short period, S_S, and 1-s, S_1, spectral acceleration values (ASCE 7-05 A 2006; IBC 2006). Despite the importance of these values defined by different modern building codes to establish the safe building design against seismic loadings and seismic uncertainty of densely populated Karachi city, these values have not been well-assessed for the Karachi city, as per authors' best knowledge based on the literature review. Karachi is located close to active tectonic boundaries and surrounded by active faults, literally analogous to Los Angeles city; however, luckily, in around two centuries, no catastrophic earthquake has occurred in Karachi. Though Karachi has not experienced damaging seismic events in recent times, it has experienced the Allah Bund earthquake in 1819. Moreover, it has also been jolted by recent distant earthquakes of Awaran ($M_W = 7.7$) in 2013, Khash ($M_W = 7.7$) in 2013, and Bhuj ($M_W = 7.7$) in 2001 (Bilham et al. 2007; Rehman and Paul 2020). In the present study, the PSHA of Karachi city is performed to achieve PGA, S_S, and S_1 values for the administrative boundaries of the city, taking modern building codes into account. The results of this study could provide a foundation for the preparation of seismic risk maps, the estimation of earthquake insurance premiums, seismic zonation for region lying on Arabian and Indian plates, and the preliminary site evaluation of critical facilities.

Tectonic setting

Karachi, a densely populated region and one of the world's largest cities, is breathing in the vicinity of a major triple junction lying 150 km in its south (Fig. 1a); here, Indian, Eurasian, and Arabian plates join each other. The triple junction then extends further into the Arabian Sea in the form of Murray Ridge. Makran subduction zone lies in the west of Karachi. Its eastern flank has remained silent in the past, but its western flank has reported a tsunami in 1945, which has reported some serious damages (Musson 2009). Tsunami waves were also observed on the coasts of Karachi. The northward movement of the Arabian plate into the Eurasian has generated many thrust faults in Baluchistan Province, some of which are the Hoshab Fault, Panjgur Fault, and Siahan Fault. A new fault, namely Sonne Fault, has been identified by Kukowski et al. and has been recognized as a plate
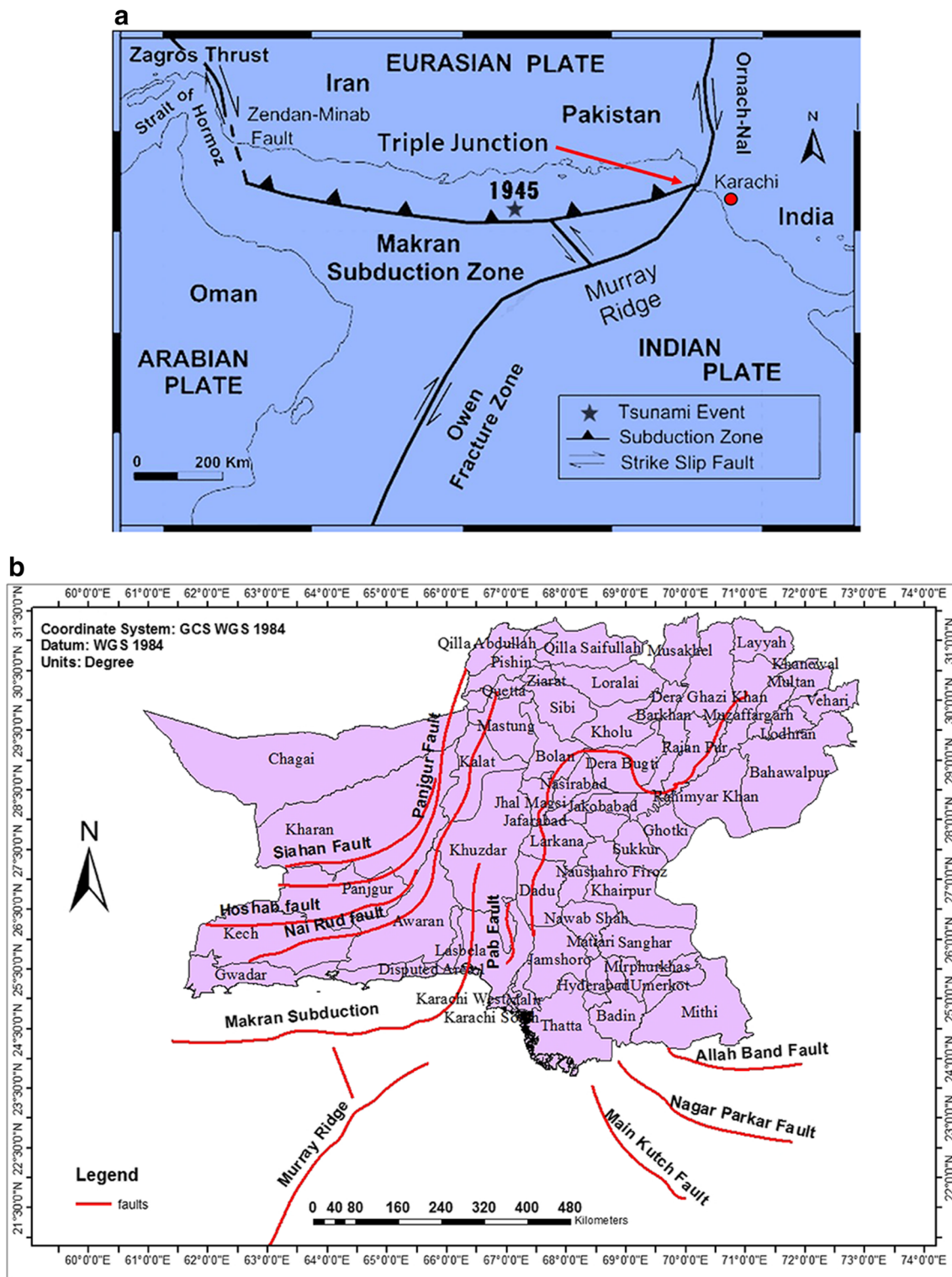
Fig. 1 Geological setting of study area (**a**) tectonic setting of the region (**b**) fault map of the study area

boundary separating the Arabian plate from the newly recognized Ormara plate (Kukowski et al. 2000). The great Chaman-Ornach-Nal Fault runs north-south from Quetta towards Awaran and then turns westwards from here into Iran. This fault is responsible for the 1935 earthquake in Quetta which destroyed the city. The north of Karachi is accompanied by the active plate boundaries of Indian and Eurasian plates. The great Rann of Kutch lies in the east of Karachi, which consists of three main faults, namely Allah Band Fault, Nagar Parkar Fault, and Kutch Main Fault. This region has

produced the devastating Bhuj earthquake of 2001 which reported cracks in some buildings existing in Karachi. The distribution of faults around Karachi is displayed in Fig. 1b.

Seismic hazard analysis

Seismic hazard analysis (SHA) is a package of uncertainties whose "cookbook" does not exist as it is an ongoing research. There are two types of SHAs in practice: deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA). PSHA has the advantage that a range of earthquake magnitude and source to site distance can be incorporated into the analysis and also the probability of occurrence of desired ground motions can be estimated. PSHA is based on the wisdom that the past is the key to the future (Yeats et al. 1997). PSHA allows the use of a combination of different attenuation models with their uncertainties and that is why it is considered a rational solution to the dilemmas posed by different types of uncertainties (GENÇ 2004).

PSHA was selected for this study as the seismic loading in BCP 2007, and IBC 06/09 is defined in terms of PGA having a certain probability of exceedance over a given return period (BCP 2007; IBC 2006). The general steps involved in the analysis are the identification of seismic sources, characterization of recurrence law, ground motion attenuation, and estimation of probabilities of exceedance of desired ground motions. The procedure adopted in this study is discussed below.

Identification of seismic sources

The study area considered ranges between latitude 22°–30° N and longitude 62°–72.5° E. To identify seismic sources, seismic history was studied. For this purpose, the instrumental earthquake catalog was acquired from three different agencies, i.e., the Pakistan Meteorological Department (PMD), International Seismological Centre (ISC), and the United States Geological Survey (USGS). The catalogs were filtered for any duplicate events, events with missing data, and aftershocks. A comprehensive catalog was then prepared by merging these catalogs. The three sets of instrumental catalogs were first converted into a single format which is the standard catalog format followed by United States Geological Survey; then a comprehensive catalog was prepared manually which included only those seismic events that were present in at least two of the available catalogs. Correspondingly, unconfirmed and incomplete events were disregarded. The earthquake magnitudes were reported in different formats including local magnitude M_L, body wave magnitude M_B, surface wave magnitude M_S, and moment magnitude M_W. Differently reported magnitudes were converted into the most authentic and stable

one, i.e., moment magnitude (M_W) using the following a set of equations suggested by Scordilis as follows (Scordilis 2006):

$$M_W = 0.67M_S + 2.07 \qquad \text{For } 3.0 < M_S < 6.1 \qquad (1)$$

$$M_W = 0.99M_S + 0.08 \qquad \text{For } 6.2 < M_S < 8.2 \qquad (2)$$

$$M_W = 0.85M_B + 1.03 \qquad \text{For } 3.5 < M_B < 6.2 \qquad (3)$$

In addition, the equation suggested by Idriss (1985) is also utilized in this regard as follows (Idriss 1985):

$$M_W = M_L \qquad \text{For } M_L \leq 8.2 \qquad (4)$$

The catalog was then prepared in the Nordic format as required by the SEISAN software. To identify seismic source zones, the catalog was mapped using the ArcGIS software. As fault data of the region is not available, area source zones were utilized in this study. A total of 13 zones were identified as shown in Fig. 2 owing to the distributed seismicity and tectonic setting of the region, which are represented from A-1 to A-13. These zones were numbered from 1 to 13 arbitrarily. The vertices of these zones are shown in Table 1, which are numbered in a counter-clockwise direction. Zones only showing high seismicity are discussed below.

A-1

This zone mainly includes the Bhuj and Run of Kutch regions of India and touches the southern coasts of Sindh, Pakistan. This is one of the most active regions in the near past and has witnessed large events. The most disastrous event in this zone occurred on 26 January 2001 at Bhuj (India) of magnitude M_W 7.6. The event was followed by at least 40 aftershocks the same day most of which were above M_W 5.0.

A-7

This region lies on the coasts of Pakistan, while its southern end connects to the Arabian Sea. Gawadar is present at its center, which is an important seaport of Pakistan from a trade point of view. This zone suffered a disastrous earthquake cum tsunami M_W 8.1 back in 1945 on 27 November. These tsunami waves were also seen on the seashores of Karachi, and a considerable amount of damages were reported. Another mega-event was reported in 1947 (M_W = 7.7). It is the Makran subduction zone that is responsible for the seismic activity in this zone.

A-8

This zone lies at the border of Iran and Pakistan. The thrust faults originating from the Chaman fault bend towards the west and pass through this zone into Iran. The southern part of Iran is active seismically and has experienced an M_W 7.7
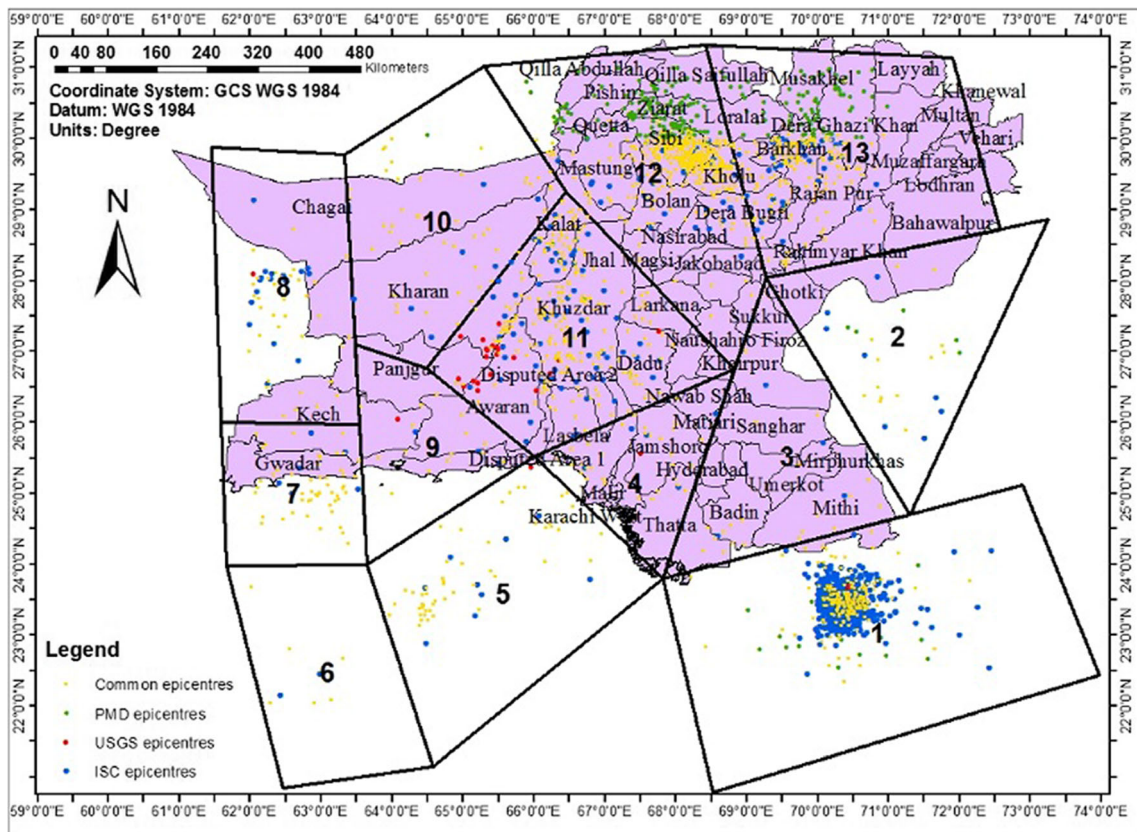
Fig. 2 Seismicity map of the study area

earthquake recently on 16 April 2013. The tremors also jolted many areas of Karachi which made this zone concerning for hazard computation of Karachi.

A-11

On 24 September 2013, an M_W 7.7 earthquake jolted this zone and Karachi. After this event, almost 24 aftershocks were recorded the same day of which 13 were above M_W 5.0. Such kind of seismic activity has not been observed before within the radius of 200 km around the epicenter.

Characterization of seismicity

This step involves the characterization of seismicity. For areas where geologic evidence of earthquakes on faults is not available, the historical frequency assessment technique is used for characterizing seismicity. It involves statistical analysis of the catalog of earthquakes that have occurred in a particular region. Beno Gutenberg and Charles Francis Richter were the two pioneers in developing the relationship between earthquake magnitude and frequency. The classical Gutenberg-Richter Law developed in 1954 is still being utilized in researches.

$$\log \lambda_M = a - bM \tag{5}$$

$$a_{norm} = a - \log N \tag{6}$$

$$\lambda_M = a_{norm} - bM_{thresh} \tag{7}$$

where λ_M is the number of earthquake events that exceeds magnitude, M, per year, and N is the duration of catalog, while a and b are seismic constants or also known as Gutenberg-Richter constants. Constant a is a measure of the frequency of the seismicity of a particular region, and hence, it varies from region to region. If a region exhibits large a value, it means that seismic activity in this region is very frequent, while a lower a value describes the low seismicity of a region. The frequency magnitude coefficient b is a tectonic parameter that represents the properties of the seismic medium (Al-Heety 2011). Equation 5 is based on Poisson's principle, i.e., earthquakes are spatially and temporally independent. The presence of aftershocks in the catalog is a violation of Poisson's model because that makes earthquake occurrence dependent on spatial and temporal parameters (Nasir et al. 2013). Owing to this reason, all aftershocks were removed from the catalog, as mentioned in the previous section. The SEISAN software was used to calculate a and b values for each source zone. The values of a and b along with the regression analyses graphs for A-1, A-7, A-8, and A-11 are shown in Figs. 3, 4, 5, and 6. The seismicity model generated by performing regression analysis of source zones is presented in Table 2. In Table 2, constants a and b are Gutenberg-Richter constants, α is $a[ln(10)]$, while β

Table 1   Coordinates of seismic zones

A (source zone)	Vertices	1	2	3	4	5
1	Longitude	67.82	68.52	73.97	72.88	-
	Latitude	23.79	20.79	22.43	25.11	-
2	Longitude	71.30	73.24	69.27	-	-
	Latitude	24.70	28.86	28.04	-	-
3	Longitude	67.82	71.30	69.27	-	-
	Latitude	23.79	24.70	28.04	-	-
4	Longitude	67.82	68.83	66.00	-	-
	Latitude	23.79	26.75	25.53	-	-
5	Longitude	67.82	66.00	63.64	64.58	-
	Latitude	23.79	25.53	23.99	21.14	-
6	Longitude	64.58	63.64	61.66	62.46	-
	Latitude	21.14	23.99	23.98	20.84	-
7	Longitude	61.66	63.64	63.53	61.59	-
	Latitude	23.98	23.99	25.97	26.00	-
8	Longitude	63.33	61.46	61.59	63.53	-
	Latitude	29.78	29.89	26.00	25.97	-
9	Longitude	63.64	66.00	64.48	63.47	-
	Latitude	23.99	25.53	26.77	27.09	-
10	Longitude	64.48	66.44	65.30	63.33	63.47
	Latitude	26.77	29.26	31.02	29.78	27.09
11	Longitude	64.48	66.00	68.83	66.44	-
	Latitude	26.77	25.53	26.75	29.26	-
12	Longitude	68.83	69.27	68.41	65.30	66.44
	Latitude	26.75	28.04	31.33	31.02	29.26
13	Longitude	69.27	72.57	71.89	68.41	-
	Latitude	28.04	28.72	31.14	31.33	-

is $b[ln(10)]$; Equation 6 is used to calculate a_{norm}; M_1 is the maximum magnitude reported by each zone in the past. The assessment of maximum magnitude, M_{max}, for seismic source zones is a fundamental task in PSHA. We utilized the standard deviation of the magnitude within a source zone to estimate maximum earthquake potential M_{max} by adding this standard deviation to the maximum magnitude reported in the zone, i.e., M_1. M_{thresh} is the limiting minimum magnitude that was used in the analysis, which was set to be 5.0. Table 2 clearly shows that A-3, A-4, A-5, A-6, and A-9 possess very low seismicity. A-10, A-11, A-12, and A-13 are the most active zones possessing high a values, while A-7 and A-8 show moderate seismicity. A-1 and A-7 possess low b values, making them a real threat for producing large earthquakes in the future. A-8 possesses a b value of 0.395, which is unreliable due to the absence of small magnitude events in this zone.

Ground motion attenuation

Ground motion is a term related to earthquake magnitude, source to site distance, and soil properties. Similarly,

earthquake duration is dependent on magnitude, source to site distance, and soil classification. For instance, earthquake duration is more at soil sites than on rock sites (Solomos et al. 2008). Ground motion attenuation can be defined as the reduction in the intensity of ground motions as they propagate. The earthquake ground motions are established using empirical ground motion relationships (GMPEs) worldwide. For civil engineering purposes, related ground motion parameters are PGA, pseudo-spectral acceleration, pseudo-spectral velocity, and spectral displacement. The most basic form of a ground motion prediction equation is:

$$\ln Y = c_1 + c_2 M - c_3 \ln R - c_4 R + c_5 + c_6 S + \varepsilon \qquad (8a)$$

where Y defines the ground motion, M is the magnitude of the earthquake, R refers to the source to site distance, F is the faulting mechanism of the region, S is the site soil condition, and ε is the random error term. Unfortunately a GMPE has not been yet formulated specifically for Pakistan, owing to which, we have to rely on GMPEs formulated for other regions. The Ambraseys and Simpson model was the first GMPE with spectral ordinates for the European, Mediterranean, and Middle East region (Ambraseys and Simpson 1996). These equations were then modified by Bommer et al. (2003) utilizing the same dataset. The influence of the style of faulting on the ground motion was integrated into the Ambraseys and Simpson model as a result of this modification. Ambraseys et al. then defined a brand new set of GMPEs for spectral ordinates using an extended dataset which was later on modified by Akkar and Bommer (Akkar and Bommer 2007; Ambraseys et al. 2005). After objections to the variability term in this model, it was again modified by Akkar and Bommer, which was used in this study as it is an updated model (Akkar and Bommer 2010). The dataset utilized in the development of this model comprises records from the Middle East and Europe. It is capable of calculating spectral acceleration values for different structural periods. This model has also been recommended for hazard computations in active crustal regions by Stewart et al. (2013). The GMPE model used in this study is defined by using Eq. 8b.

$$
\begin{aligned}
\log(\mathrm{PSA}) = {} & b_1 + b_2 M + b_3 M^2 \\
& + (b_4 + b_5 M)\log\sqrt{R_{jb}^2 + b_6^2} + b_7 S_s \\
& + b_8 S_A + b_9 F_N + b_{10} F_R + \varepsilon\sigma \qquad (8b)
\end{aligned}
$$

The values of seismic constants b_1–b_{10} are computed by following Akkar and Bommer (2010), M represents the moment magnitude (from catalog), R_{jb} is the distance from source in km, S_S and S_A are binary variants (taken as unity in this study), F_N and F_R are based on the faulting mechanism existing in a seismic event, ε represents the number of standard deviations above or below the mean value of $\log(\mathrm{PSA})$, and σ is the variability.

Fig. 3 Seismicity of A-1

$a = 3.79226$
$b = 0.52827$

Fig. 5 Seismicity of A-8

$a = 3.14961$
$b = 0.395165$

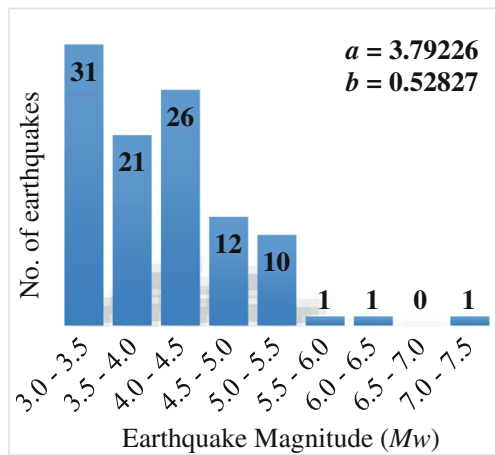## Spectral ordinates and return period

The Building Code of Pakistan defines seismic loading for structures in terms of PGA. But it is not suitable to consider PGA as a parameter to gauge the damage potential of an earthquake as it does not represent the dynamic nature of loading. Modern building codes define seismic loading in terms of spectral ordinates; e.g., IBC 2006/09 defines seismic loading in terms of spectral acceleration values for a structural period of 0.2 s and 1.0 s. In this study, spectral acceleration values (including PGA) were calculated for 0.1, 0.2, 0.5, 0.8, 1.0, and 1.5 s. Intermediate values of the structural period were selected to obtain a uniform hazard curve.

In modern building codes, the risk level is often defined in terms of the percentage of exceedance rate in the lifetime of a structure. BCP 2007 restricts design seismic loading to have a 10% probability of exceedance in 50 years. IBC 2006 restricts it to a 2% probability of exceedance in 50 years. Return period is another term used in defining seismic loading. It is the gap
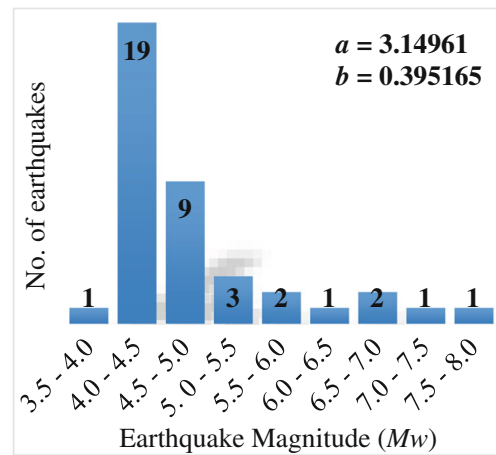
(in years) after which an earthquake can re-occur. It can be defined as follows:

$$T_R = \frac{-T}{\ln(1-P)} \qquad (9)$$

where T is the life span of a building, P is the probability of exceedance, and T_R is the return period. This equation means that IBC requires to estimate hazard for a return period of 2500 years, while BCP requires the same for a return period of 500 years (BCP 2007). The return periods considered for this study were 100, 250, 500, 1000, and 2500 years. R-CRISIS was used to compute the hazard in this study. It is a state of the art system to obtain ground motion exceedance rates for the desired site. It also allows us to calculate the contribution of each source zone into the hazard.

Probability of exceedance

The last step of the analysis is to generate the exceedance probabilities for different levels of ground motions. These exceedance probabilities depend on the time frame and the
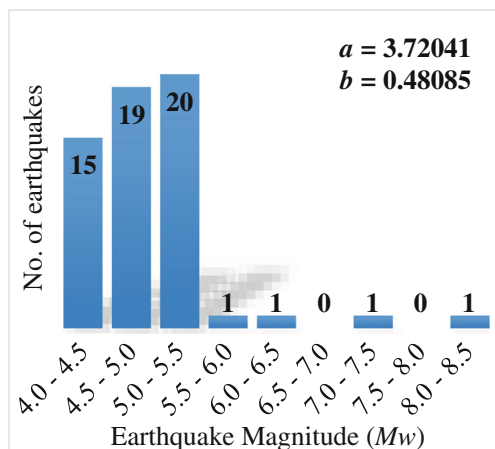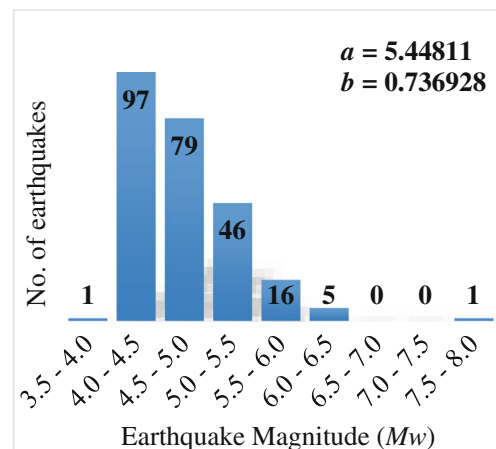
Fig. 4 Seismicity of A-7

$a = 3.72041$
$b = 0.48085$

Fig. 6 Seismicity of A-11

$a = 5.44811$
$b = 0.736928$

Table 2 Seismicity model of the study area

S. no.	Zones	Gutenberg-Richter constants					M_1	Std. D of M_1	M_{max}	M_{thresh}	λ	No. of years
		a	α	b	$a_{(norm)}$	β						
1	A-1	3.792	8.731	0.528	2.036	1.216	7.6	0.8	8.4	5	0.249	57
2	A-2	2.878	6.627	0.429	1.249	0.988	6.8	0.8	7.6	5	0.127	43
3	A-3	2.624	6.042	0.336	0.727	0.774	5.8	0.7	6.5	5	0.111	79
4	A-4	3.682	8.478	0.502	1.996	1.156	5.1	0.4	5.5	5	0.306	49
5	A-5	5.643	12.99	0.890	3.739	2.049	6	0.4	6.4	5	0.194	80
6	A-6	2.716	6.254	0.425	1.269	0.979	5.4	0.5	5.9	5	0.139	28
7	A-7	3.720	8.566	0.480	1.872	1.105	8.1	0.7	8.8	5	0.296	71
8	A-8	3.149	7.251	0.395	1.215	0.910	7.7	0.9	8.6	5	0.174	86
9	A-9	4.911	11.31	0.815	3.000	1.877	6	0.5	6.5	5	0.084	82
10	A-10	4.904	11.29	0.724	2.907	1.667	7	0.6	7.6	5	0.194	99
11	A-11	5.448	12.54	0.736	3.668	1.695	7.7	0.5	8.2	5	0.973	60
12	A-12	4.833	11.13	0.600	2.818	1.382	7.5	0.6	8.1	5	0.657	104
13	A-13	4.981	11.47	0.682	3.198	1.570	6.5	0.5	7	5	0.614	61

return period. R-CRISIS uses the following expression to calculate the exceedance probabilities.

$$\Pr(A \geq a | M_i, T_j, k)$$
$$= 1 - \sum_{s=0}^{Ns} P_k(s, M_i, T_j) \left[1 - \Pr(A \geq a | M_i, R_j) \right]^s \quad (10)$$

where $\Pr(A \geq a | M_i, T_j, k)$ is the probability that intensity a exceeded given that a seismic event of magnitude M_i occurred at source k, that is at a distance of R_k from the earthquake source. This probability depends on the magnitude and source-to-site distance which is calculated through the probabilistic interpretation of intensities using the GMPE. As IBC 06/09 defines seismic loading for ground motions having 2% exceedance probability in 50 years, therefore, consistent assumptions are made in this study as per IBC (2006); consequently, a return period of 2500 years is adopted.

Response spectra

Earthquake design engineers are well aware of the importance of response spectra in the seismic design of structures. ASCE 7-05 describes the procedure to obtain response spectra from the spectral acceleration values computed as a result of hazard analysis for a particular site (7-052006). A response spectra (Fig. 7) have been developed for Karachi city based on these set of equations available in ASCE 7-05 (2006).
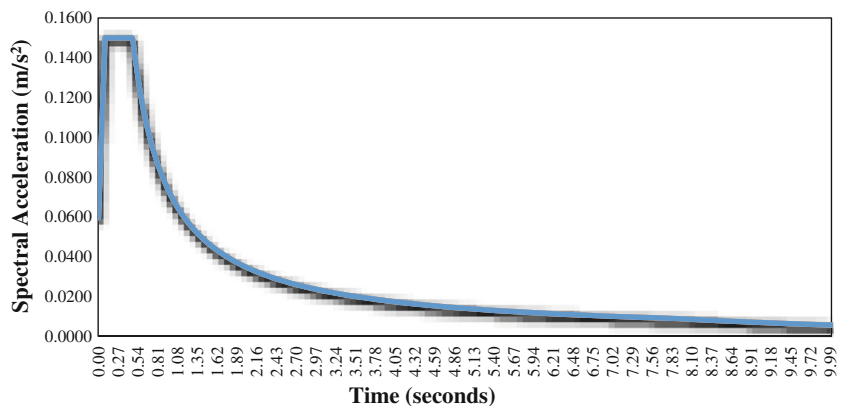
$$S_a = S_{DS}\left(0.4 + 0.6\frac{T}{T_0}\right) \quad T < T_0 \quad \text{where } T_0 = 0.2\frac{S_{D1}}{S_{DS}} \quad (11)$$

$$S_a = S_{DS} \quad T_0 \leq T \leq T_S \quad \text{where } T_S = \frac{S_{D1}}{S_{DS}} \quad (12)$$

$$S_a = \frac{S_{D1}}{T} \quad T_S \leq T \leq T_L \quad \text{where } T_L = 8 \text{ sec} \quad (13)$$

$$S_a = \frac{S_{D1}T_L}{T^2} \quad T > T_L \quad (14)$$
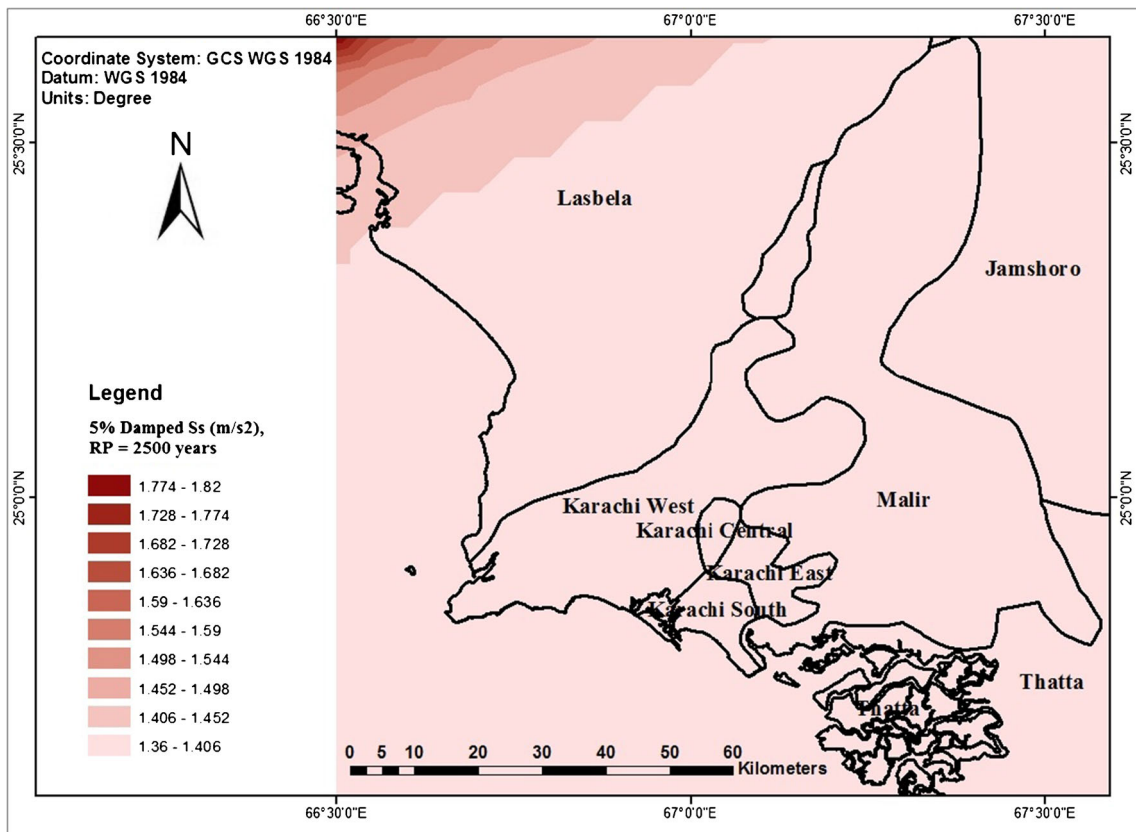
Fig. 7 Generated response spectra

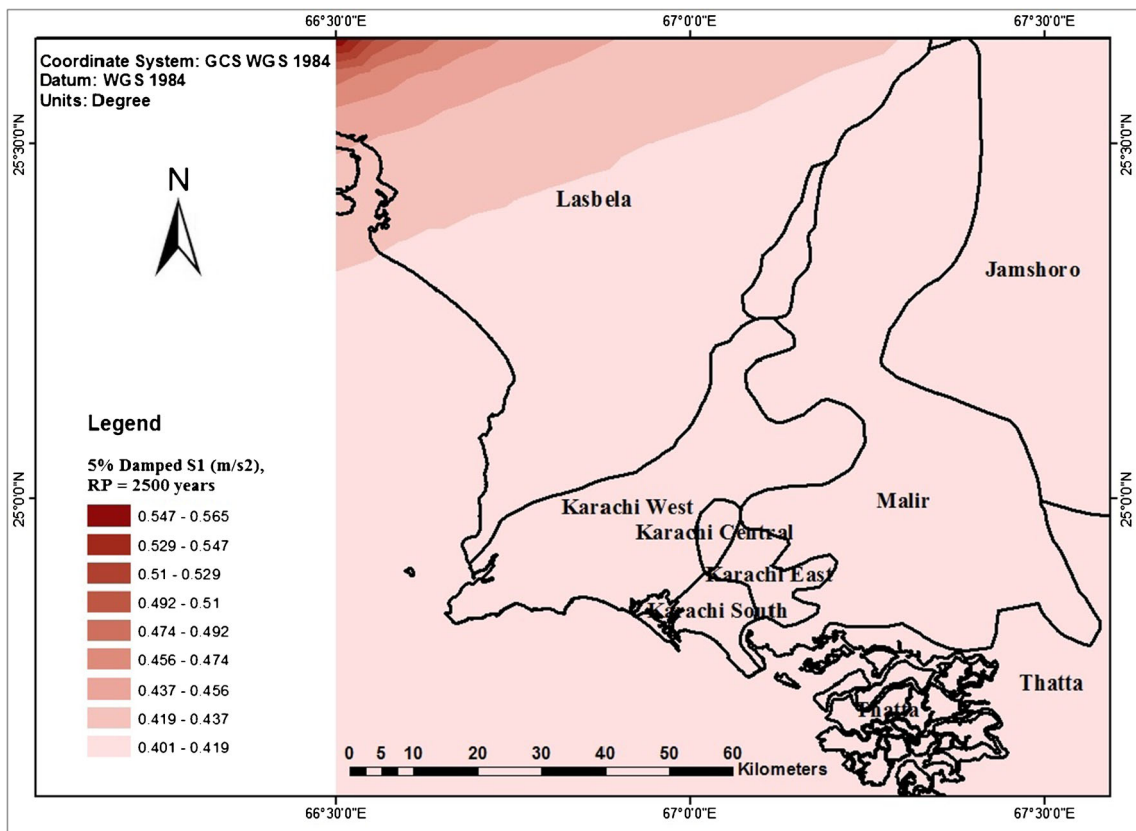**Fig. 8** Contour map 5% damped S_s (m/s^2); return period = 2500 years

Fig. 9 Contour map 5% damped S_1 (m/s^2); return period = 2500 years

Table 3 Ground motion scenarios in m/s^2

S. no.	Area Return period (years)	PGA^{500} 500	PGA^{2500} 2500	S_S^{2500} 2500	S_1^{2500} 2500
1	Karachi Central	0.580	0.770	1.370	0.406
2	Karachi East	0.579	0.768	1.370	0.405
3	Karachi South	0.580	0.770	1.370	0.405
4	Karachi West	0.579	0.770	1.370	0.407
5	Malir	0.580	0.768	1.370	0.410

Discussion

The computational grid was reduced to administrative boundaries of Karachi city which ranges from 24.5° to 25.70° N latitude and 66.50° to 67.60° E longitude. This makes approximately 14,848 km^2. The size of the grid was limited because this reduces the calculations and processing time required by the software to calculate the results.

The SHMs for different levels of spectral acceleration contours, which were estimated by the attenuation relationship of Akkar and Bommer with an approximate return period of 2500 years and a 2% probability of exceedance in 50 years, are shown in Figs. 8 and 9 (Akkar and Bommer 2010). The 5% damped pseudo-spectral acceleration values calculated for rock sites for districts of Karachi are presented in Table 3, which depict that despite being located near many active faults, Karachi city holds low seismicity. The highest hazard levels were observed in the northwest part of the study area located in Lasbella district, while the lowest hazard level was observed in the southeast of the study area that is in the vicinity of Karachi city. As suggested by previous studies, the

selected area possesses very low levels of seismic hazard. The hazard, especially in Karachi city, is distributed smoothly around 1.37 m/^{2}(S_s). The Karachi Arc: a series of parallel and non-parallel dome-shaped anticlinal hills which are a continuation of the Kirthar Mountains located in the north of Karachi City are the reasons behind the low seismicity of the city as they absorb most of the ground motions originating from A-11.

Disaggregation of PSHA was carried out to identify the most contributing source zone in the seismic hazard of the city. It is evident from Fig. 10 that A-11 is the largest source contributing to the seismic hazard of Karachi city over the computed range of S_s spectral acceleration values. The recent seismic activity (2014) in this zone has redefined its seismic potential, and it is quite capable of generating large earthquakes in the future. A-7 is the second major contributor, but its seismicity is less frequent as compared with A-11. Moreover, its source to site distance from Karachi city is also large as compared to of A-11.

Conclusions

The statistical properties of earthquakes in Karachi city were analyzed and correlated with the present tectonics and rheology of the region. Based on facts and figures, seismic hazard in terms of spectral acceleration has been calculated for the Karachi city. The calculated values are based on the latest set of GMPEs, and thus, more accurate values of *PGAs* are estimated. The following conclusions are drawn:

Fig. 10 Zonal contributions into the hazard
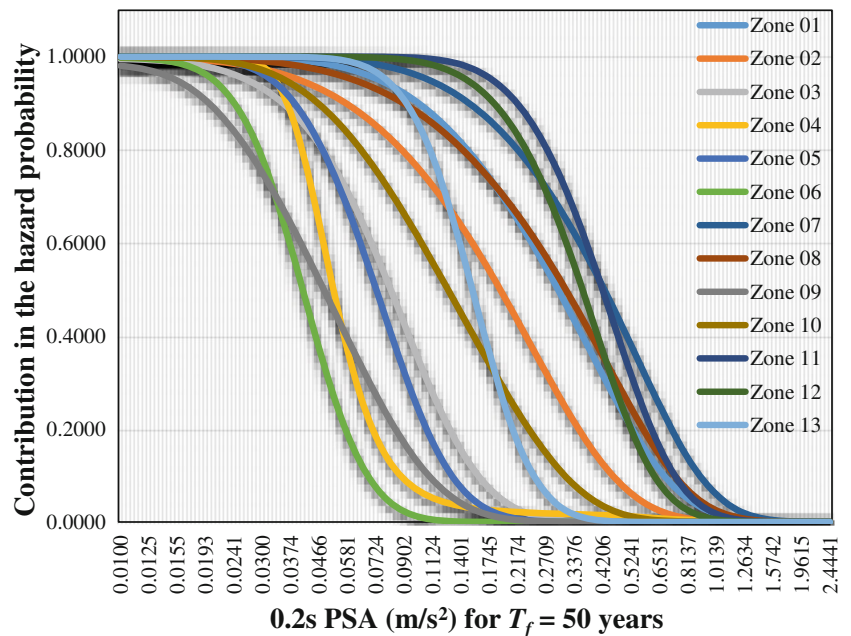
1. PMD has reported PGAs for a return period of 2500 years for different cities of Pakistan. The value reported for Karachi is 0.54 m/s^2, which is less than that calculated in the current study and could be unsafe for the design of civil structures. The PGA calculated in this study is 0.70–0.77 m/s^2.

2. It was found that there is no considerable variation in PGAs for the Karachi city and calculated values of PGAs are found to be uniform in most parts of the city.

3. Seismic zonation was more specific to the city and based on the latest seismic records. S_S (spectral acceleration at 0.2 s having a return period of 2500 years) and S_1 (spectral acceleration at 1 s having a return period of 2500 years) were calculated as 1.37 m/s^2 and 0.41 m/s^2, respectively. The results could enable practitioners to define seismic loading based on IBC 06/09 and ASCE 7-05 criteria to produce safe and economical design of the structures.

4. This study can be incorporated with the current building authorities of Pakistan to develop improved guidelines for the Karachi city.

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