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A FRAMEWORK FOR EARTHQUAKE RISK ASSESSMENT FOR DEVELOPING COUNTRIES

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ABSTRACT

An Earthquake Risk Assessment (ERA) framework that can provide acceptable estimates based on the limited data available in developing countries is developed for probabilistic earthquake risk assessment of building structures. A region of Pakistan of known geological and building inventory was selected as case study to demonstrate the efficiency of the proposed ERA framework. Based on a GIS-based software, spatial analyses are performed to develop the seismic hazard map of the selected region by using a new modified probabilistic earthquake risk assessment method. Basic seismic vulnerability assessment relationships are used in the development of the ERA framework but these may be easily upgraded to a more sophisticated vulnerability assessment in future. The ERA framework developed in this project can be easily extended to consider different hazards associated with earthquakes such as tsunami, liquefaction and landslides. This paper presents an outline of this framework and some preliminary results.

Introduction

The effects of earthquakes on the behaviour of structures are considered in modern design codes but these codes are not always implemented, especially in developing countries. The majority of the existing infrastructure is either pre-code, or has not been designed and constructed according to seismic codes. Hence, the vulnerability for most of the existing building stock in developing countries is very high. The high vulnerability, coupled with population expansion and constructions in areas with high seismic hazard is the root cause of highly increasing earthquake risk in developing countries. Previous works done on Earthquake Risk Assessment (ERA) for example HAZUS in USA (FEMA 1999), RADIUS in Japan (Cardona et al. 2000) and RISK-UE in Europe (Mouroux and Burn 2006) are focused on developed countries and little work has been done on the vulnerability of substandard construction typically found in developing countries. With Cyprus as case study Kythreoti (2002) and Kyriakides (2008), at the University of Sheffield, have developed an ERA framework suitable for developing countries. Kythreoti implemented a Probabilistic Seismic Hazard Assessment (PSHA) method, which assumes that the historical seismicity levels of the past century will continue into the future. In this method Monte Carlo simulations are used by partially randomising the historical data which leads to determination of acceleration probability distributions for specific locations. Kythreoti assumed that low magnitude earthquakes have relatively small rupture length and they spread from the focal point. This simplification is valid for low magnitude earthquake regions such as

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Cyprus where fault lines are not well defined. However, such simplification will not properly represent regions with higher magnitude seismicity where the seismic sources are well defined (e.g. China, India, Iran, Nepal, and Pakistan).

Seismic vulnerability is an important component of ERA. Limited work has been done on seismic vulnerability of deficient structures in developing countries. Kyriakides worked on the seismic vulnerability of buildings with substandard construction and developed analytical vulnerability relationships for Cyprus (Kyriakides, 2008). Mapping of building inventories is another challenge in the developing countries where data on building inventories are not readily available. To address this issue satellite imagery may be used instead of exhaustive field surveys.

This research further develops the work of Kythreoti by improving the PSHA model for use in regions of large magnitude seismicity and implementing basic vulnerability relationships for deficient structures constructed with weaker materials. A GIS based ERA framework for developing countries is developed and implemented in Pakistan where the seismo-tectonics are more diverse and the buildings are deficient due to use of weaker materials and lack of seismic resistant design. Satellite imagery is used with field sampling and census data for the development of a building inventory at large scale.

Outline of the ERA Framework

The ERA framework is incorporated in ArcGIS (ESRI 2009) so that the spatial inputs and outputs are represented directly into maps. The major components of the ERA framework are PSHA, seismic vulnerability assessment and building inventory development using satellite imagery. Fig. 1 shows the schematic representation of the ERA framework. The following sections present the components of the ERA framework.

Probabilistic Seismic Hazard Assessment

The existing PSHA methodology is based on the method developed by Cornell (1968) and involves the analytical solution of the total probability theorem (Chen and Scawthorn 2006). The implementation of this methodology has problems such as (a) smearing of the seismicity over the source zones whereas the actual seismicity may not be equally distributed over the source zone (Abrahamson 2006), (b) use of power law for recurrence relationships is assumed where the source may not be following the power law over the whole range of magnitude size (Wesnousky et al. 1994), (c) selection of the minimum magnitude or maximum magnitude (Abrahamson, 2006), and (d) dealing with uncertainty in PSHA (Thenhaus and Campbell 2003). Another approach for PSHA is use of Monte Carlo simulation method (or stochastic method) where a large number of synthetic earthquake catalogues are generated for all the source zones (Musson and Sargeant 2007). The method is rarely mentioned in literature, but it has been used in various parts of the world (Shapira 1983, Johnson and Koyanagi 1988, and Musson 2000). The Monte Carlo simulations method is a more direct and easy to incorporate into a computer program but it is also based on the same principles as the conventional PSHA methodology and produces similar results (Musson 2000).

Integration of the PSHA methodology into the ERA framework is required for probabilistic calculation of risk which may lead to overestimation of results due to the above mentioned problems. 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 100 year seismicity. Although the method solves the issue of overestimation (Kythreoti 2002), the assumption of spreading earthquakes from their focal points (see Fig. 2a) is not valid for regions with large magnitude seismicity since the intensity of the earthquake spreads perpendicular to the line of rupture. In 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).

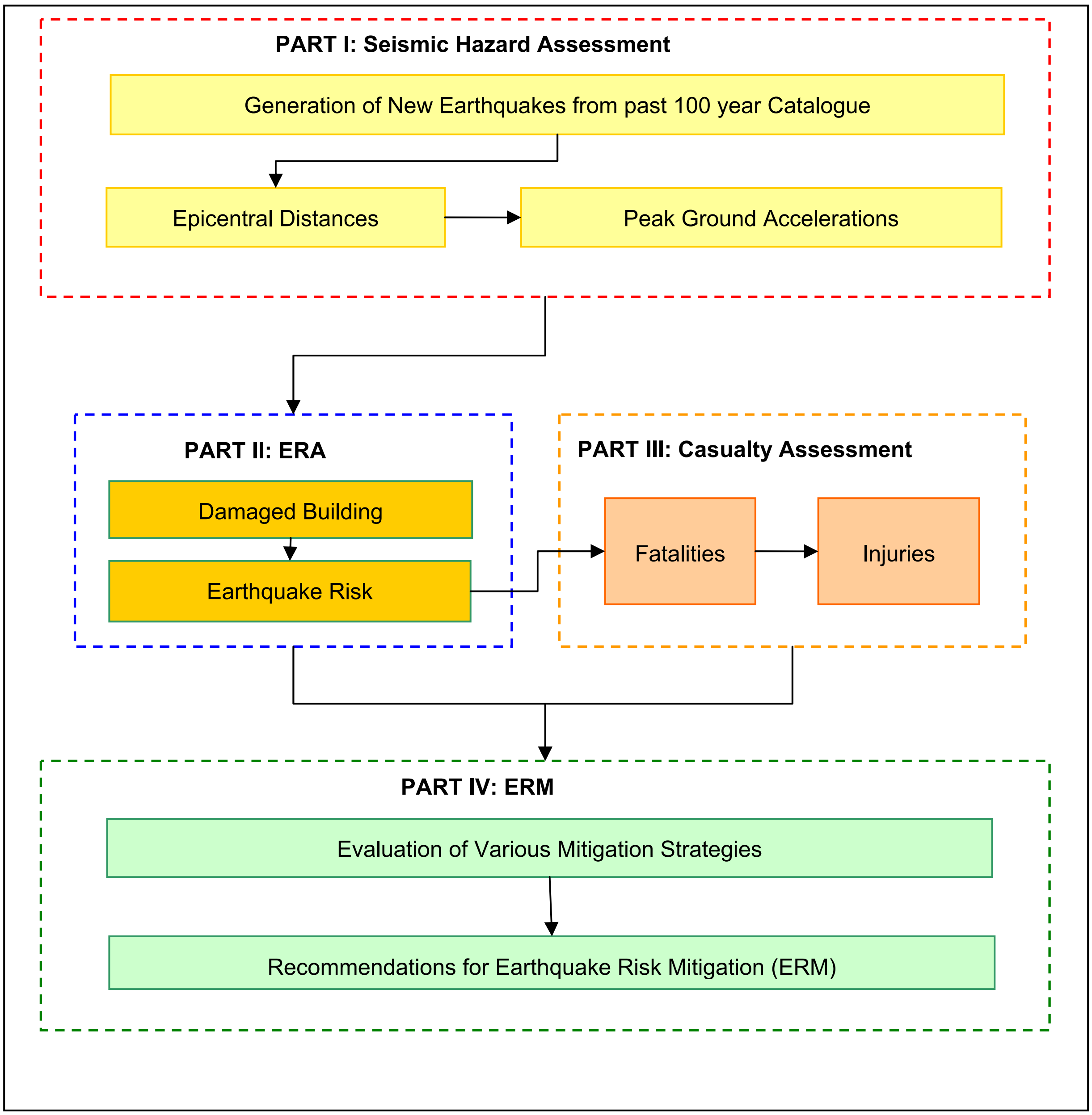

Figure 1. Outline of the ERA framework.

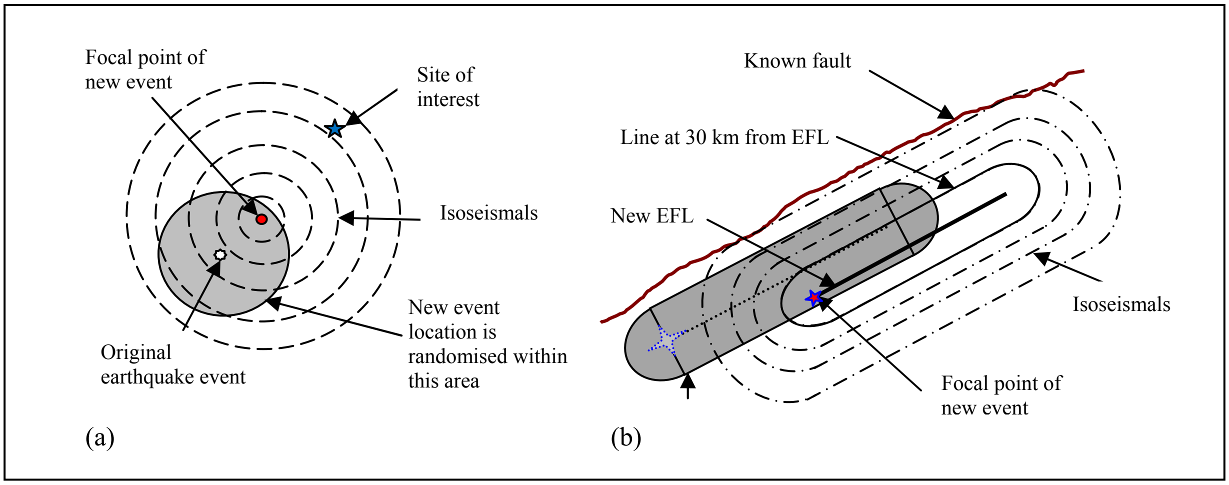

Figure 2. Generation of new random event and earthquake intensity, (a) spreading from focal point and (b) spreading from the rupture line (EFL).

To modify the PSHA procedure by Kythreoti (2002), a new term "Epicentral Fault Length" (EFL) is introduced to represent the rupture length due to an earthquake event with $M_W > 6$ (Khan 2008). The Peak Ground Acceleration (PGA) due to an earthquake is assumed to be distributed around the EFL and is calculated by nearest distance from site to the EFL. Fig. 2b shows the distribution of PGA with respect to the EFL. The PSHA procedure is simple and integrated well into the ERA framework which allows probabilistic assessment of risk directly. The flowchart for the PSHA procedure is shown in Fig. 3.

PSHA map of Pakistan developed using this procedure 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). Hazard maps of Pakistan by Khan (2008) and GSP are compared in Fig. 4. It is observed that the results of these two studies compare reasonably well as there is a resemblance in the spatial distribution of hazard shown in Fig. 4. The PSHA result by PMD-NORSAR gives higher hazard values as compared to the GSP and BCP hazard values. The reason could be due to the fact that building codes generally reduce the hazard to avoid high cost of buildings. The hazard values of this study lies between PSHA by PMD-NORSAR and NBCP.

The hazard results produced by this study are also 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 hazard and can be compared with the spatial distribution of hazard assessment.

Fig. 5 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 2008) models of intensity

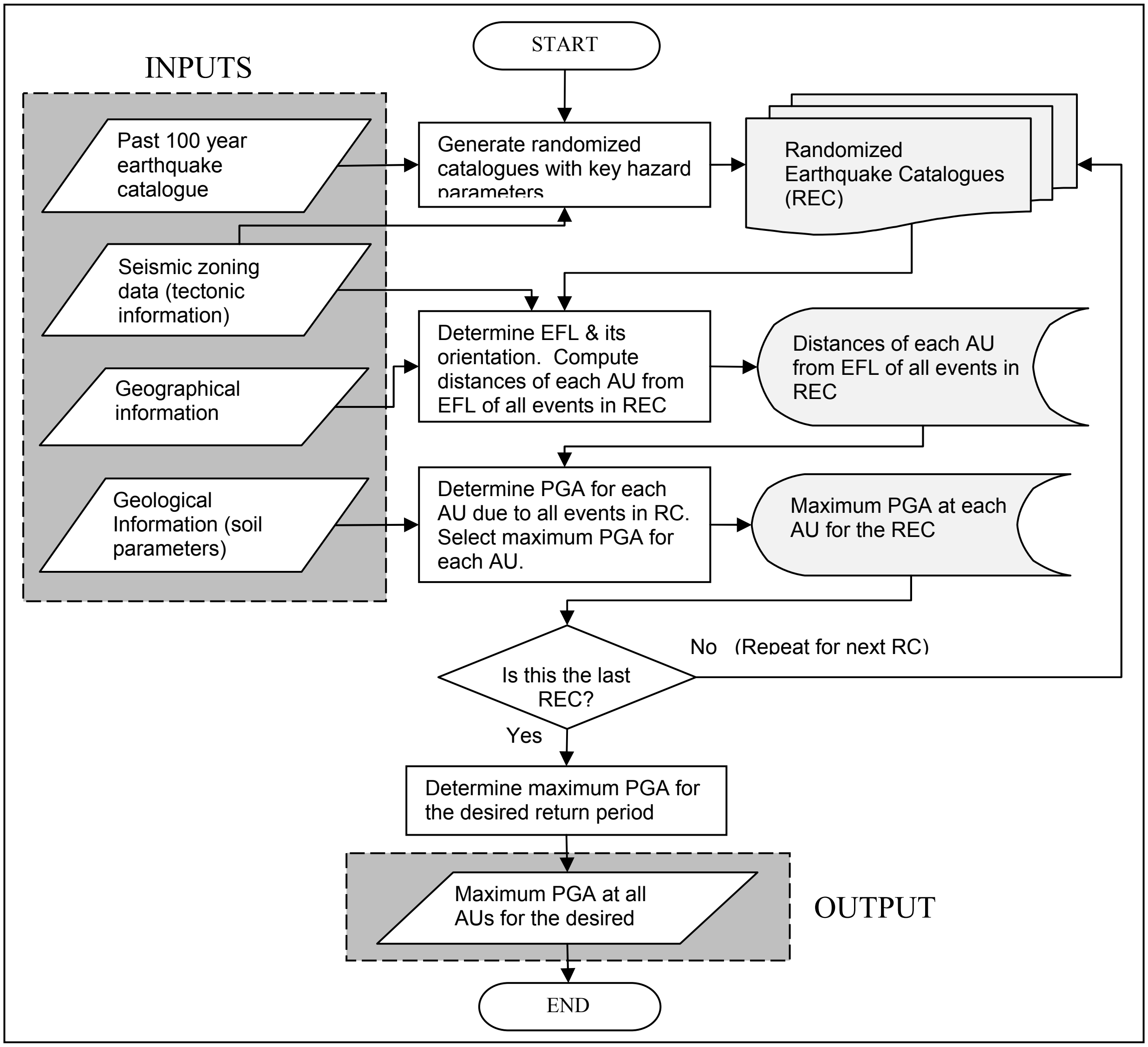

Figure 3. Flowchart of the PSHA process.

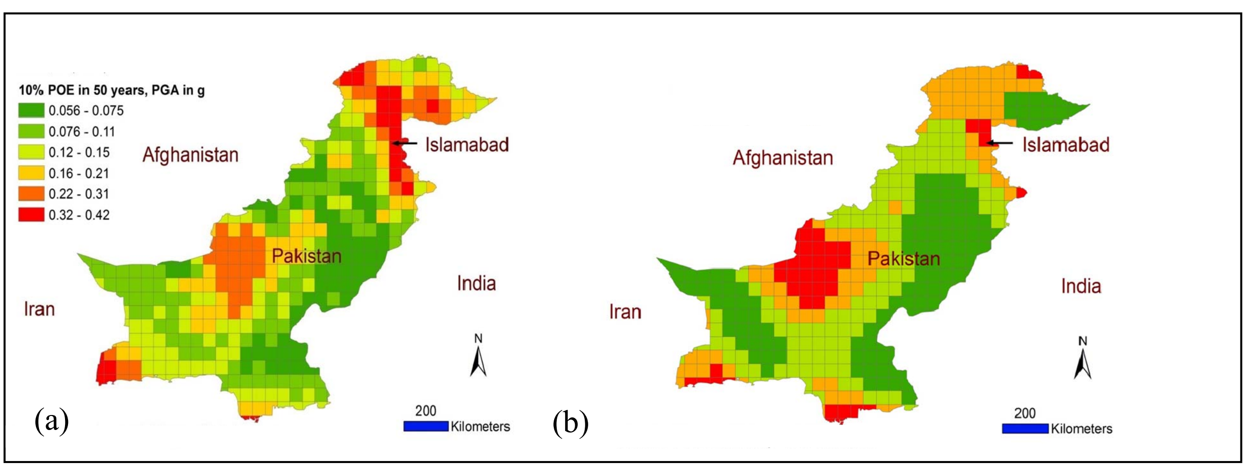

Figure 4. PSHA map of Pakistan by (a) Khan (2008) and (b) PMD-NORSAR (2007)

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 2008) models of intensity distribution leads to significantly better agreement with the observed damage in Kashmir (2005) earthquake in the Abbottabad district. Another advantage of the modified model is that it requires minimal knowledge of the regional seismo-tectonics and past 100 year seismicity which makes it suitable for developing countries where extensive information on seismo-tectonics is not readily available.

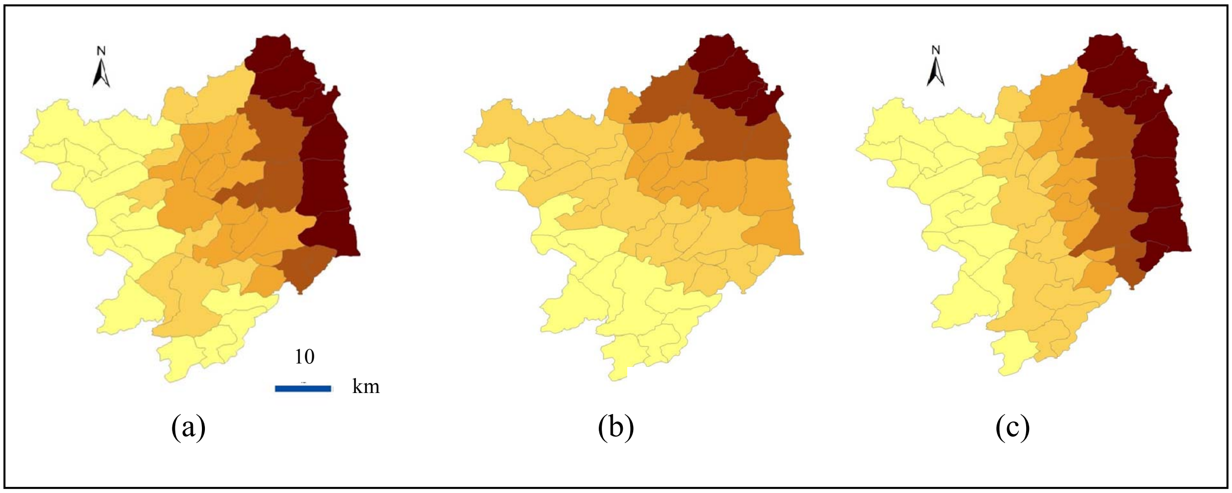

Figure 5. (a) Map of district Abbottabad showing damage after Kashmir (2005) earthquake, (b) Hazard map of district Abbottabad using Kythreoti (2002) model, and (c) Hazard map of district Abbottabad using Khan (2008) model.

Seismic Vulnerability Assessment

The second important component of the ERA is the vulnerability assessment, within which the damage is related to the peak ground motion levels. Large populations and limited resources make the implementation of modern seismic provisions quite difficult. Hence, the building stock in many developing countries such as Pakistan, India, Nepal, China, Iran and Afghanistan is highly vulnerable. Observation of damaged buildings subsequent to the Kashmir (2005) earthquake shows that (1) non-engineered structures comprise the majority of residential buildings, (2) the majority of engineered structures which comprise mainly of institutional buildings are either pre-code or designed only for gravity loads, (3) materials used in the construction of the non-engineered buildings are of very poor quality and (4) construction practices are poor and there is no supervision or control of non-engineered structures.

Detailed damage surveys and comprehensive vulnerability relationships for Pakistan building stock are not available. However, some vulnerability relationships are available for developing countries with similar constructional practices such as Greece and Turkey (Ambraseys and Jacson 1981), Middle East region (Akkas and Erdik 1984) and Costa Rica and Latin America (Sauter and Shah 1978). Kyriakides (2008) produced analytical vulnerability curves for low rise reinforced concrete buildings in the region of Cyprus. He found that at higher PGAs there is a sudden rise in damage due to brittle failures in reinforced concrete members.

The above mentioned studies conclude that deficient buildings in developing countries have high vulnerability due to brittle failure modes during earthquakes. GeoHazards International (GHI) developed vulnerability relations in their "Global Earthquake Safety Initiative pilot project" (GESI 2001) that included contribution of experts from developing countries. The GESI vulnerability relationships are used in the development of the ERA framework used in this study.

Mapping of Building Inventory

Mapping of the building inventory is an important component of ERA, where spatial distribution of building stock is required since hazard varies spatially. In many of the developing countries such as Pakistan data on building inventory are not readily available or do not exist. Census record provides very crude information on the building stock and field surveys could be a time consuming and expensive process. In this study satellite imagery was used to develop building inventory for the study region.

Building stock texture and knowledge of the area may be used to identify the rural and urban building stock types by visually observing satellite imagery of the study region. Fig. 6 (Google Earth 2008) shows examples of various types of buildings in different populated areas within the study region. Fig. 6(a) is a well planned area in Islamabad, 6(b) shows an unplanned area in Rawalpindi city, 6(c) shows a small rural town and 6(d) shows scarce rural villages.

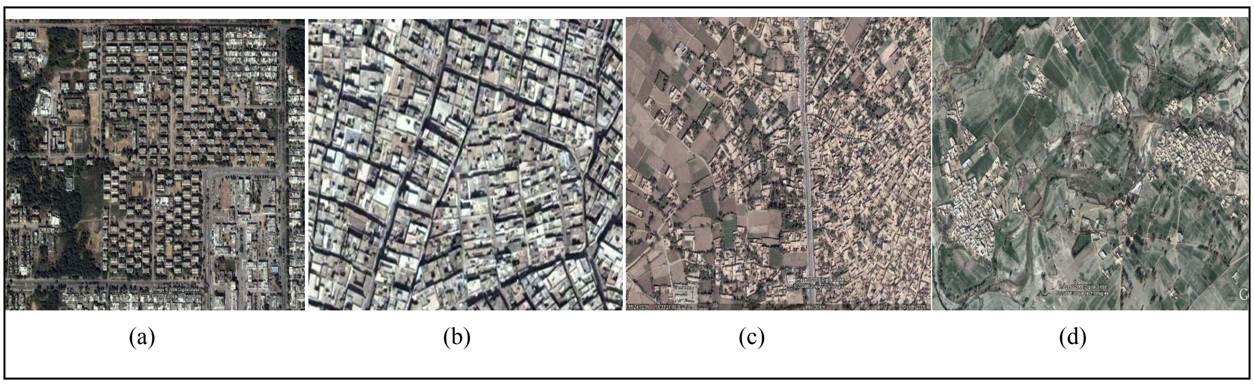

Figure 6. (a) Planned urban area (Islamabad), (b) unplanned urban area (Rawalpindi), (c) small rural town (Peshawar) and (d) scarce rural area (Google Earth 2008).

The study area is divided into smaller administrative units such as census wards or, in case of Pakistan, Union Councils (UC), which are the smallest local government administrative units. Using expert judgement, the satellite imagery of the study region is used to visually identify and mark built areas. Built areas are graded according to their building composition (the building composition is percentage of building classes in the area) by visual inspection, expert judgement and selected field observations. The data is saved as separate layers in GIS and contribution of each layer to the respective UC is determined digitally. Building inventory for the study region is obtained by multiplying the building composition of respective areas with each UC.

Earthquake Risk Assessment for the Study Region within Pakistan

A study area (7300 sq-km) within the Potowar region of Pakistan ranging from Islamabad to Peshawar is selected for ERA. Using the proposed ERA framework, risk is calculated for the study region. Fig. 7a and 7b show the hazard map and calculated risk map, respectively.

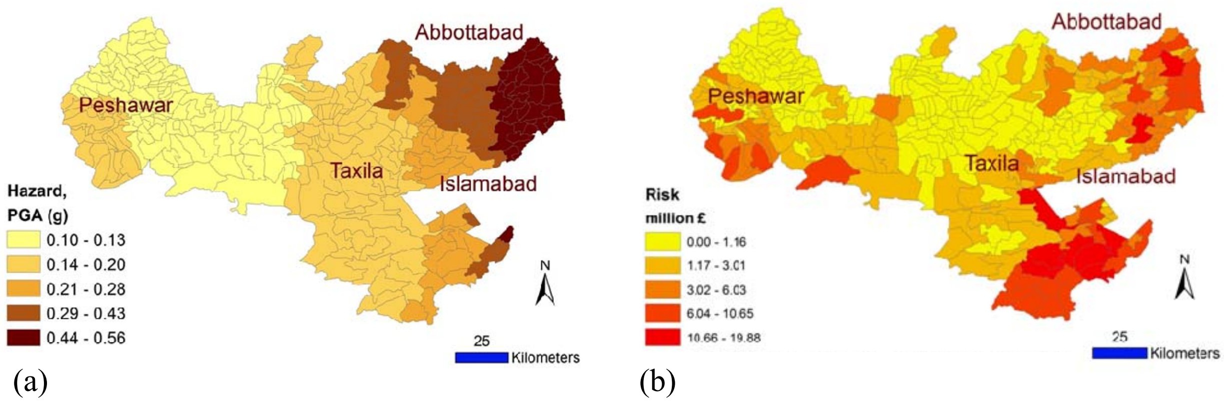

Figure 7. (a) Seismic Hazard and (b) ERA for the study region.

By comparing the results it is observed that the spatial distribution of risk is relatively different compared to hazard map. The reason is that risk is the product of hazard, vulnerability, exposure and value. For instance, the risk in Islamabad and Peshawar is high even for lower seismic hazard because of high building density in these areas. However, in Abbottabad, where the density of buildings is relatively lower, the high risk is more due to the high seismic hazard.

Conclusion

An ERA framework is proposed for developing countries where there is limited data on seismo-tectonics, vulnerability of infrastructure and building inventory. The PSHA method originally developed by Kythreoti (2002) was modified and implemented in the ERA framework as an attempt to address the issues of overestimation in conventional PSHA methodology and allowing direct assessment of earthquake risk. The modification in Kythreoti’s model enabled the ERA framework to include the effects of seismic area sources on large magnitude earthquakes and correct the spatial distribution of PGA for such events. A simplified and low cost procedure using visual inspection of satellite imagery supported by selected field inspections was employed to produce building inventories. The ERA framework was demonstrated by carrying out ERA study on a selected study region within Pakistan. It is shown that PGA results obtained by the proposed ERA framework compare well with the building damage observed in Kashmir (2005) earthquakes.

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