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Seismic risk assessment for developing countries: Pakistan as a case study

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Abstract: Modern Earthquake Risk Assessment (ERA) methods usually require seismo-tectonic information for Probabilistic Seismic Hazard Assessment (PSHA) that may not be readily available in developing countries. To bypass this drawback, this paper presents a practical event-based PSHA method that uses instrumental seismicity, available historical seismicity, as well as limited information on geology and tectonic setting. Historical seismicity is integrated with instrumental seismicity to determine the long-term hazard. The tectonic setting is included by assigning seismic source zones associated with known major faults. Monte Carlo simulations are used to generate earthquake catalogues with randomized key hazard parameters. A case study region in Pakistan is selected to demonstrate the effectiveness of the method. The results indicate that the proposed method produces seismic hazard maps consistent with previous studies, thus being suitable for generating such maps in regions where limited data are available. The PSHA procedure is developed as an integral part of an ERA framework named EQRAM. The framework is also used to determine seismic risk in terms of annual losses for the study region.

Keywords: risk management; seismic hazard assessment; developing countries; Pakistan

1 Introduction

Extensive human and economic losses in recent major earthquakes (Indonesia 2009, Haiti 2010, Nepal 2015, and Ecuador 2016) highlight the need for appropriate cost-effective Earthquake Risk Assessment (ERA) tools in seismic-prone developing countries. The first step in the ERA process is the Seismic Hazard Assessment (SHA), which may be deterministic (DSHA) or probabilistic (PSHA) (McGuire, 2001). DSHA determines the maximum magnitude event for a seismic source based on historical seismicity and good geological knowledge of the seismic source (Oliveira and Campos Costa, 2006). However, such information is not always available in developing countries, whereas the maximum magnitude event (on its own) for a specific zone is not enough to perform ERA (Thenhaus and Campbell, 2003). On the other hand, PSHA procedures determine a probabilistic solution based on a series of seismic events generated using appropriate probability functions (McGuire, 1976; Hanks and Cornell, 1994; Abrahamson, 2000).

In general, the selection of the approach required to determine seismic hazard at a particular location depends on how the results will be used (Bommer, 2002; Krinitzsky, 2003). For instance, PSHA is usually performed for seismic hazard mapping, development of design codes, and insurance/reinsurance and financial planning for earthquake losses at the country level (Sokolov *et al.*, 2007). Therefore, PSHA is suitable for ERA, where a final goal is to determine earthquake losses at the regional or country level.

Modern PSHA methodology is based on initial work by Cornell (1968), where probability distributions for magnitude and source site distance were used for the first time. Subsequent work by Cornell and VanMarcke (1969) and Cornell (1971) improved the initial approach by including an upper bound on the earthquake magnitude in each region to avoid the inclusion of unrealistically large earthquakes. Algermissen and Perkins (1972) also utilized this method to produce a seismic-hazard map by assuming a point source for each earthquake rupture. However, earthquakes result from the rupture of finite fault segments and, therefore, their sources can be considered to have a finite length on the earth's surface and not just a point. Der Kiureghian and Ang (1977) studied this effect and recommended that ground motion should be estimated on the basis of the distance from the site to the closest point of the fault rupture projection. This effect is more important for large magnitude earthquakes that often dominate the seismic hazard in plate boundary areas.

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Monte Carlo simulation methods can be used for PSHA by considering epistemic uncertainty in the hazard parameters (Shapira, 1983; Musson, 2000) to generate synthetic earthquake catalogues. Each synthetic catalogue represents the earthquakes that could occur in the study region for a given period consistent with past observations. The seismic events in the synthetic catalogues can be positioned anywhere within the seismic zones. The Monte Carlo simulation is an event-based method that does not directly solve the classic probability equations. However, previous research (Musson, 1999; Crowley and Bommer, 2006) showed that by using a large number of simulations, such stochastic PSHA methods can lead to hazard estimates close to the conventional PSHA methods based on the original approach by Cornell. Also, unlike previous studies that also use the Monte Carlo method (e.g. Assatourians and Atkinson, 2013), the approach used in this ERA framework is different because the events in an earthquake catalogue are smudged to generate a large number of catalogues by randomizing key hazard parameters.

To aid in modelling seismicity within a region based on the modern PSHA methodology, several computer codes have been developed in the past such as EQRISK (McGuire 1976), SEISRISK III (Bender and Perkins, 1987), EZ-FRISK (McGuire, 1993), OHAZ (Zabukovec *et al.*, 2000), CRISIS (Ordaz *et al.*, 2003), OpenSHA (Field *et al.*, 2003), EQRM (Robinson and Fulford, 2005), USGS-NSHM (NHSM, 2008), FRISK88MTM (RE, 2009) and GEM (GEM, 2011). These computer software model the seismicity within a seismic zone by assuming a uniform or smoothed variable (using spatial or kernel methods) earthquake occurrence rate. Whilst the above codes have been widely used for PSHA, their methodology is, in general, associated with the following drawbacks:

- The selection of shape, size and orientation of seismic source zones is subjective as it depends on the users' choice/decisions. Studies by Krinitzsky (1993) on the expert opinion PSHA showed that the experts usually chose different orientations, shapes and sizes for the same seismic source zones. Therefore, available seismicity and tectonic information can lead to different seismic hazard assessments depending on the user-selected seismic source zones (Khan, 2011). However, different plausible source models may be consistently accounted for probabilistically by logic trees (e.g. Bommer and Scherbaum, 2008).
- Conventional PSHA methods assume that the historical seismicity distributes uniformly over source zones, or that it is smoothed spatially (Beauval *et al.*, 2006). Therefore, the seismicity is sometimes smoothed over large regions, which spread the possible occurrence of earthquakes in regions without historical seismicity. This may lead to lower estimations of seismicity in locations near the area source, and to higher estimations of seismicity in regions with few or no historical earthquakes (Abrahamson, 2006).
- The maximum magnitudes M_{max} for the seismic sources are determined from the fault lengths or from the seismicity of the area sources. As these M_{max} values are then smeared over the larger area of the seismic source zone, high 'artificial' Peak Ground Acceleration (PGA) values can be attributed to neighboring regions.
- In current practice, it is assumed that earthquakes with a magnitude below a selected lower bound are not considered in the PSHA as they are not potentially destructive for well-designed structures. Typically, the lower bound is set at a magnitude of 4 to 5 since well-engineered structures are rarely damaged in earthquakes less than this magnitude (Abrahamson, 2006). Also, catalogues are often incomplete for smaller earthquakes (Reiter, 1990). However, the use of a fixed lower bound is a source of inaccuracy as a small magnitude earthquake occurring very close to a site may still produce a high level of ground motion.

Previous studies have proposed approaches where only historical epicenters are need to carry out hazard assessment (Woo, 1996). Such approaches are extremely practical for parts of the world where the observed seismicity cannot be directly associated with geological structures (e.g. active faults), or in areas where scarce earthquake data makes estimation of earthquake recurrence rather problematic.

This study follows this rationale and proposes a practical event-based PSHA methodology to integrate available historical seismicity information with instrumental seismicity. The methodology also takes into account the effects of tectonic setting by considering that, in a given zone, earthquake rupture lines are oriented along known faults. The methodology attempts to address some of the above mentioned drawbacks associated with existing PSHA methods, and aims to be applied mainly in developing countries for which detailed seismic-tectonic information is not readily available. The efficiency of the method is assessed by considering Pakistan as a case study. This study contributes towards developing faster and reliable seismic risk assessments in residential areas of developing countries to assist relevant stakeholders and decision-makers on preparedness, emergency response and mitigation actions.

2 Proposed PSHA approach

The flowchart in Fig. 1 shows the various components of the proposed PSHA methodology, whereas the subsequent sections describe in detail the steps involved in the calculations.

2.1 Generation of synthetic earthquake catalogs

As shown in Fig. 1, the proposed PSHA methodology starts with the creation of a catalogue of seismic events, based on the historical and instrumental seismicity of the region. Seismic zones are then assigned preliminarily to determine the fault type and direction of the fault associated with the event under consideration. Monte Carlo simulations are then used to randomize key hazard parameters to reflect their uncertainty and generate a large number of synthetic earthquake catalogues. The key hazard parameters used in this study include the earthquake magnitude, epicentral location, depth of hypocenter, and soil type. The epistemic errors in the estimation of the key hazard parameters are used in the randomization process.

2.2 Integration of historical and instrumental seismicity

Historic earthquake catalogues are generally incomplete since the regional history (and geology) only provides information about large magnitude earthquakes, whereas small magnitude events are missing. Moreover, historical seismicity can play an important role in SHA as it may add information on seismic sources of a region that are not captured by instrumental records. However, before the instrumental seismicity can be accepted as being valid to predict future events in a new study region, it should be examined to ensure that it is consistent with the historical seismicity. For instance, Kythreoti (2002) investigated the seismicity of Cyprus and found that the instrumental seismicity was consistent with the historical seismicity of the studied region.

Fig. 2 compares the magnitude-recurrence curves computed based on historical and instrumental catalogues for Pakistan, which is taken as a case study region in this research project. It is shown that, contrary to Kythreoti's study, the seismic activity from the 13th to the 19th century does not compare well, and it underestimates the seismicity of the 20th century obtained from instrumental data. However, the underestimation is very likely to be due to the lack of historical data. This is partly supported by the presented data since the recurrence curves for the different centuries converge at the large magnitudes ($M_w > 7.0$), at which historical data are known to provide more reliable information. Since the 20th century instrumental curve does not underestimate historical seismicity, it can be considered as a reasonable representation of the general seismicity of Pakistan. It should be mentioned that the instrumental seismicity only provides a view of a short time frame for the seismicity, which may not represent the long term seismic activity of a region at the meso-level. To generate reliable synthetic earthquake catalogues, it is thus necessary to include the historical seismicity. However, it should be borne in mind that historical seismicity is usually very limited and does not include small to moderate earthquakes. Indeed, whilst historical data are available for the past 2000 years in countries like Italy, Japan, China etc. (Mulargia *et al.*, 2017), such data does not exist in many developing countries. The insufficiency of earthquake catalogues is a limitation in all existing methods, including the proposed ERA framework.

To combine historical and instrumental seismicities, either Bayesian statistics or methods like Kijko and Sellevoll's (1989) may be used. In this study, a simple approach which is easily incorporated into the code (and that can be improved in future studies) is proposed. Accordingly, the historical seismicity was integrated into the instrumental seismicity so that the recurrence pattern of the instrumental seismicity at the macro level remained unchanged. For this purpose, the available seismicity data for the study region was grouped into five magnitude ranges, as shown in Table 1. To generate a synthetic earthquake catalogue, for each magnitude range, n_j^i earthquakes were randomly chosen out of $\sum n_j^i$ earthquakes; where i and j are century and magnitude range, respectively (see

Table 1). Based on this technique, the number of earthquake events in each magnitude range remains similar to that of the 20th century. This ensures that all the synthetic catalogues respect the recurrence relationship of the study region. The observation time window in the proposed PSHA method depends on the time span of the existing reliable instrumental data (usually 100 years). Note that the proposed method generates earthquakes at locations of historical events, even if events have not occurred in the last few centuries. Therefore, spatial distribution of earthquakes covers areas of the 20th century and well before that. Note also that foreshocks and aftershocks are not removed in this study, which implies that the generated catalogues may not strictly follow a Poissonian model. However, the initial screening removes events of non-

significant consequence ($PGA < 0.05 \text{ g}$), including most foreshocks and aftershocks. As a result, the events in these catalogues follow approximately a Poissonian model. Note that the Poissonian model does not predict rare events with large magnitude in active earthquake zones (Shende *et al.*, 2009; Ben-Naim *et al.*, 2013). Therefore, this ERA framework uses the screened catalogue as it is for generating the annual risk for the region. Moreover, ERA is significantly influenced by large magnitude events (as compared to low and moderate events) that are rare and do not necessarily follow the Poissonian model. It should also be mentioned that the proposed ERA framework requires an annual frequency of exceedance (AFE) to calculate annual monetary and casualty risk. In this study, a PE of 10% in 50 years was selected to compare results of the proposed model with previous PSHA studies for the selected region (which only considered such PE, see next sections). However, the ERA can accommodate other PE values. The depth of the earthquakes considered in the calculation of PGAs ranges from 10 to 370 km. Finally, in this PSHA method, there is no need to assume earthquake recurrence relationships or to calculate maximum expected magnitude for the seismic sources. This can address some of the drawbacks associated with using conventional PSHA methods, as discussed earlier.

2.3 Seismic sources

The PGA contours in small magnitude earthquakes ($M_w < 6$) are expected to be nearly circular around their focal point due to the small rupture lengths, as shown schematically in Fig. 3(a) (Kythreoti, 2002). Conversely, the PGA contours for strong earthquakes can be assumed as perpendicular to the rupture line. In a large magnitude event, the rupture line is usually oriented along existing fault lines (Wells and Coppersmith, 1994). For example, Fig. 4 illustrates the spatial distribution of observed intensity for the Sichuan (2008) and the Chile (2010) earthquakes.

In this study, the focal point for new random events with large magnitudes (i.e. $M_w > 6$) was placed within a distance equal to the expected error around the original epicenter, as described in the following section and shown in Fig. 3(b). From the epicenter of each new random event, an "Epicentral Fault Line" (EFL) was defined parallel to the general fault direction of the seismic source zone corresponding to the original seismic event. Seismic source zones were allocated using tectonic information on the direction and type (if known) of the main tectonic features.

Based on the magnitude of the earthquake event, the length of its corresponding EFL can be estimated using an appropriate fault length-magnitude relationship. In this study, the following relationships were adopted (Wells and Coppersmith, 1994):

$$\log(SLR) = -3.22 + 0.69M_w \quad (1)$$

$$\log(RLD) = -2.44 + 0.59M_w \quad (2)$$

where M_w is the moment magnitude of the earthquake; whereas SLR and RLD are the surface length and subsurface fault rupture length in kilometers (km), respectively. Accordingly, EFL was assumed to be the maximum of SLR and RLD calculated using the above equations.

Note that to generate synthetic earthquake catalogues in the proposed method, the locations of the new seismic events were randomly placed within a circular area around the original focal point for small magnitude earthquakes (Fig. 3(a)), or within an elliptical shape area around the original EFL for large magnitude earthquakes (Fig. 3(b)). It should be also mentioned that, in many cases, systematic spatial variability of ground motion around seismic sources exists, thus inducing forward directivity effects that would modify the patterns shown in Fig. 3 (Somerville *et al.*, 1997). Whilst this effect can be taken into account in PSHA (Tothong *et al.*, 2007), the proposed model assumes the simple acceleration attenuation pattern shown in the figure. Therefore, further research should investigate ways of improving near-fault assessment.

Note that this ERA framework not only randomizes the location of significant earthquakes over large distances (within rupture length on either side of the original epicenter), but it also replaces events with similar magnitude historical events that may be located farther from the replaced location (that too randomized over rupture length on either side of the original epicenters). This will give results significantly different from the "smoothed seismicity" approach. The authors have also adapted the framework to consider seismic gaps using a time-dependant approach (Mulyani, 2013), but this will be presented in future publications.

2.4 Uncertainty in the estimation of key hazard parameters

In an attempt to quantify the epistemic errors in the key hazard parameters for the study region, available

information on earthquake records (i.e. location, depth and magnitude of earthquakes) from different sources were collected and compared for the study region. By comparing existing earthquake catalogues in Pakistan, the mean error of the epicentral location of an earthquake was estimated as ± 0.23 degrees (± 25.4 km) for the instrumental seismicity (Khan, 2011; ISC, 2009). Fig. 5(a) shows the distribution of calculated errors for location and magnitude of past earthquakes (1908 to 2008) in Pakistan. The calculated mean error in the epicentral location of earthquakes agrees well with previous research (Kagan, 2003) that found this error to be between 20 and 40 km, depending on the depth and magnitude of the earthquakes.

Fig. 5(b) shows the distribution of absolute errors in magnitude of the instrumental seismicity in Pakistan based on the existing earthquake catalogues. The results indicate that the mean error in magnitude determination of instrumental seismicity in Pakistan was around ± 0.26 magnitude units (Khan, 2011).

It should be mentioned that in the proposed PSHA method, the magnitude of all earthquake events is expressed using the moment magnitude scale (M_w). However, the magnitude of some of the instrumental and historical earthquakes in Pakistan was measured using body-wave magnitude (M_b) or surface-wave magnitude (M_s). Therefore, the error in the conversion of the earthquake magnitude to M_w was another source of uncertainty (Kagan, 2003). Fig. 6 shows the relationship between the measured M_w and its corresponding M_b and M_s for different recorded earthquakes in Pakistan and the surrounding region. Based on this information, the error of the conversion to M_w was ± 0.24 and ± 0.18 for M_b and M_s , respectively, with a 95% confidence level. Therefore, to convert the earthquake magnitudes to M_w the following equations were adopted:

$$M_w = 1.0092M_b + 0.1341(\pm 0.24) \quad (3)$$

$$M_w = 0.6334M_s + 2.2540(\pm 0.18) \quad (4)$$

For events not recorded in M_w , the effective mean error in the earthquake magnitude was calculated by using the Square Root of the Sum of the Squares (SRSS) of the errors in the magnitude determination (i.e. ± 0.26) and magnitude conversion (i.e. ± 0.24 and ± 0.18 for M_b and M_s , respectively). Likewise, the mean errors in the depth of hypocenters and the soil parameters required for attenuation relationships were considered to be 15% based on a sensitivity analysis carried out by Kythreoti (2002). The soil parameters were obtained from the geologic maps of the region. Whilst PSHA can be considered a site-specific analysis (McGuire, 2004) and therefore geological maps may not be adequate to provide comprehensive information for microzonation, this is often the only available information in many developing countries and therefore such maps are used in this study. Note also that the magnitude conversion relationships used here were derived from seismic data specific for the region under consideration. However, the proposed framework can accept more general conversion equations should the user consider magnitude conversion as epistemic uncertainty.

Based on the above information, a significant number of random synthetic earthquake catalogues were generated to represent possible future events for a given period of time. Each synthetic catalogue contained all relevant events of the original instrumental catalogue, but their locations, magnitudes, and depths were modified according to their corresponding error values as discussed in previous paragraphs. To estimate the seismic hazard parameters for each new event in the synthetic catalogue, the following equation was used:

$$HP_R = HP_0 + (e \times N_R) \quad (5)$$

where HP_R and HP_0 are the new and original hazard parameters, respectively; e is the expected error for that specific hazard parameter, and N_R is a random number between -1 to 1 from a uniform distribution. Alternatively, more sophisticated distributions (such as normal distribution) can be used if they can be derived for a particular region. The current ERA study is carried out at union council level considering large areas. Whilst micro level soil variations are not considered in the calculations carried out in this study, the developed ERA framework can be used to perform risk studies at the micro level if the local soil data is available. The proposed PSHA method is general and flexible, and therefore, uncertainty in other hazard parameters (such as ground motion variability) can be easily incorporated in the calculations if deemed necessary. However, the procedure differs from conventional PSHA methods as the new catalogues are not generated from the recurrence relationship, but by assuming that recent seismicity (100 years) is representative of the general seismicity for small events. To respect the recurrence rates for each zone, compensation is made for known historical events.

3 Determination of PGA

For all generated random events, an attenuation relationship was used to calculate the PGA level at the center of each unit area considered for PSHA. In the case of Pakistan, this unit area (UA) was the 'Union Council' which is the smallest local administration unit. The results were then used to determine the PSHA map of the study region for the desired return period. The epicentral distance required to use this attenuation relationship was calculated from the geodetic coordinates of the epicenter (or nearest point on EFL) of the random event and the center of each UA using the World Geodetic System (WGS) (Burke, 2003). The geodetic coordinate system WGS was incorporated into the PSHA framework, rather than a Cartesian coordinate system, to enable the study of much larger areas.

To determine the PGA in this study, the Ambraseys *et al.* (2005) attenuation relationship was utilized as it incorporates the fault type and site soil specification without requiring detailed geological information. Fig. 7 shows that the Ambraseys *et al.* (2005) attenuation relationship compares reasonably well with the recorded field data (Raghukant, 2008) and recorded PGA at Abbottabad (Javed *et al.*, 2006), Barotha, Maree and Tarbela (Burton and Cole, 2006) stations after the 2005 Kashmir earthquake in Pakistan. It should be mentioned that whilst Ambraseys *et al.* (2005) GMPE was used in this study, other recent equations (e.g. Akkar *et al.*, 2014) or even a set of GMPEs can also be used in the proposed methodology. However, the use of the Akkar *et al.* (2014) model in the calculations in this study is expected to change the hazard results by less than 10%. More sophisticated attenuation relationships can be easily incorporated in the proposed methodology as more information becomes available in the future.

In the proposed PSHA method, the inclusion of earthquake events in the catalogue uses a minimum PGA at a UA rather than the earthquake magnitude. The minimum PGA that can cause damage depends on the vulnerability of the building stock in the area (in this study, the damage ratio was around 3% for the minimum PGA). Therefore, unlike conventional PSHA methods, no lower bound magnitude 'cutoff point' needs to be considered. The proposed methodology is also independent of the selected seismic area sources, as new events are smeared around their original location, and the seismic source zones are used only to determine the general fault orientation. Whilst the selection of seismic source zones in this method is based on the direction and type of existing faults, other information can be included if required by the attenuation relationship.

4 Earthquake risk assessment model (EQRAM)

The proposed PSHA methodology was incorporated into an ERA framework called EarthQuake Risk Assessment Model (EQRAM). Fig. 8 shows the three modules of the EQRAM program: 1) PSHA, 2) vulnerability assessment and 3) risk assessment. The first module was discussed in detail in Sections 2 and 3, whereas the vulnerability module is the relationship (or relationships) between damage and ground shaking levels. EQRAM uses vulnerability relationships correlating mean damage ratio (MDR) to PGA. Vulnerability assessment is a complicated process as the existing building stock in the majority of the developing countries is mostly non-engineered with weak materials and poor construction practices. Comprehensive data on damage from past earthquakes are in general not available in developing countries. However, if applied at the macro scale level, basic vulnerability relationships can give reasonable results (Kythreoti, 2002). In this study, a general framework for determining the vulnerability of structures in developing countries (Ahmad *et al.*, 2015) was used to provide input data for the vulnerability module of EQRAM.

The third module of EQRAM addresses risk and casualty assessments. In the case of casualty risk calculation, casualty models are required either as simple relationships such as mean fatality/injury ratios against PGA or more advanced models such as the Coburn and Spence (1992) model. EQRAM uses the Coburn and Spence (1992) model which takes into account multiple parameters such as building damage, population occupancy trends, number of entrapped occupants and rescue capability at various levels. The third module of EQRAM also includes the building inventory (and population) assessment. A simple and low cost methodology was developed and used in EQRAM for building inventory assessments. EQRAM is based on a geographic information system using proprietary software (Zeiler, 1999; Burke, 2003), which facilitates the incorporation of the spatial aspects of hazard and risk. The probability or likelihood of damage and consequent loss of elements at risk can be calculated from the results of module 3.

Using results from the PSHA (module 1), appropriate vulnerability relationships (module 2), and casualty models, EQRAM calculates building damage and casualty risks (module 3). The subsequent sections describe

how EQRAM was used to carry out PSHA for Pakistan and arrive at risk assessment information for a region in Pakistan.

5 Seismotectonics and source zoning data for Pakistan

The geomorphology of Pakistan (area = 796,095 km²) varies from the high mountains of the Himalayas, Hindukush, Karakorum and Pamirs in the north to the coastline of the Arabian Sea in the south. Pakistan is situated on the western-rifted margin of the Indo-Pakistan sub-continental plate and lies on the northwestern corner of the Indian lithospheric plate, the southern part of the Afghan craton, and the northern part of the Arabian oceanic subducting plate (Zaigham and Mallick, 2000). The Indian plate has been in collision with the Eurasian plate for more than 35 million years, and it is still moving with a velocity of approximately 40 mm/year (PMD-NORSAR 2007). This high rate of movement is the cause of the high seismicity of the region as well as of the high mountain ranges. Fig. 9 shows the seismic activity around the Indian plate boundaries between 1973 and 2008 (ISC, 2009). The major tectonic features of Pakistan and surrounding areas are shown in Fig. 10 based on the information provided by BCP (2007). The major fault zones in Pakistan include the Sulaiman stretch in transpression and the Himalayan zone under-thrusting the Eurasian plate (Jadoon, 1992). Based on the studies of the Pakistan Meteorological Department (PMD-NORSAR, 2007), Pakistan and its surrounding regions were divided into 19 seismic zones by considering the direction of movement of the region, source mechanism of the fault system, and seismic activity and geology of the region (see Fig. 11). Note that whilst the source mechanism is not amongst the key parameters randomized in the proposed methodology, this information is used as an input. The tectonic characteristics of these seismic zones are listed in Table 2. For each seismic zone, the general fault direction was determined on the basis of existing faults within each seismic zone.

6 PSHA for Pakistan

To implement the proposed PSHA methodology, historical seismicity information of Pakistan was collected from the PMD-NORSAR (2007) historical database that includes seismic events from 25 AD (Taxila earthquake) and up to 1905 (Kangra earthquake), as shown in Fig. 12. The historical data show that major earthquakes cluster in the north east of the study region, as well as in the center of Pakistan near Quetta (where an earthquake occurred in 2008). Some of the important historic seismic events in Pakistan are listed in Table 3.

An instrumental earthquake catalogue ranging from 20°N to 38°N and 50°E to 85°E was obtained from the UK International Seismological Centre (ISC, 2009). Instrumental seismological data for Pakistan were recorded since 1960, and thus the instrumental seismic data are limited to the past half century. The area included in the instrumental catalogue is much more extensive than the area of Pakistan to include all earthquakes that are likely to impact Pakistan. These data are filtered to eliminate events with no impact (PGA < 0.05 g) to make the catalogue compact. These data are merged into a single catalogue as explained earlier to maintain the recurrence relationship at the macro level.

The selected instrumental and historical seismicity data (for Pakistan) categorized into different magnitude ranges are shown in Table 4. Synthetic earthquake catalogues are then generated by randomizing the key hazard parameters as explained previously in Section 2.2. Based on the sensitivity analysis, a minimum number of 50 simulations (synthetic earthquake catalogues) is recommended to lead to an adequate estimation of seismic hazard for the case study region (Khan, 2010). However, the results presented in this study are based on 100 synthetic earthquake catalogues.

The Ambraseys *et al.* (2005) attenuation relationship (Eq. (6)) was used to calculate the PGA for each event at each UA region of Pakistan.

$$\log(a) = 2.522 - 0.142M_W - (3.184 - 0.314M_W)\log\sqrt{(d^2 + 7.6^2)} + 0.137S_S + 0.05S_A - 0.084F_N + 0.062F_T - 0.044F_O \quad (6)$$

where d is the epicentral distance; $S_S = 1$ for soft soil (0 otherwise); $S_A = 1$ for stiff soil (0 otherwise); $F_N = 1$ for normal fault (0 otherwise); $F_T = 1$ for thrust fault (0 otherwise); and $F_O = 1$ for other faulting (0 otherwise). If the soil is not strictly stiff or soft based on the soil classification, the values of S_S and S_A can be chosen between 0 and 1 (Kythreoti, 2002). Note that the proposed method is different from traditional event by event calculation methods and therefore ground motion scatter is not explicitly considered in Eq. (6). However,

the ERA framework can accommodate any type of ground motion relationship, with (or without) prescribed scatter.

Note that due to the nonlinear nature of Eq. (6) ignoring the ground-motion scatter (σ) may lead to underestimated ground accelerations. Results indicate that the maximum and the average of the calculated PGA levels (POE of 10% in 50 years) for the case study example will increase by a maximum 5% and 1%, respectively, if σ is included in the calculations. Therefore, ignoring this factor does not considerably affect the predicted results.

The geological information for each UA was obtained using Pakistan's Geological Survey map (GSP, 2009), as well as from information provided by Hayat (2003) and data obtained from the National Highway Authority (NHA 2009). The calculated PGAs are then used to obtain Probabilistic Seismic Hazard maps for the region with a 10% Probability of Exceedance (POE) in 50 years as shown in Fig. 13. Note that the number of simulations is kept to 100 as less than 500 years return period assessments are usually required for ERA of residential buildings. This in turn also reduces computational time.

Fig. 14 compares the calculated hazard map (Fig. 13) with the existing hazard maps produced by the Building Code of Pakistan (BCP, 2007), Geological Survey of Pakistan (GSP, 2006), Pakistan Meteorological Department (PMD-NORSAR, 2007), and Global Seismic Hazard Assessment Program (GSHAP) developed by the US Geological Survey (USGS, 2009). Note that the GSP map was updated after the Kashmir (2005) earthquake, but the new map was based on the old 1974 GSP map and was not developed using a PSHA approach. Whilst the PMD (PMD-NORSAR, 2007) and BCP (BCP, 2007) maps were both developed by using PSHA studies, they still show different results as they are based on different seismic zonation maps. Since the BCP map is derived from the latest study, it appears to give the better results. The GSHAP map is part of the global hazard assessment program carried out at the global scale by USGS (2009), and does not present local seismic hazard distribution for the case study region in Pakistan.

The results of this study indicate that, despite some differences, in general there is a good agreement between the seismic hazard assessment carried out by the proposed methodology and the existing seismic hazard maps of Pakistan. Fig. 15 compares the ratio of areas exceeding a specific PGA level for the different hazard maps. It can be seen that, overall, the map by the Pakistan Meteorological Department (PMD-NORSAR, 2007) gives the highest PGA levels, whereas that by the Geological Survey of Pakistan (GSP, 2006) gives the lowest. Note that the latest PSHA method adopted by PMD-NORSAR places Peshawar at $PGA = 0.3g$. However, Ali and Khan (2005) provided a critical review of seismic hazard zoning of Peshawar city, suggesting that PGA should not be above $0.15g$. This indicates that the existing PSHA methods can overestimate hazard. This will increase the perceived risk, in turn increasing the cost of any mitigation measures.

It is also shown that the seismic hazard map calculated using the proposed PSHA methodology compares well with that included in the Building Code of Pakistan (BCP, 2007). However, the results of the current study lead to a more detailed local seismic hazard distribution while using only limited publicly available seismotectonic information.

7 Seismic risk assessment for the region of Islamabad to Peshawar

To demonstrate the use of EQRAM, a study region between Islamabad and Peshawar was selected to carry out ERA.

- Data on earthquake catalogue and seismic zoning is input for the study region. EQRAM automatically reduces it by removing events of lesser consequence.
- As input, EQRAM also requires soil types for use in the Ambraseys' (2005) GMPE. Fig. 16 shows the topographic and soil topology map of the study region. The different soil types and corresponding S_S and S_A values are given in Table 5. As can be seen, since the seven types of soil found in the region cannot be strictly classified as rock, stiff or soft soil, the values S_S and S_A are kept between 0 and 1 for calculations (Kythreoti, 2002).
- The EQRAM PSHA module was also used to determine the local seismic hazard map for the study region with a 10% POE in 50 years (Fig. 17(a)).
- The building inventory was developed for the case study region by using 1998 census data (FBS, 2007) and satellite imagery (Khan, 2010). This is input to EQRAM.

- Initially, basic vulnerability curves from GESI (GESI 2001) were used. A further study at the University of Sheffield (Ahmad *et al.*, 2015) has recently produced new vulnerability curves for the typical RC structures in the region, and these curves will be adopted in future studies (input to EQRAM).
- Reconstruction costs for each category of buildings were also obtained from local engineers based on the Net Present Value (NPV) of 2008. This is also input with the corresponding vulnerability curves.
- EQRAM produced the monetary risk assessment for the study region, as shown in Fig. 17(b). The monetary risk was also converted into insurance premium. Note that the reported risk in Fig. 17(b) is the average annual risk within the considered timeframe.
- EQRAM also includes a casualty module, of which details can be found in Khan (2010). To demonstrate the use of this module, Fig. 18(a) and (b) show the likely annual fatality and annual injury results for the study region, respectively.
- As expected, most casualty risk is concentrated in and around the large urban areas of Peshawar and Islamabad.

Finally, note that the present study is part of a wider project on earthquake risk mitigation framework for developing countries currently underway at the University of Sheffield. The completed EQRAM program will include additional components for tsunamis, landslides, industrial facilities, services, and optimum risk mitigation strategies.

8 Conclusions

A practical PSHA methodology is proposed for integrating with a new ERA framework (EQRAM) for countries where limited studies on tectonics and seismicity exist. This PSHA method is based on synthetic earthquake catalogues that are generated by randomizing the key hazard parameters of earthquake magnitude, epicentral location, depth of hypocenter, and basic tectonic and geological parameters. Existing historical seismicity data are integrated with the more complete instrumental seismicity in such a way that the recurrence pattern of the instrumental seismicity remains unchanged. The method is demonstrated by carrying out a PSHA study for Pakistan. The PSHA results compare well with previous PSHA studies. In particular, the results are consistent with the PSHA map included in the most recent National Building Code of Pakistan. This indicates that the proposed method can be suitable for generating hazard maps in regions where limited data are available. EQRAM, which integrates the PSHA method, was then used to generate ERA for a selected region between Islamabad and Peshawar. As expected, most casualty risk is concentrated in and around the large urban areas of Peshawar and Islamabad. The proposed framework can be extended to other developing regions around the world and its results can be used to assist relevant stakeholders and decision-makers on preparedness, emergency response and mitigation actions.

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Figures

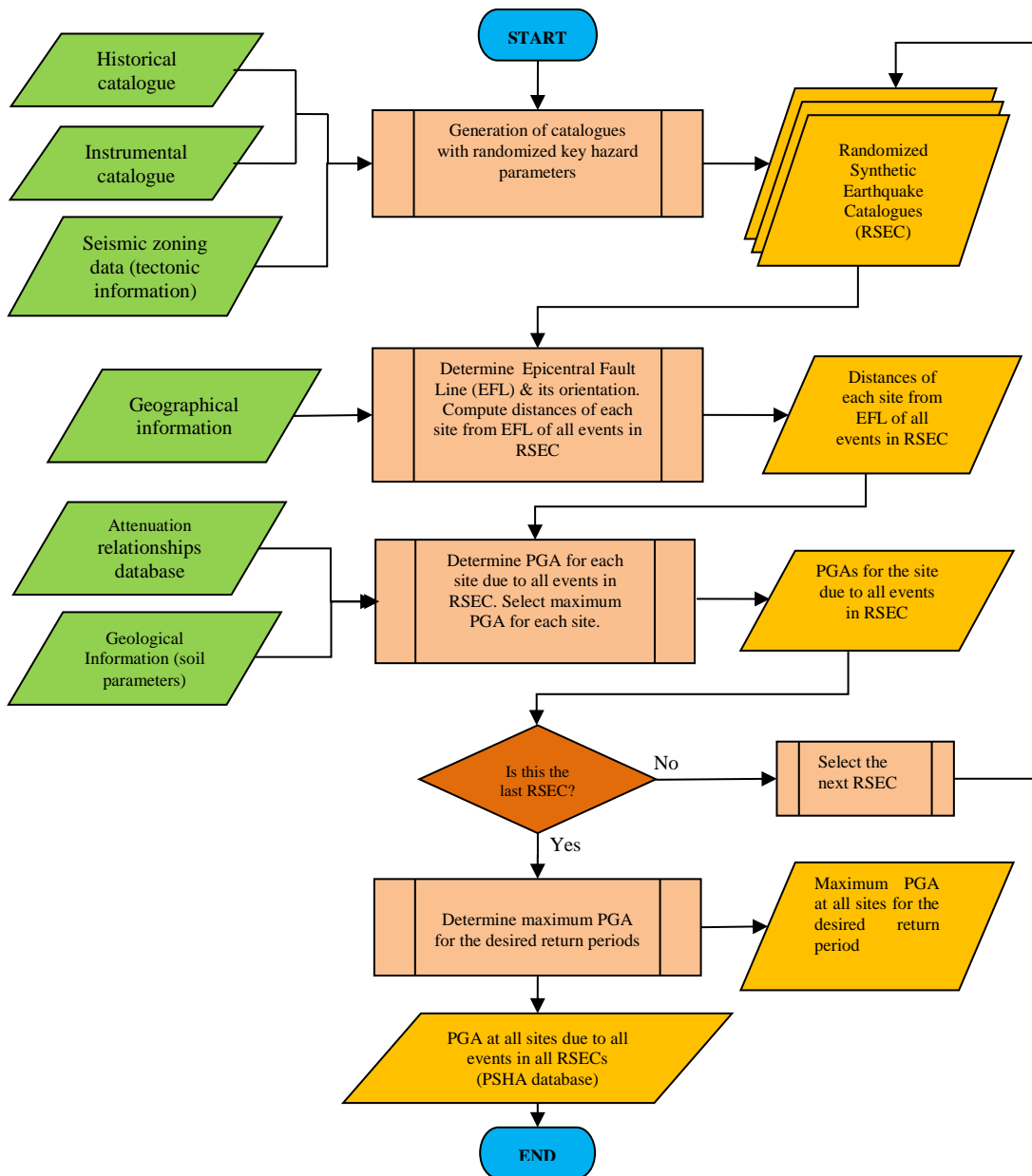


Fig. 1 Flowchart of the proposed PSHA process

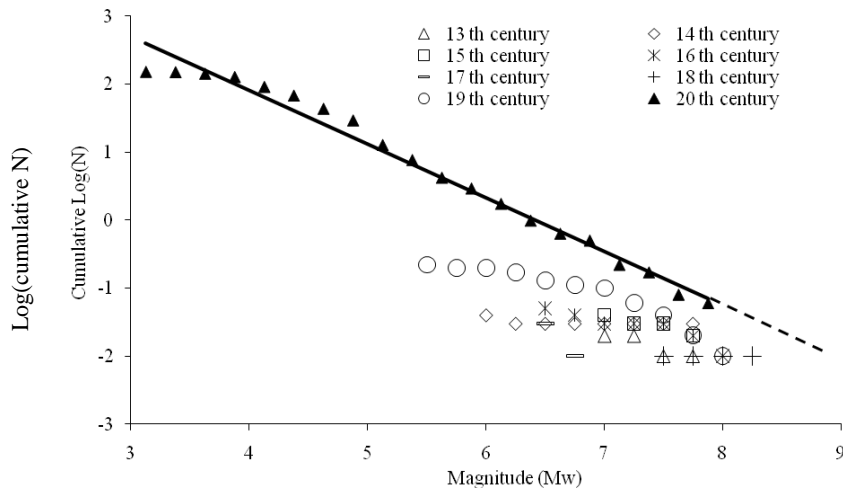


Fig. 2 Magnitude-recurrence relations computed with the data from historical and instrumental catalogues in different centuries for the study region in Pakistan

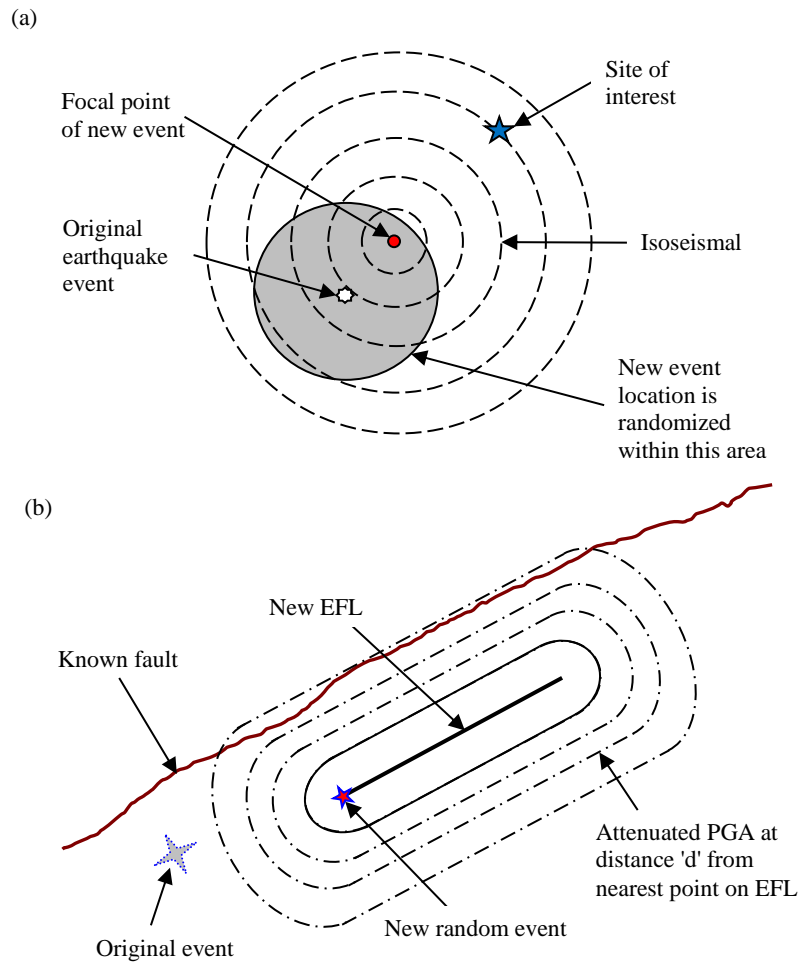


Fig. 3 Generation of new random event and earthquake intensity: (a) spreading from focal point, and (b) spreading from the rupture line (EFL)

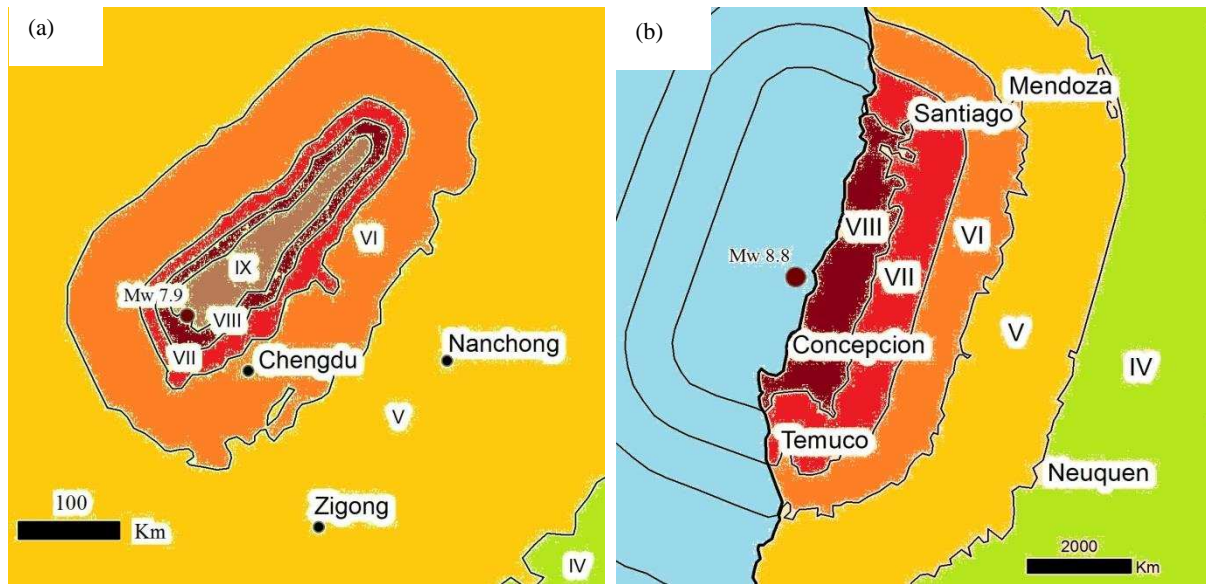


Fig. 4 Estimated earthquake intensity patterns for: (a) Chengdu in China (2008) and (b) Concepcion in Chile (2010) adopted from USGS website (USGS, 2010)

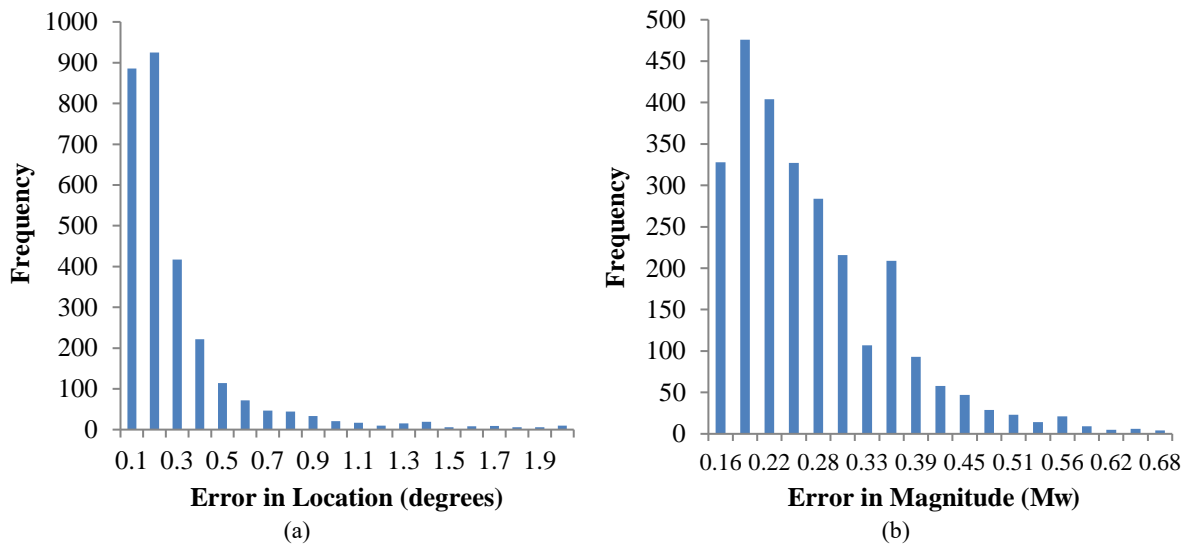


Fig. 5 Distribution of errors in the determination of (a) location and (b) magnitude of instrumental seismicity in Pakistan

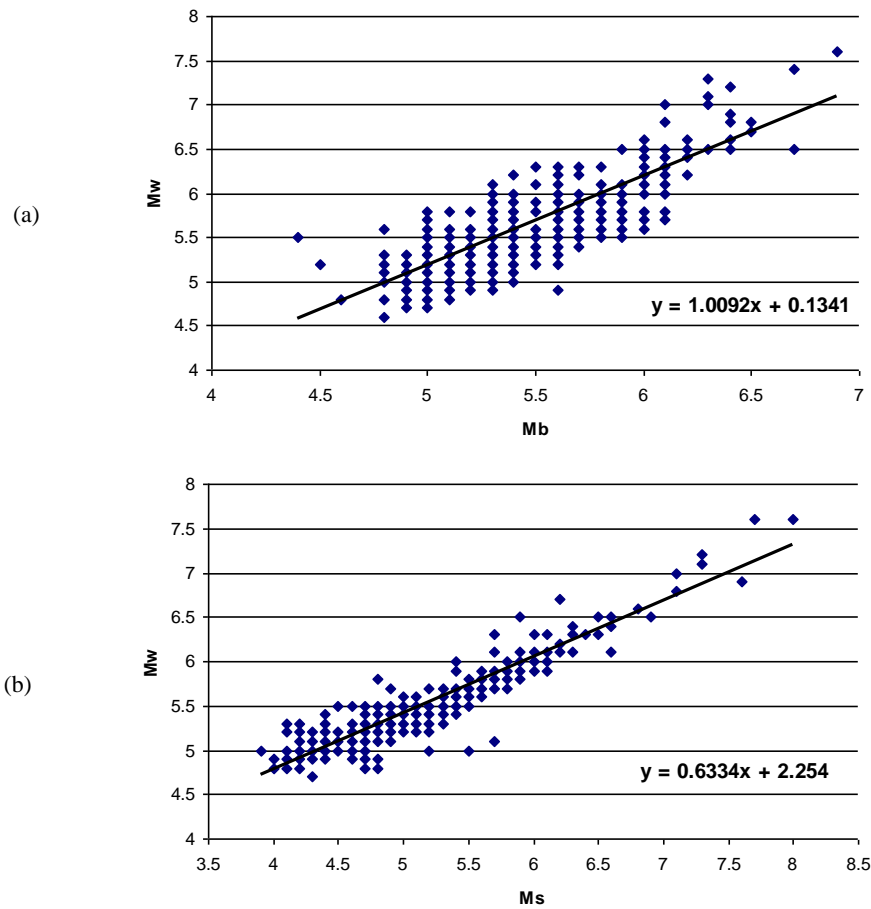


Fig. 6 Conversion of (a) M_b into M_w , (b) M_s into M_w

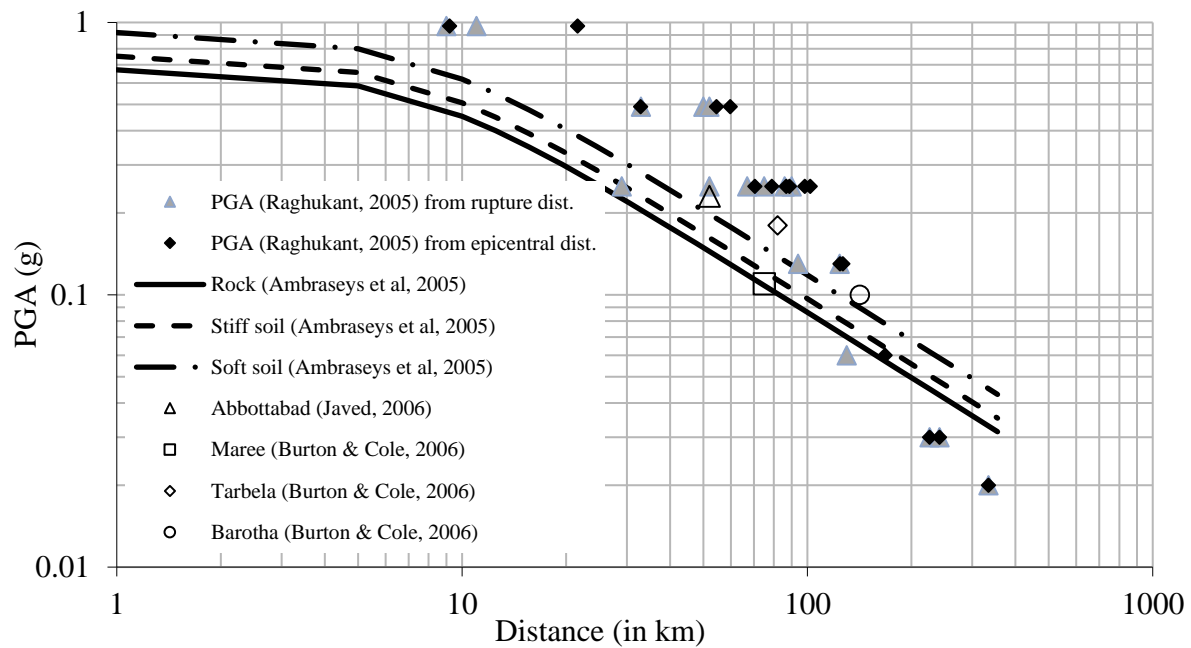


Fig. 7 Comparison between Ambraseys *et al.* (2005) attenuation relationship with the observed PGA recorded after 2005 Kashmir earthquake

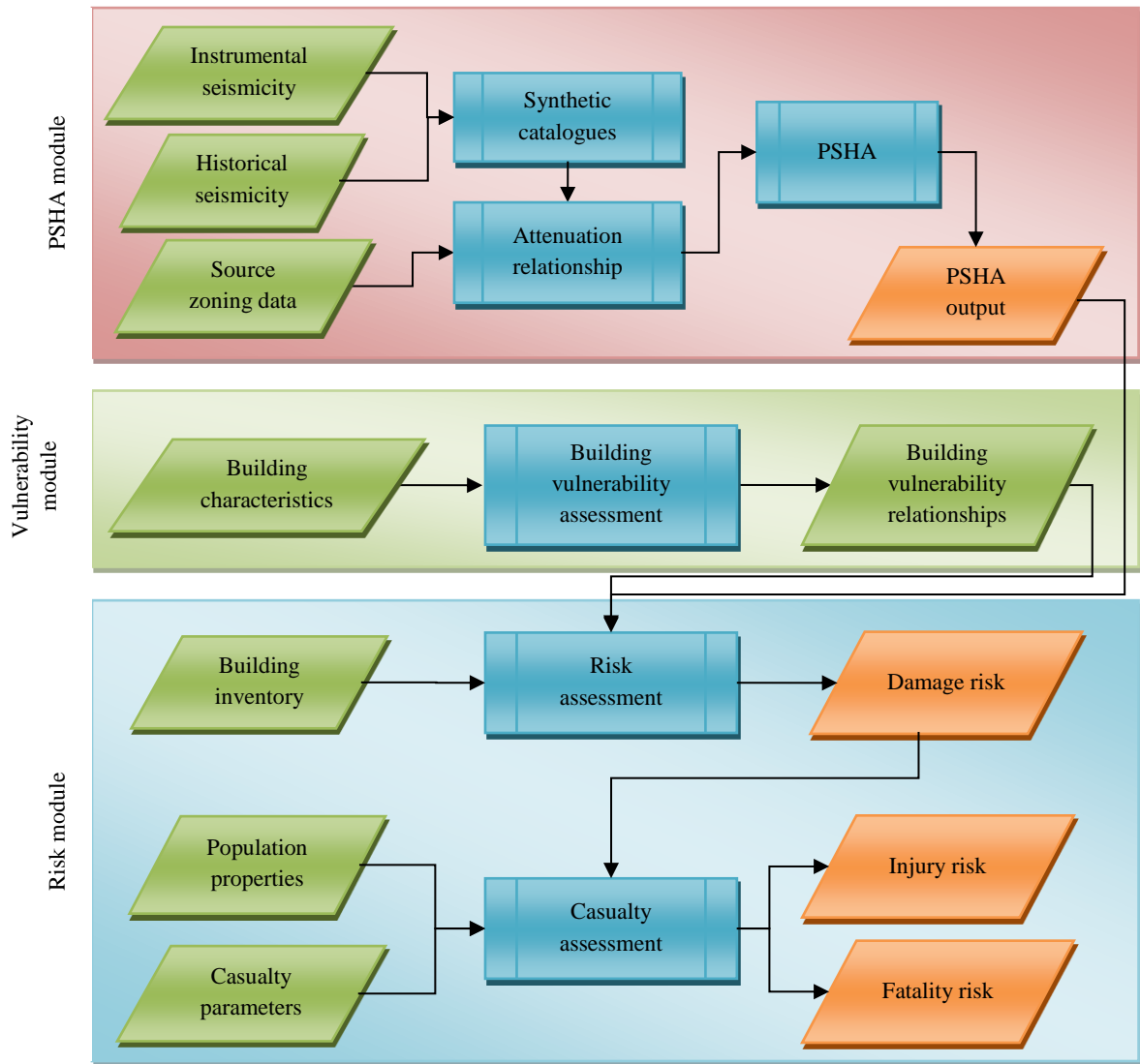


Fig. 8 General outline of the EQRAM program

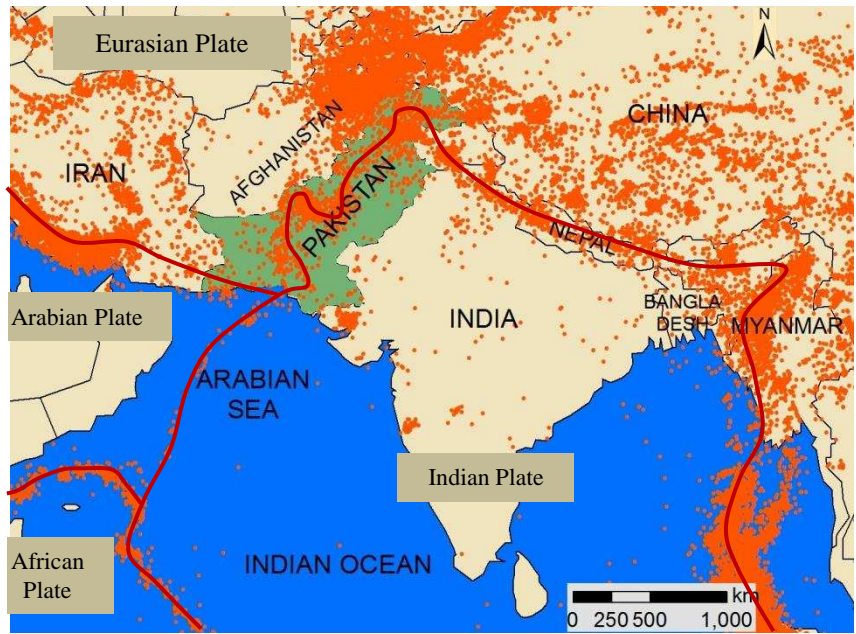


Fig. 9 Seismic activity around the Indian plate boundaries between 1973 and 2008 (after ISC, 2009)

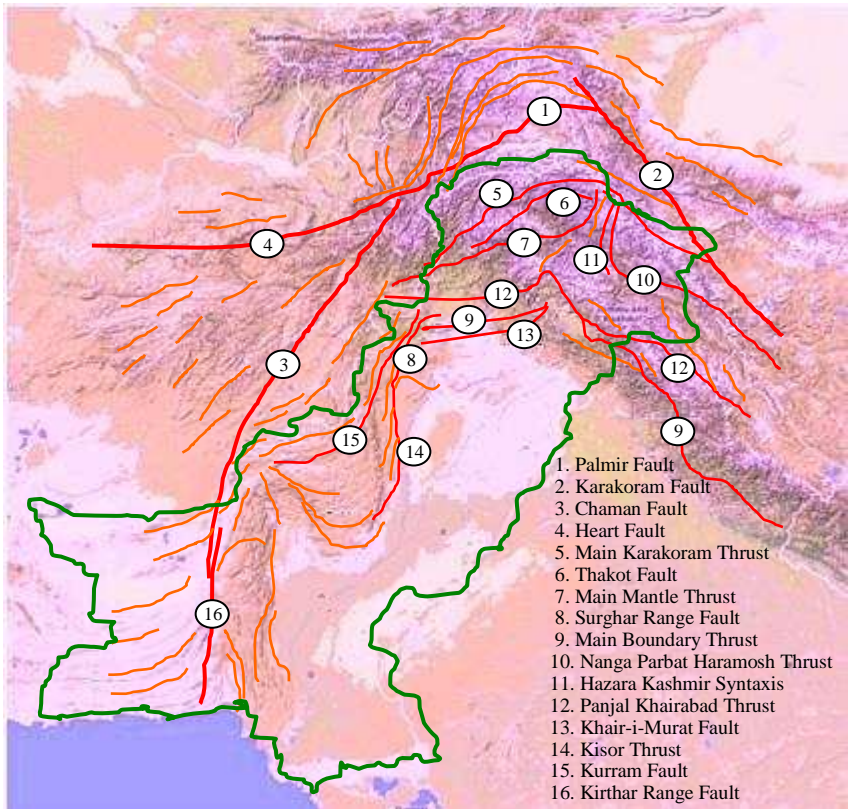


Fig. 10 Major tectonic features in Pakistan (after BCP, 2007)

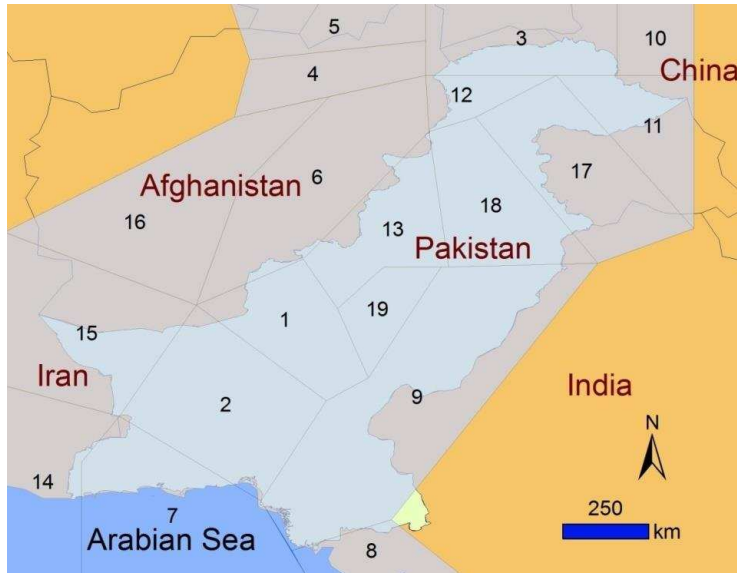


Fig. 11 Seismic source zoning of Pakistan region (after PMD-NORSAR, 2007)

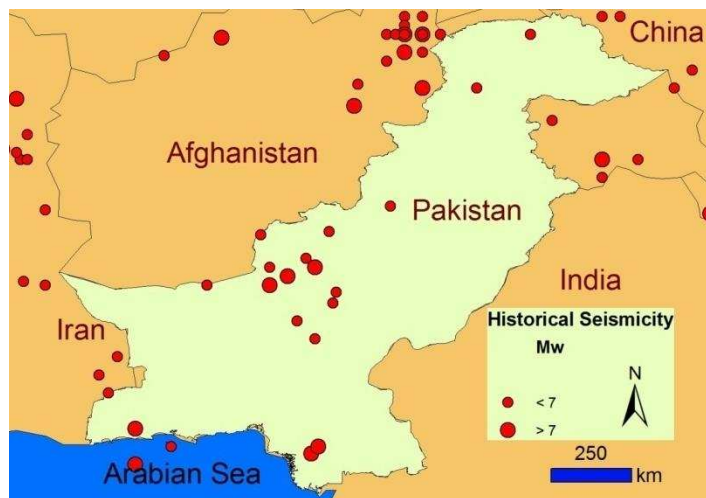


Fig. 12 Major historical earthquakes from the PMD-NORSAR catalogue (25-1905 AD)

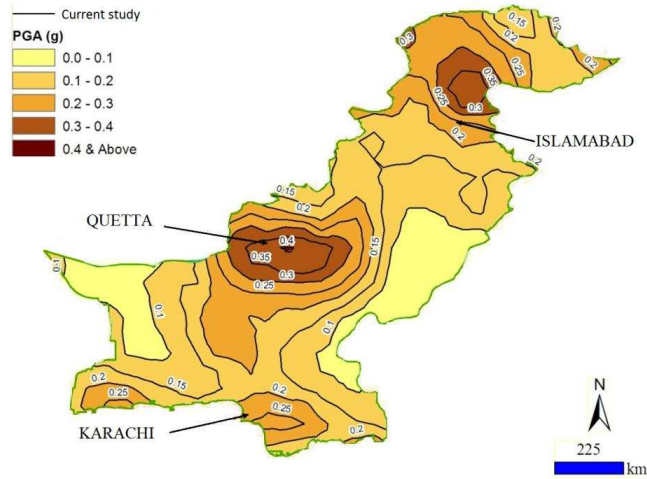


Fig. 13 Seismic hazard map with 10% POE in 50 years using the proposed PSHA methodology

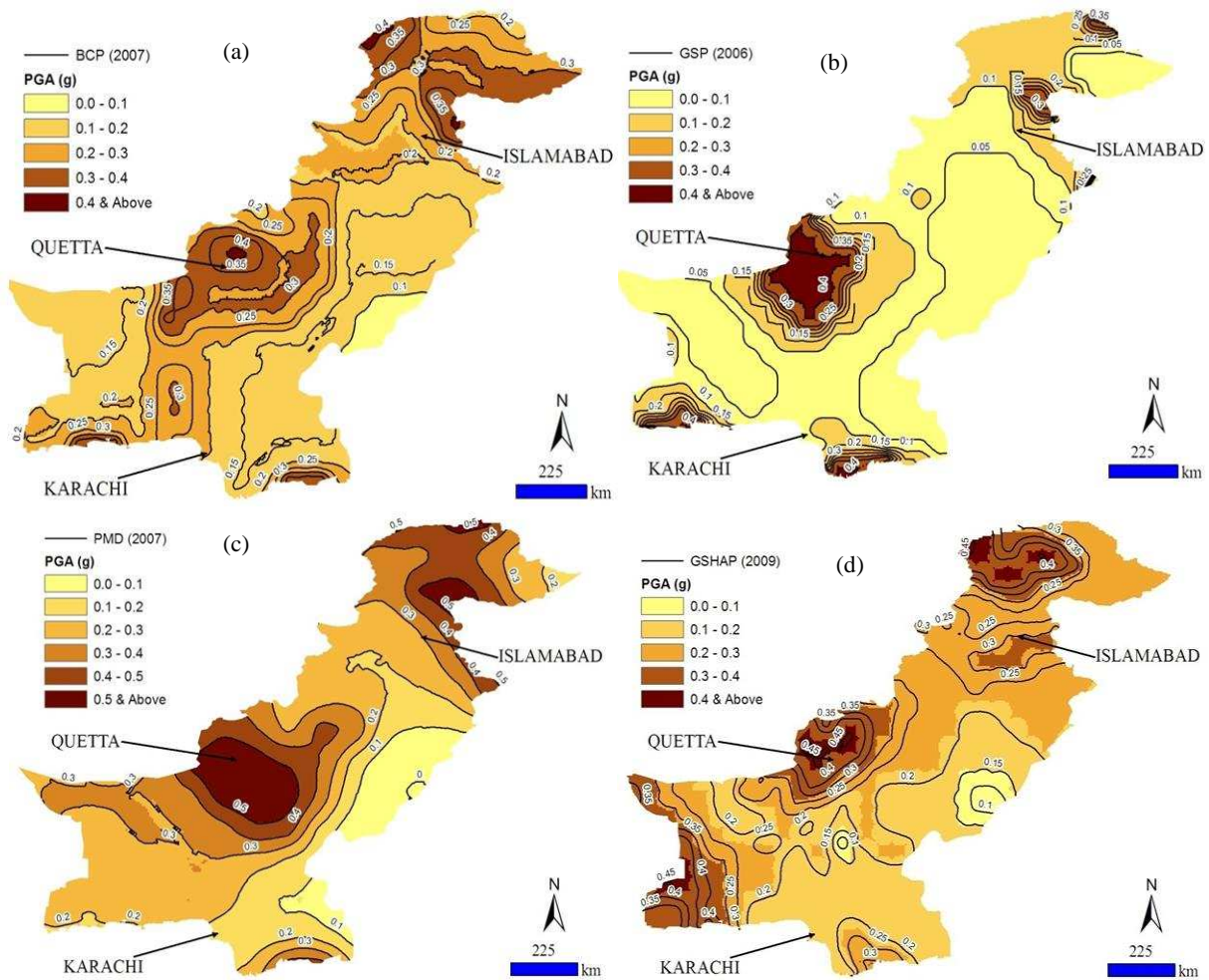


Fig. 14 Seismic hazard maps for a 10% POE in 50 years according to (a) Building Code of Pakistan (BCP, 2007), (b) Geological Survey of Pakistan (GSP, 2006), (c) Pakistan Meteorological Department (PMD-NORSAR, 2007) and (d) Global Seismic Hazard Program (GSHAP) by USGS (2009)

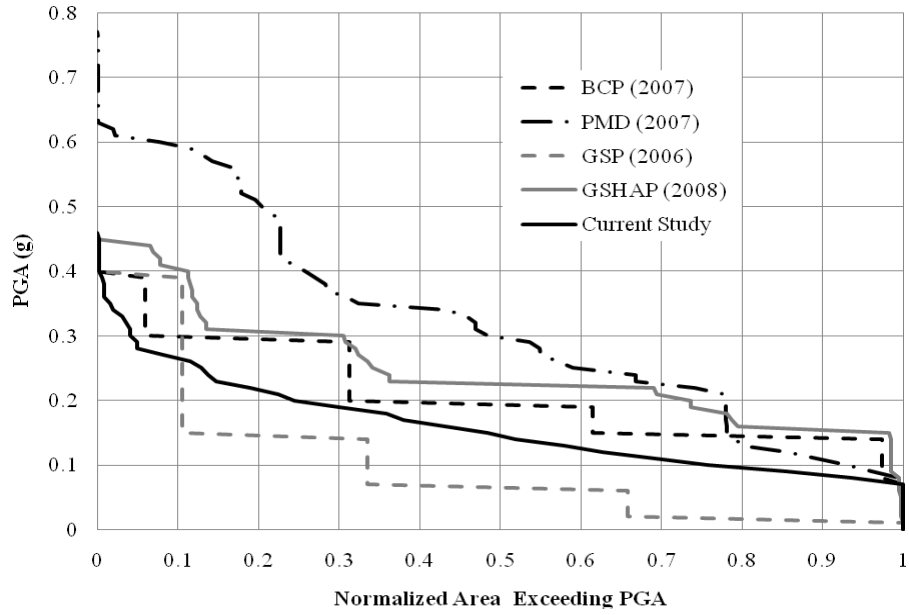


Fig. 15 Normalized area exceeding a specific PGA level (50 year with 10% POE) based on different seismic hazard maps of Pakistan

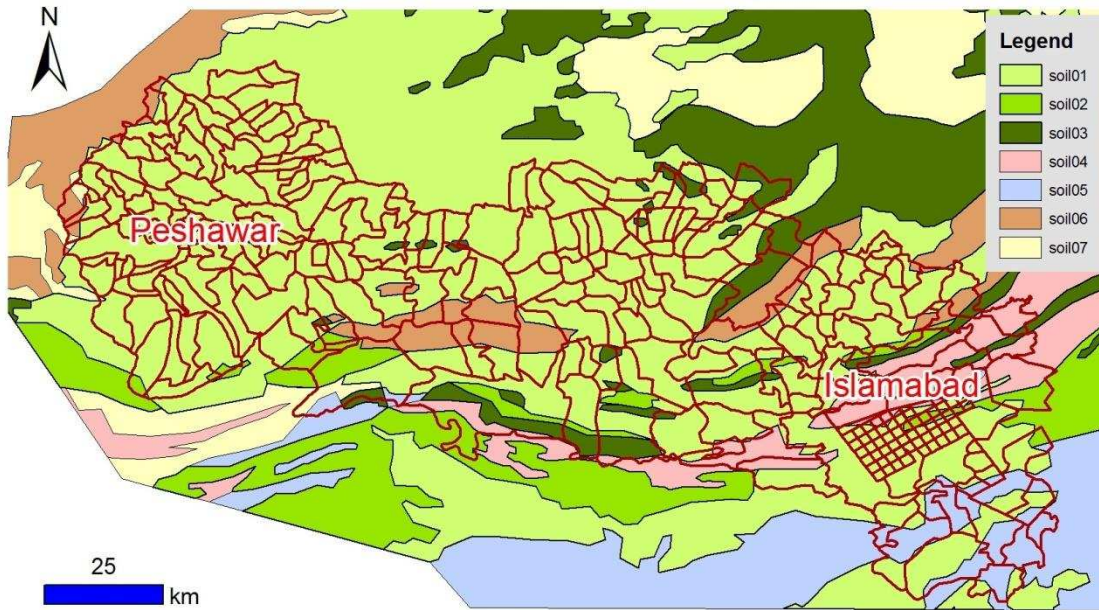


Fig. 16 Soil typology map overlaid by the UCs within the study region

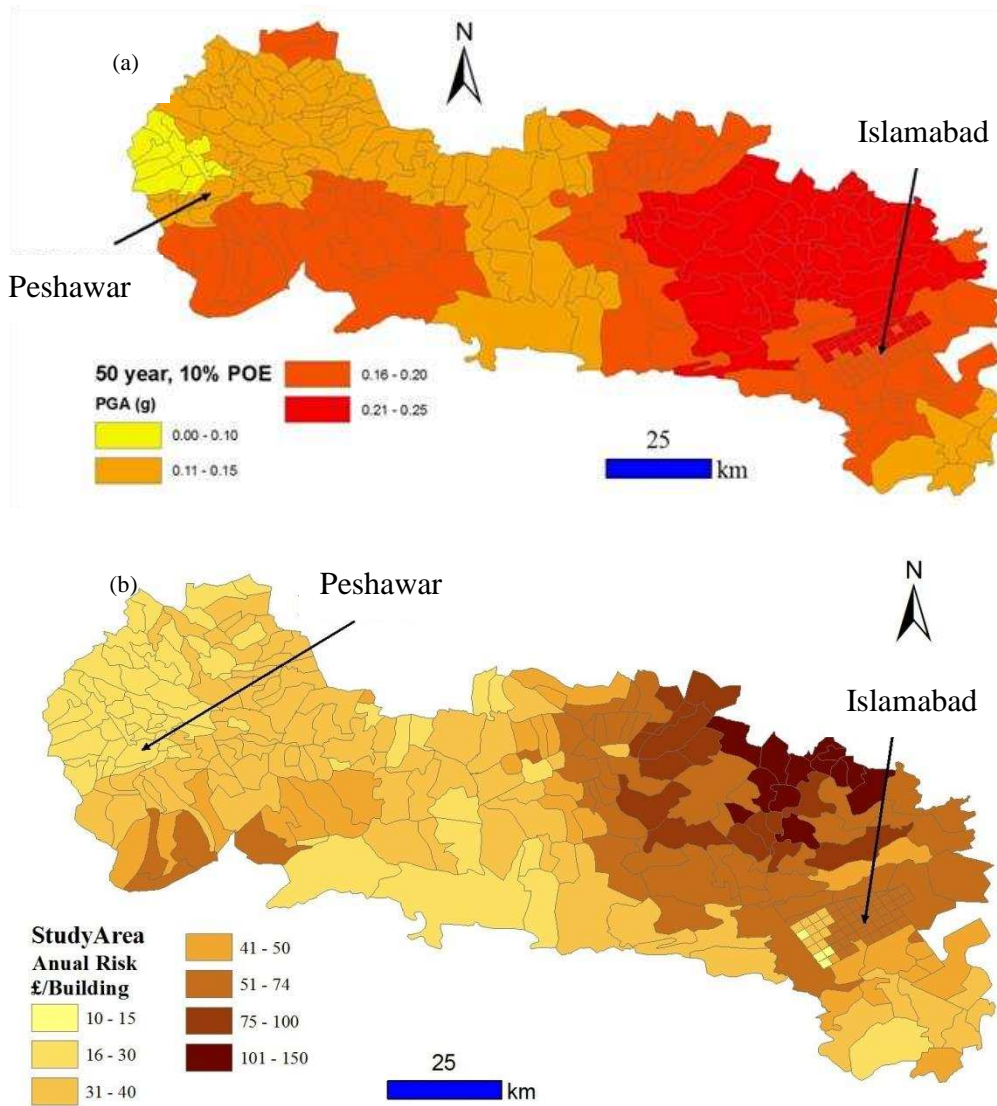


Fig. 17 Results for hazard and monetary risk assessments by EQRAM applied to the study region (a) PSHA, (b) monetary risk assessment (NPV of 2008)

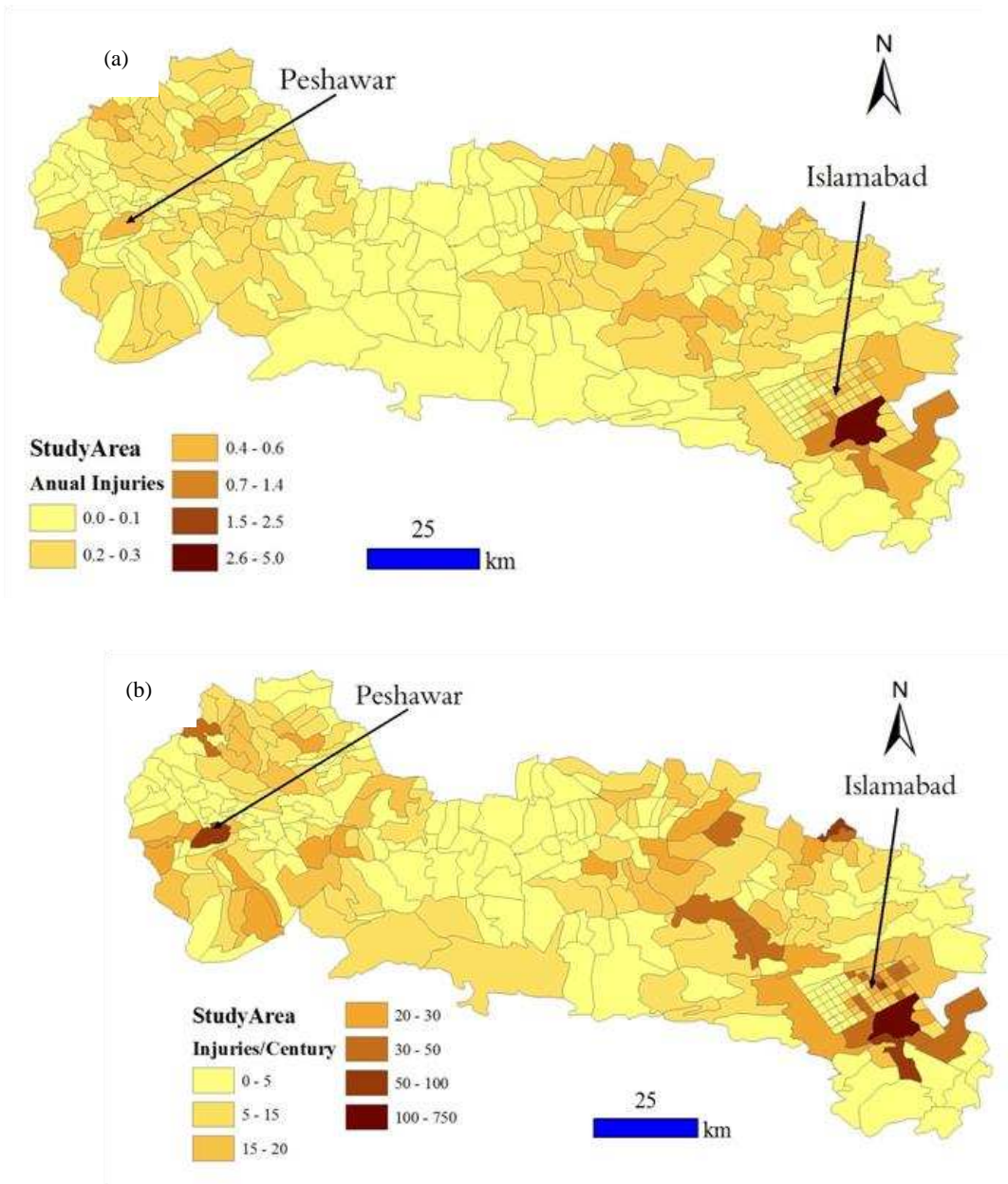


Fig. 18 Results for casualty assessment by EQRAM applied to the study region (a) fatality risk and (b) injury risk (POE of 10% in 50 years, 2008 population data)

Tables

Table 1 Inclusion of historical seismicity into the synthetic instrumental catalogues

	Magnitude (M_w)	Magnitude ranges				
		1	2	3	4	5
		< 5	5 - 6	6 - 7	7 - 8	> 8
1	20 th Century	n^1_1	n^1_2	n^1_3	n^1_4	n^1_5
2	19 th Century	n^2_1	n^2_2	n^2_3	n^2_4	n^2_5
3	18 th Century	n^3_1	n^3_2	n^3_3	n^3_4	n^3_5
4	17 th Century	n^4_1	n^4_2	n^4_3	n^4_4	n^4_5
5	16 th Century	n^5_1	n^5_2	n^5_3	n^5_4	n^5_5
6	15 th Century	n^6_1	n^6_2	n^6_3	n^6_4	n^6_5
Total number of events		$\sum n^i_1$	$\sum n^i_2$	$\sum n^i_3$	$\sum n^i_4$	$\sum n^i_5$

Table 2 Tectonic characteristics of seismic zones

Zone	Name	Seismic activity	Max. magnitude	General fault direction (bearing from north)	Fault mechanism
1	Kohistan-Kashmir	Very high	7.6	NW-SE (110°)	Thrust
2	Northern Balochistan	Very high	7.0	NE-SW (315°)	Thrust
3	Quetta-Sibi	Very high	7.5	E-W (285°)	Thrust
4	Southern Baluchistan	Low	5.0	NE-SW (320°)	Strike-slip
5	Northern Afghanistan-Tajakistan	High	6.0	E-W (265°)	Thrust
6	Hindu Kush	Very high	7.0	N-S (235°)	Strike-slip
7	North Western Afghanistan-Tajikistan Border Region	Very high	7.0	NE-SW (325°)	Thrust
8	Eastern Afghanistan	Low	4.0	NE-SW (320°)	Strike-slip
9	Makran Coast	Low	5.0	E-W (250°)	Thrust
10	Runn of Kuchch	High	8.1	NW-SE (115°)	Strike-slip
11	Sindh-Punjab	Very low	4.0	NE-SW (170°)	Strike-slip
12	Pamir Kunlun	Low	6.0	NW-SE (125°)	Thrust
13	Indian Kashmir	Low	6.0	NW-SE (95°)	Thrust
14	Upper Punjab-NWFP	Low	5.0	NE-SW (170°)	Thrust
15	Chitral	High	6.5	NW-SE (95°)	Thrust
16	Koh e Sulaiman	Low	4.0	NE-SW (170°)	Strike-slip
17	South West Iran	High	6.0	E-W (240°)	Strike-slip
18	Western Baluchistan	High	6.0	N-S (190°)	Strike-slip
19	Central Southern Afghanistan	Very low	4.0	NE-SW (320°)	Strike-slip

Table 3 Some major seismic events in Pakistan from the PMD-NORSAR catalogue

Place	Year	Latitude	Longitude	Magnitude/Intensity
Taxila	25AD	33.7	72.9	X
Dabul	893AD	24.8	67.8	VIII - X
Runn of Cutch	1819	23.3	68.9	IX - X
Kashmir	1828	34.1	74.8	X
Kashmir	1885	34.1	74.8	IX - X
Kangra	1905	32.1	76.3	8.0
Quetta	1935	29.5	66.8	7.7
Makran	1945	24.5	63.0	8.0
Kashmir	2005	34.5	73.6	7.6
Quetta	2008	30.5	67.4	6.4

Table 4 Instrumental and historical seismicity data of Pakistan categorized into different magnitude ranges

Centuries	Magnitude (M_w) range					
	≤ 6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5-8.0	≥ 8.0
20 th	9000	114	45	22	8	3
19 th	101	5	4	5	2	0
18 th	16	-	0	0	1	1
17 th	-	-	3	0	0	0
16 th	-	-	1	0	1	0
15 th	-	-	1	2	0	1
14 th	-	-	-	0	3	0
13 th	-	-	-	1	1	0
Total Events	9117	119	54	30	16	5

Table 5 Formation of different soil types and S_s and S_A values in the study area.

Soil type	Formation	Soil type	S_s	S_A
Soil 01	Holocene: Unconsolidated, Silt, Clay, Sand and Gravel	Soft	1	0
Soil 02	Eocene and paleocene rocks: Shales, Limestone, Sandstone and Silts with Conglomerate.	Stiff	0	0.75
Soil 03	Pre-Cambrian and Jurassic rocks: Quartzite, Marble, Graphite Schist, Granite, Syenite and Diorite.	Rock	0	0
Soil 04	Miocene rocks: Siltstone, Sandstone, Conglomerate, Red-brown Mudstone and Hard Sandstone.	Stiff	0	0.25
Soil 05	Holocene: Silt, Sand and Gravel.	Soft	0.50	0
Soil 06	Pre-Cambrian metamorphic sedimentary and Carboniferous to pre-Cambrian rocks: Schist, Quartzite, Dolomite, Marble, Phylites, Limestone, and Slate.	Rock	0	0
Soil 07	Cambrian igneous rocks: mostly Granite and Leucocratic Siliceous Gness.	Rock	0	0