A New Framework for Earthquake Risk Assessment in Developing Countries

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SUMMARY:
Modern Probabilistic Seismic Hazard Assessment (PSHA) methods usually require seismo-tectonic information that is not readily available in many developing countries. In this study, a new event based PSHA method is developed based on instrumental seismicity and limited information on historical seismicity, geology and tectonic setting of the study region. The effect of tectonic setting is included by assigning seismic source zones associated with known major faults. Historical seismicity, when available, is integrated with instrumental seismicity to determine long term hazard. The method uses Monte-Carlo simulations to generate synthetic earthquake event catalogues with randomized key hazard parameters. The proposed PSHA method is tested using Pakistan as a case study. The results of this study compare well with the National Building Code hazard map of Pakistan, while they show more detailed local hazard distribution. This methodology is part of a wider general framework called EQRAM for ERA and mitigation studies.

Keywords: Seismic Hazard Assessment, Monte-Carlo simulations, Risk Assessment, Building Inventory

1 INTRODUCTION

The devastation of earthquakes has become subject of importance in today's world. Especially in developing countries where population is generally large, building structures are highly vulnerable and there is not enough knowledge of seismic hazard. The devastating seismic events of Kashmir (2005) in Pakistan, Chengdu (2008) in China and Haiti (2010) occurred in the present decade. The humungous loss of life and property emphasises the need for Earthquake Risk Assessment (ERA) in the developing countries.

Seismic Hazard Assessment (SHA) is an important component of ERA as risk is highly dependent on hazard. Seismic hazard is unpredictable due to uncertainties associated with earthquakes and it is desirable to treat SHA probabilistically. ERA depends on special distribution of hazard which makes it important to accurately determine the special distribution of hazard. The existing Probabilistic Seismic Hazard Assessment (PSHA) methodology gives overestimated results from the ERA point of view. Earthquake recurrence relationships are usually determined by power law, such as Gutenberg-Richter relationship (Gutenberg and Richter, 1954), where as some fault systems may not follow the power law up to the maximum magnitude (Wesnousky et al. 1994 in Dahmen et al. 1998). It is possible that hazard may be overestimated in PSHA if the power law is not obeyed by earthquakes in a region. Selection of minimum magnitude (M_{min}) is usually based on events of least engineering significance, say M_w 4 to 5. For example for M_{min}=5 the events with M_w= 4.99 will be excluded whereas M_w= 5 will be included in PSHA (Abrahamson, 2006). This is a source of inaccuracy for use in ERA because a small magnitude earthquake occurring very close to a site of interest may produce a high level of ground motion as compared to a large magnitude earthquake at a distance (Khan, 2010). Conventional PSHA methods use seismicity distributions that are spatially smeared over source zones or are smoothed using some function at distances which may lead to spatial inaccuracies in hazard values (Abrahamson, 2006). The inaccuracies in the spatial distribution of hazard will result in overestimation of risk at certain location within the region of interest.

Computer codes such as EQRISK (McGuire, 1976), CRISIS (Ordaz, 2003), SEISRISK III (Bender and Perkins, 1987), EQRM (Robinson et al. 2005), FRISK88M (McGuire, 1978), OpenSHA(Field et al. 2003) and NSHM (Frankel et al. 2009), use different approaches in the modelling of seismicity within a seismic source (Danciu et al. 2009). These codes are more like black boxes and cannot be easily modified to be implemented in the new ERA framework.

Although the conventional PSHA methodology is appropriate for design purposes it may not be suitable for ERA studies which require a more realistic estimation of hazard levels during the time period of interest. To carry out ERA studies a new PSHA approach is required where the shortcomings of the conventional PSHA methodology are rectified. Moreover, in developing countries the lack of information on historical seismicity and tectonics needs to be address so that speedy and reasonable PSHA studies may be carried out. An alternative method was proposed by Kythreoti (2002) where it was assumed that the seismic behaviour of future seismicity will be consistent with the past century (instrumental) seismicity. Although the method solves the issue of overestimation (Kythreoti 2002), the assumption of spreading earthquakes from their focal points (see Figure 1.1a) is not valid for regions with large magnitude seismicity since the intensity of the earthquake spreads perpendicular to the line of rupture (see Figure 1.1b). In a high magnitude event the size of rupture is considerably large and is oriented along (or parallel) to the existing fault line (Wells and Coppersmith 1994).

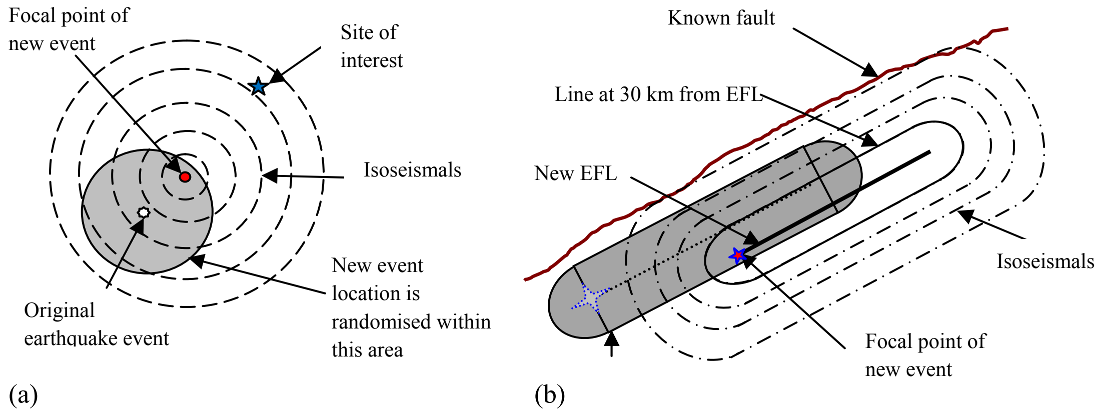


Figure 1.1. Generation of new random event and earthquake intensity, (a) spreading from focal point and (b) spreading from the rupture line (EFL).

2 THE PSHA METHODOLOGY

The PSHA methodology proposed in this paper is based on use of instrumental seismicity catalogue with available information on tectonics and historical seismicity. Using the instrumental seismicity, which covers at least a seismic cycle of largest earthquake and contains events of all probable magnitudes, may well characterise earthquake rate of the investigated area and therefore, substitutes the use of recurrence relationships. Minimum magnitude selection is no more required and the elimination of insignificant ground motions can be implemented by using a lower bound for ground motion values. The generation of new random events around rupture area ensures that the spatial distribution of earthquakes remains realistic with real seismicity as it does not uniformly smear the seismicity over the seismic area sources. The PSHA process is integrated into an ERA framework where risk may be determined probabilistically for a given region.

In the new methodology Monte Carlo simulations are used for PSHA as described in the following section.

2.1 Use of Monte Carlo simulations method for PSHA

Monte Carlo simulations are applied on a significant number of synthetic catalogues that are developed by randomising key hazard parameters of the earthquake events in the instrumental seismicity catalogue (Kythreoti, 2002). A parametric study carried out by Kythreoti (2002) concluded that the key hazard parameters are the earthquake magnitude, depth, epicentral location, and site geology. The errors encountered in the determination of the key hazard parameters such as error in magnitude (or location) are used in randomising these key hazard parameters. For example: a synthetic catalogue will contain all events of the original instrumental catalogue but their locations, magnitudes, and depths will be slightly modified according to the corresponding errors values. Magnitude of a new event in the synthetic catalogue will be given by the following equation 2.1:

$$M_R = M_0 \pm (e \times N_R) \tag{2.1}$$

Where, M_R is magnitude value of new random event, M_0 is magnitude original of the original, e is the error and N_R is a random number based on uniform distribution.

Similarly new location and depth are also determined for the new event (see Figure 1.1). For epicentral location, the new event is placed in a circular area with radius equal to the error in location and centre at the focal point of the original event. In simple words the events in original catalogue are smudged to produce new random synthetic catalogues that represent new random centuries. Figure 2.1 shows a flowchart of computer code for the PSHA process that will be incorporated into the ERA Framework.

The PSHA procedure is simple and can be integrated easily into the ERA framework which directly allows probabilistic assessment of risk.

2.1.1 New randomised locations of large magnitude events

Ground motion levels such as intensities or peak ground accelerations (PGA) are distributed around the rupture line instead of focal point of the earthquake (see Figure 1.1). For moderate to small events (say $M_w \leq 6$) the ground motion contours can be considered nearly circular due to small rupture lengths where as in large magnitude events the rupture lengths are significantly large and ground motion contours may be considered as elliptical. Therefore, locations of new random events (with large magnitudes) are placed within a radius equal to the error and around the rupture line here by called as “Epicentral Fault Length” (EFL). The EFL is oriented parallel to the general fault direction of the seismic source zone for the original event. Location of new randomised event with respect to original event for a typical large magnitude earthquake is shown in Figure 1.1b.

Using attenuation relationship the ground motion levels (PGAs) for the new large magnitude events are also calculated from the EFL instead of their focal points (see Figure 1.1b).

2.1.2 Inclusion of historical earthquakes into the instrumental seismicity

Historic earthquake catalogues are generally incomplete since the regional history (and geology) provides information only on the large magnitude earthquakes, whereas the low magnitude seismicity is missing. However, historical seismicity can play an important role in SHA as it may add important information on seismic sources of a region that are not captured in the instrumental records. The instrumental seismicity only provides a view of a short time frame for the seismicity, which may not be a suitable representation of the long term seismic activity of the study region at the meso-level. Therefore, to generate reliable synthetic earthquake catalogues, it is necessary to include the historical seismicity in an appropriate way. However, it should be borne in mind that historical seismicity is usually very limited and does not include small to moderate earthquakes.

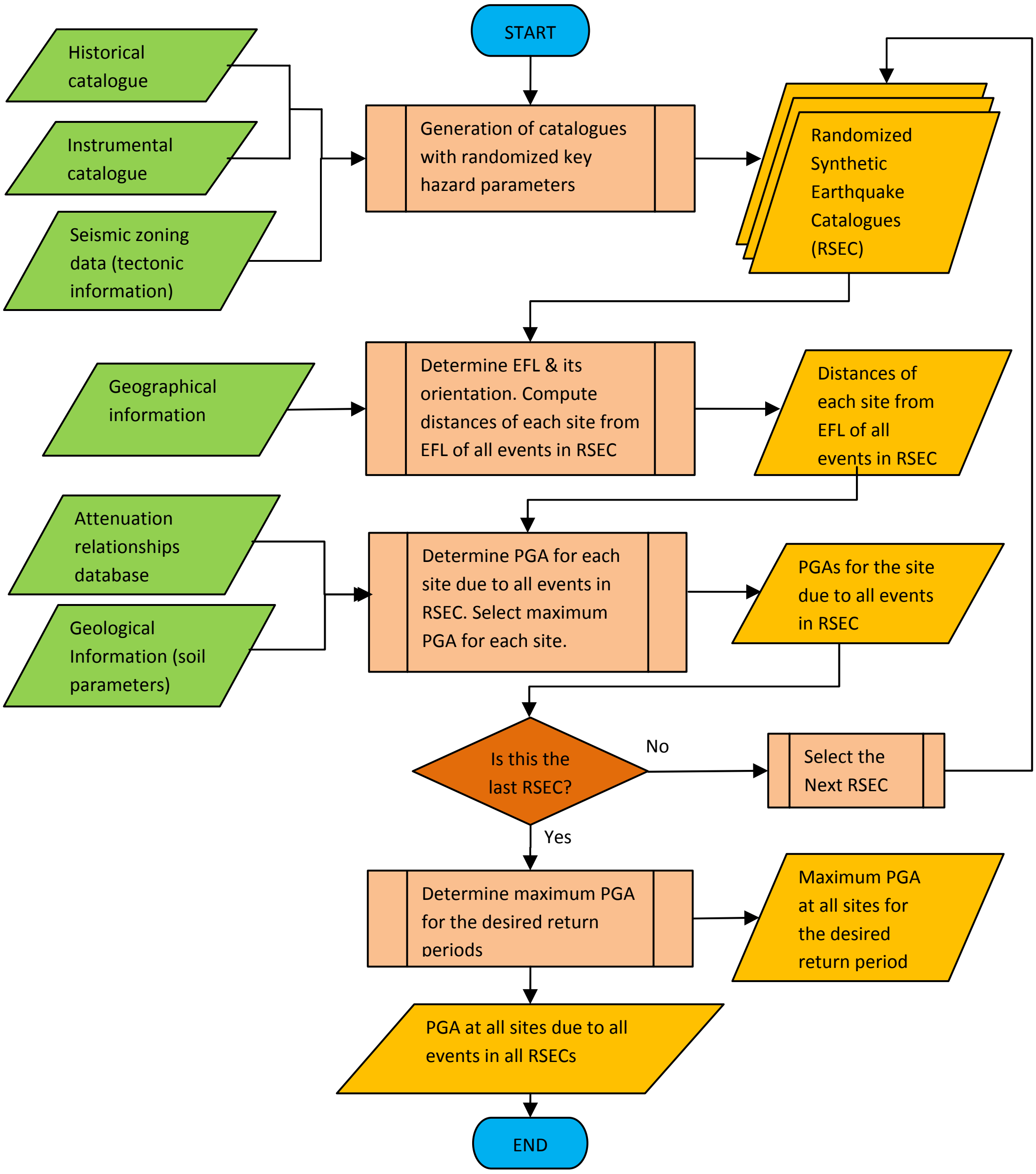


Figure 2.1. Flowchart of the proposed PSHA process

In this study, the historical seismicity is integrated into the instrumental seismicity in such a way that the recurrence pattern of the instrumental seismicity at the macro level remains unchanged. For this purpose, the available seismicity data for the study region is banded into magnitude ranges, as shown for example in Table 1. To generate a synthetic earthquake catalogue, for each magnitude range n^1_j earthquakes are randomly chosen out of $\sum n^i_j$ earthquakes; where i and j are century and magnitude range index, respectively (see Table 1). Utilizing this technique, the number of earthquake events in each magnitude range remains similar to the current 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). 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 issues associated with using conventional PSHA methods, as discussed earlier.

Table 1. Inclusion of historical seismicity into the synthetic instrumental catalogues

		Magnitude Ranges				
		1	2	3	4	5
	Magnitude (*M*w)	< 5	5 - 6	6 - 7	7 – 8	> 8
1	Current 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		$\sum n^i_1$	$\sum n^i_2$	$\sum n^i_3$	$\sum n^i_4$	$\sum n^i_5$

2.1.3 Ground motion attenuation relationship and soil effects

The ERA framework is capable of including multiple ground motion attenuation relationships. It is flexible enough to implement complex attenuation relationships such as Next Generation Attenuation (NGA) relationships (Campbell and Bozorgnia, 2006). However, for evaluation purpose the methodology is implemented for Pakistan using Ambraseys (2005) attenuation relationship (see equation 2.2).

$$\text{Log}(a)=2.522 - 0.142M_w - (3.184 - 0.314\,M_w)\log\sqrt{(d^2+7.6^2)} + 0.137S_s + 0.055S_A - 0.84F_N + 0.062F_T - 0.044F_0 \quad (2.2)$$

Where M_w is moment magnitude; d is epicentral distance; S_s is 1 for soft soil 0 otherwise; S_a is 1 for stiff soil 0 otherwise; F_N is 1 for normal fault 0 otherwise; F_T is 1 for thrust fault 0 otherwise; and F_0 is 1 for other fault 0 otherwise. If 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).

The geological information for each Union Council was obtained using the Geological Survey of Pakistan map (GSP, 2009), information provided by Hayat (2003) and data obtained from the National Highway Authority (NHA, 2009) of Pakistan. The calculated PGAs are then used to obtain Probabilistic Seismic Hazard maps for the study region.

3 THE EARTHQUAKE RISK ASSESSMENT MODEL (EQRAM)

The proposed PSHA methodology is incorporated into an ERA framework called EarthQuake Risk Assessment Model (EQRAM). Figure 3.1 shows the outline of the EQRAM program. The main components of EQRAM are PSHA, vulnerability assessment, and risk assessment. The first component has been discussed in detail in the above sections whereas the second component of vulnerability 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 quite a complicated process because 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, basic vulnerability relationships can give reasonable results (Kythreoti, 2002). A general framework for determining the vulnerability of structures in developing countries has also been developed at The University of Sheffield (Ahmad, 2011), and the results of that study provide input data for the vulnerability module of EQRAM.

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 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 component 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 in a single package.

Using results of the PSHA module, appropriate vulnerability relationships, and casualty models, EQRAM calculates building damage and casualty risks. In the subsequent sections EQRAM is used to carry out PSHA for Pakistan and arrive at risk assessment information for a region from Islamabad to Peshawar within Pakistan.

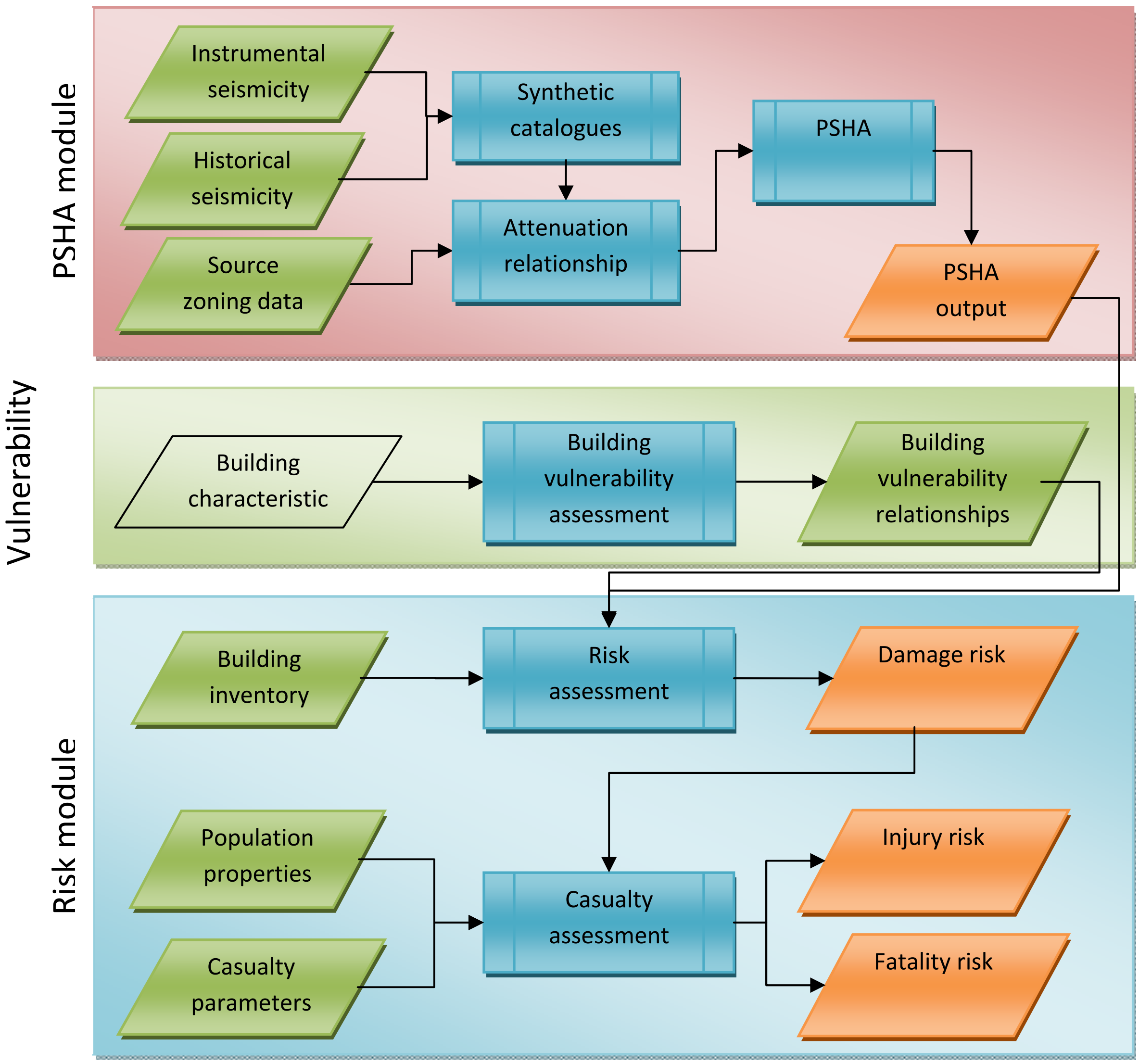
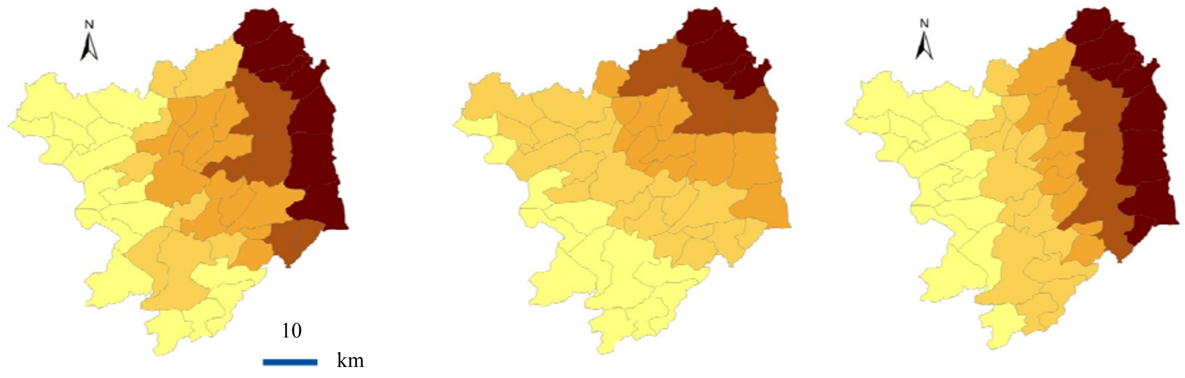


Figure 3.1. General outline of the EQRAM programme

4 IMPLEMENTATION OF METHODOLOGY ON PAKISTAN

The PSHA methodology implemented using Pakistan as a case study. To validate the methodology the hazard results produced by this study are compared with observed building damage in Kashmir (2005) earthquake. Following the Kashmir (2005) earthquake damage was assessed by the claims made by the residents of the earthquake affected areas and were confirmed for random sites by Earthquake Recovery Rehabilitation Authority (ERRA) of government of Pakistan (ERRA 2007). The level of damage gives an indirect measure of the seismic hazard and can be compared with the spatial distribution of seismic hazard assessment carried out by this methodology.

Figure 4.1 shows the normalised spatial distribution of hazard and damage resulting from Kashmir (2005) earthquake in the Abbottabad district. Hazard due to Kashmir earthquake was calculated using both the focal point (Kythreoti 2002) and EFL (Khan, 2010) models of intensity distribution for the event. It is observed that in general there is a consistency between spatial distribution of earthquake damage and calculated PGA for district Abbottabad using these two methods. However, using EFL (Khan 2010) models of intensity distribution leads to significantly better agreement with the observed damage in Kashmir, 2005, earthquake (ERRA, 2007) earthquake in the Abbottabad district. Another advantage of the Khan (2010) model is that it requires minimal knowledge of the regional tectonics and seismicity which makes it suitable for developing countries where extensive information on seismo-tectonics may not be readily available.



(a) (b) (c)

Figure 4.1. (a) Map of district Abbottabad showing damage after Kashmir (2005) earthquake, (b) Hazard map of district Abbottabad using Kythreoti (2002) model, and (c) Hazard map of district Abbottabad using Khan (2010) model.

PSHA map of Pakistan developed using this methodology is compared with hazard maps already produced by Building Code of Pakistan (BCP 2006), Geological Survey of Pakistan (GSP 2006), Pakistan Meteorological Department (PMD-NORSAR 2007) and Global Seismic Hazard Program (GSHAP) by United States Geological Survey (USGS 2008) shown in Figure 4.2.

Using the proposed PSHA method, the hazard maps of Pakistan are calculated as shown in Figure 4.3 (Khan (2010)). It is observed that the results of this study compares reasonably well with the spatial distributions of hazard shown in Figure 4.2. The PSHA result by PMD-NORSAR gives higher hazard values as compared to the GSP and BCP hazard values. The hazard values of this study lies between PSHA by PMD-NORSAR and BCP.

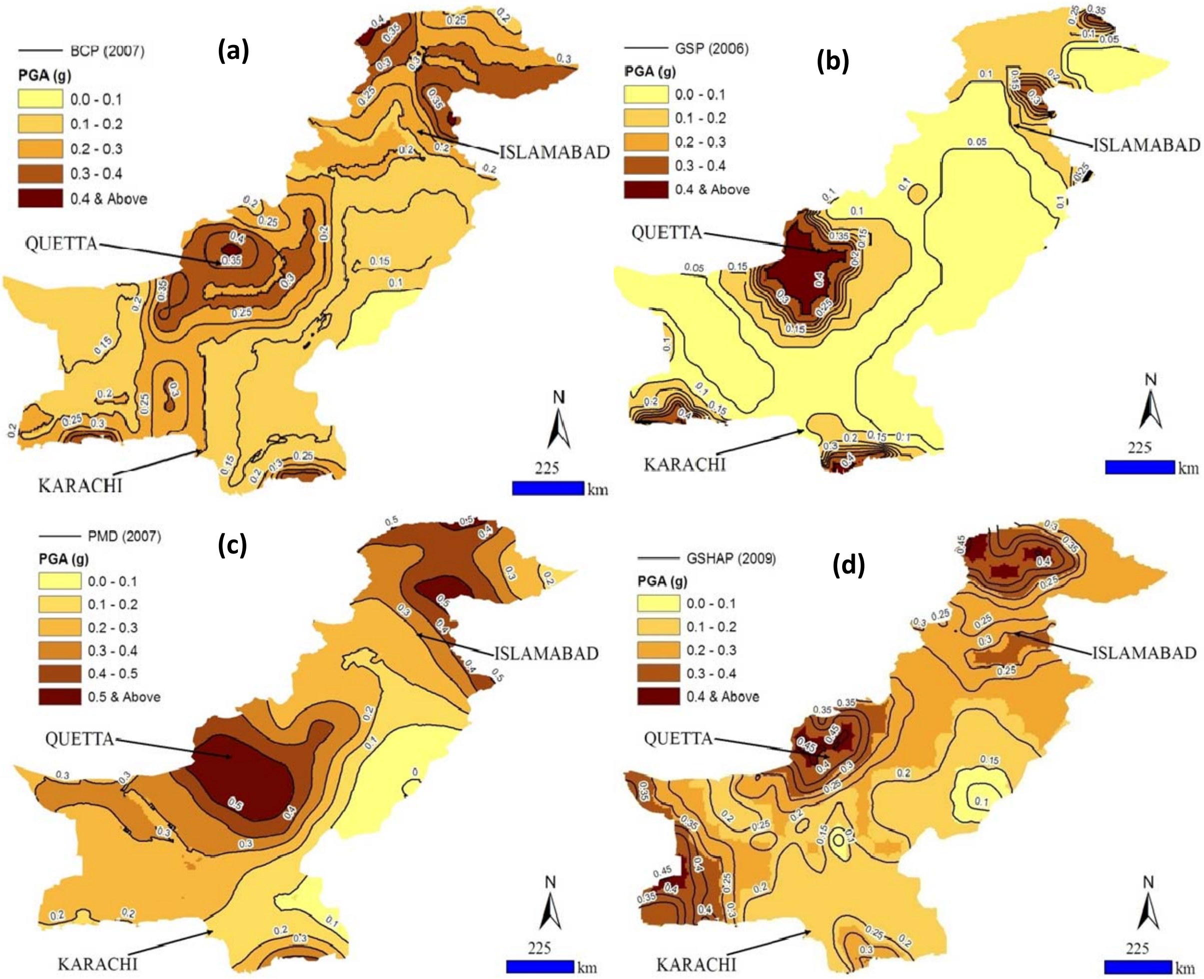


Figure 4.2. 50 year with 10% POE seismic hazard map by (a) Building Code of Pakistan (BCP, 2007), (b) Geological Survey of Pakistan (GSP, 2006), (c) Pakistan Meteorological Department (PMD-NORSAR, 2007) and (d) Global Seismic Hazard Program (GSHAP) by United States Geological Survey (USGS, 2008)

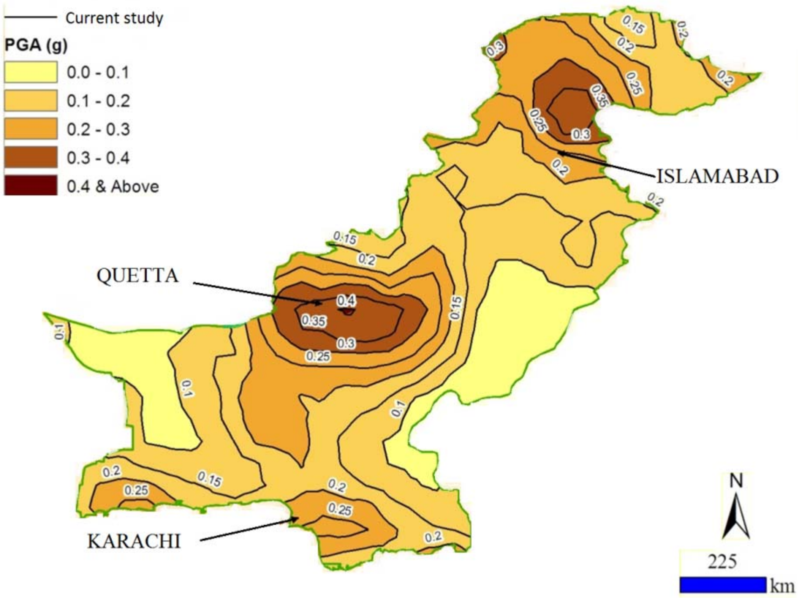


Figure 4.3. 50 year with 10% POE seismic hazard map using current PSHA methodology

5 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. The EQRAM PSHA module was first used to determine the local seismic hazard map for the study region with 10% POE in 50 years (Figure 5.1.a). The building inventory was developed for the case study region by using 1998 census data (FBS, 2007) and satellite imagery (Khan, 2010). Initially basic vulnerability curves from GESI (GESI, 2001) were used. Reconstruction costs for each category of buildings were obtained from local engineers based on the Net Present Value (NPV) of 2008. EQRAM produced the monetary risk assessment for the study region as shown in Figure 5.1b. EQRAM also includes a casualty module, details of which can be found in Khan (2010).

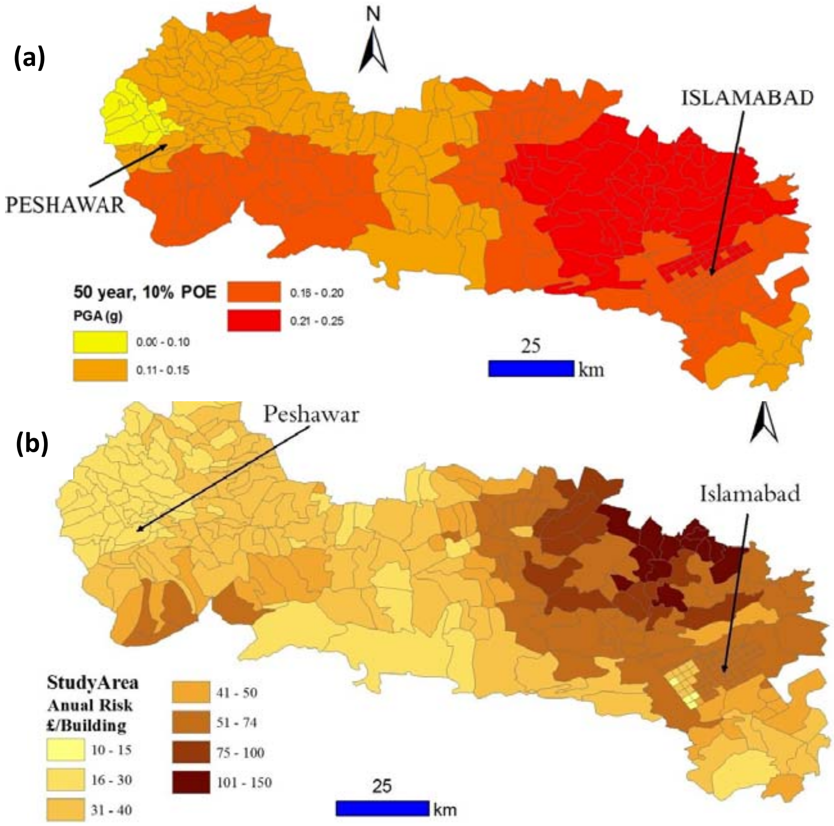


Figure 5.1. Results for hazard and monetary risk assessments by EQRAM applied to the study region (a) PSHA, (b) monetary risk assessment (NPV of 2008)

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

6 CONCLUSION

A new PSHA methodology is proposed for ERA for countries where there are limited available studies on tectonics and seismicity. This PHSA 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 is 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 especially with the National Building Code PSHA map, and show better local hazard distribution which is desirable for ERA studies.

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