

Empirical vulnerability assessment of the non-engineered reinforced concrete structures using the Kashmir earthquake damage data

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Abstract Few empirical seismic vulnerability curves exist for non-engineered reinforced concrete buildings in developing countries, and this is particularly true for the South Asian countries. This category of buildings is widespread and is highly vulnerable, since the buildings suffer from serious problems due to poor design and construction and are prone to collapse in moderate earthquakes. In this paper, building damage data from the Kashmir earthquake (2005), Pakistan are utilized to develop empirical vulnerability curves for the non-engineered reinforced concrete structures in the region. In order to develop empirical vulnerability curves, a damage probability matrix was defined and its elements corresponding to damage ratio of different damage states are used to evaluate the mean damage ratio. The developed curve show abrupt damage accumulation at relatively small values of peak ground acceleration. The findings of mean damage ratio as a function of peak ground acceleration are compared with the most relevant existing empirical and judgmental vulnerability curves to show the severity of damage in non-engineered reinforced concrete structures of that region and to validate for use in risk assessment studies.

Keywords Empirical vulnerability curve · Non-engineered · Damage data ·
Damage probability matrix · Peak ground acceleration · Damage ratio

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1 Introduction

Post-earthquake damage data gathered in various parts of the world can be used to derive empirical vulnerability curves for buildings of a particular region. However, the quality and quantity of observed data is of prime importance for a reliable outcome and to predict realistic performance of a particular building class. In the literature, various types of empirical vulnerability assessment methods are used ranging from simple to more sophisticated methods. A simple method for assessing the vulnerability from the most probable hazard involves rapid visual screening (RVS) in accordance with the provisions of FEMA154 (2002). This procedure involves exterior inspection by trained inspectors by following a side walk procedure. Based on a scoring process, the surveyed buildings are classified into two groups (i.e. no risk and risk to life safety). ATC-20 (1989) proposed a tagging system for assessing post earthquake damaged buildings with an aim to make decisions on the spot. Three different color cards are displayed on the buildings; green, yellow and red and represent apparent safe, limited entry and unsafe buildings, respectively.

The damage probability matrix (DPM) by Whitman et al. (1973) was the first attempt to evaluate the seismic vulnerability of a large number of buildings using observed data. In this method, all buildings with the same structural system are assumed to perform in the same way in a seismic event. This assumption is also valid for the non-engineered reinforced concrete (NERC) building stock, where most of the buildings are low rise and built with a similar construction practice and lateral load resisting system. Every element in the matrix is a conditional probability to acquire a damage level D given a ground motion of intensity I for building type T as shown in Eq. (1).

$$DPM(D, I, T) = P\left(\frac{D}{I, T}\right) \quad (1)$$

DPM shows a building proportion corresponding to a particular damage state as a function of earthquake intensity. This method has been used very consistently by various researchers [Braga et al. (1982), Dolce et al. (2003), DiPasquale et al. (2005)] for various classes of buildings in the Europe by adopting different intensity scales. Rota et al. (2006) developed empirical vulnerability curves for seismically designed structures in Italy from a database of 90,000 buildings by defining DPM. In this study, the peak ground acceleration (PGA) was defined using the event magnitude, a suitable attenuation relationship and site to source distance. The DPM was further processed to define cumulative lognormal fragility curves by considering the probability of reaching or exceeding a damage limit state at a certain PGA level. More recently, it has been used by Kyriakides (2008) for empirical vulnerability assessment of masonry and reinforced concrete (RC) structures in Cyprus using EMS98 damage scale (Grünthal et al. (1998)).

Existing empirical curves were produced mainly using damage data from developed countries such as Italy and Japan by Orsini (1999) and Miyakoshi et al. (1997), respectively. Orsini (1999) considered only apartment buildings in developing the curves and no consideration was given to other building types with different lateral load resisting systems. Miyakoshi et al. (1997) curves were based on the loss of property value corresponding to only moderate and severe damage states, which are not sufficient for detailed assessment, since intermediate damage states are not included. These curves also underestimated the damage caused in the Kobe earthquake, Japan (1995). Considering the very specific nature of existing curves, they are not applicable for assessing the vulnerability of

the building stock in developing countries and if used, can lead to errors in the risk assessment process.

Schnabel (1987) developed vulnerability curves for Cyprus using the building damage data of similar seismo-tectonic environments and also by considering expert opinion. Vulnerability curves were defined for two different classes of structures which included superior and substandard construction. The “Global Earthquake Safety Initiative” GESI (2001) defined a method for deriving vulnerability curves for different types of structures including poor quality RC structures. These curves are based on the outcomes of different existing studies and site observations. In this method, the scoring scheme depends on the quality of design, construction and materials. The building score is evaluated and an appropriate vulnerability curve (from nine curves) is assigned to a building type falling in a particular vulnerability class.

Rossetto and Elnashai (2003) developed empirical vulnerability curves for RC building structures with different load resisting systems by using RC building damage data of around 340,000 (99 datasets) over a wide range of ground motions from different parts of the world. (predominantly European countries). In this study, the class specific (structure type, height, code based) and homogenized (general) empirical vulnerability curves were developed for a variety of ground motion parameters. The class specific (pre-seismic) empirical vulnerability curves by Rossetto and Elnashai (2003) are of some relevance for substandard structures, since they were derived using the dataset from the Kocaeli earthquake, Turkey (1999), where the exposed buildings had similar issues related to poor design and construction, typically found in most of developing countries. A vulnerability function which is an optimum fit for all ground motions was also evaluated after many trials as shown in Eq. 2.

$$P(d \geq DI_{HRC}/GM) = 1 - \exp(-\alpha GM^\beta) \quad (2)$$

where, GM represents a variety of ground motion parameters (PGA, $S_{a5\%}$ (Telastic), $S_{d5\%}$ (Telastic), $S_{a\mu}$ (Tinelastic) and α and β are function shape parameters derived from nonlinear regression on the damage data in a dataset.

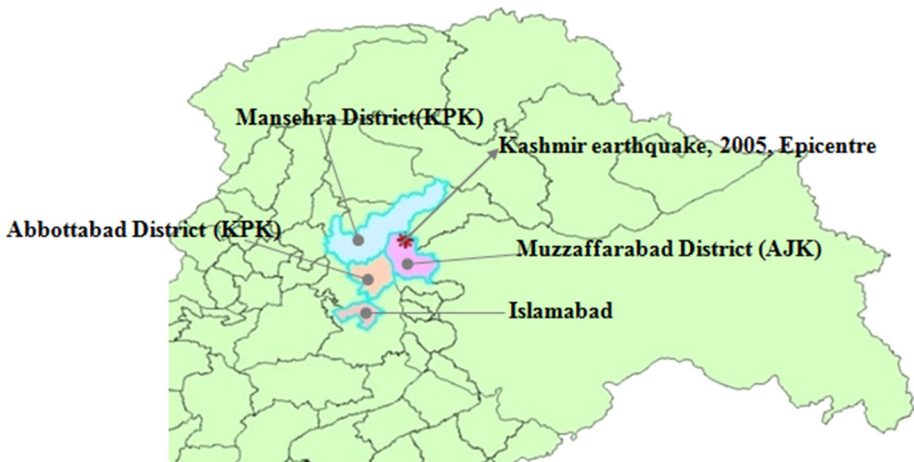


Fig. 1 Map of Northern Pakistan: different earthquake effected districts in the Kashmir earthquake

This paper begins by presenting the damages caused by the Kashmir earthquake in the affected areas. The statistics of the RC building damage data from different cities are presented and the methodology to derive the empirical vulnerability is defined. The analysis is performed to evaluate mean damage ratio (MDR) as a function of PGA using required parameters. The comparison is made between the developed empirical vulnerability curves and existing empirical and judgmental curves to assess the validity of the existing curves for use in the risk assessment of NERC building structure.

2 Damage in the Kashmir earthquake affected areas

The recent Kashmir earthquake has caused widespread damage predominantly to the non-engineered building stock in the northern regions of Pakistan. Since, the earthquake source was very close to the densely populated Muzaffarabad city (located within Muzaffarabad district) (Fig. 1), the available damage data from that city and other neighboring cities such as Mansehra and Abbottabad (located within their districts) (Fig. 1) were used to carry out empirical vulnerability assessment for the RC buildings of the regions.

Muzaffarabad was among the most severely affected districts of the Azad Jammu Kashmir (AJK) Pakistan, with 115,211 fully damaged buildings leading to the loss of life of around 33,724 people (ADB-WB 2005). The Muzaffarabad city is located approximately at a distance of 19 km from the earthquake epicenter. The damage survey of the Muzaffarabad municipal area and city has been conducted by the Japan International

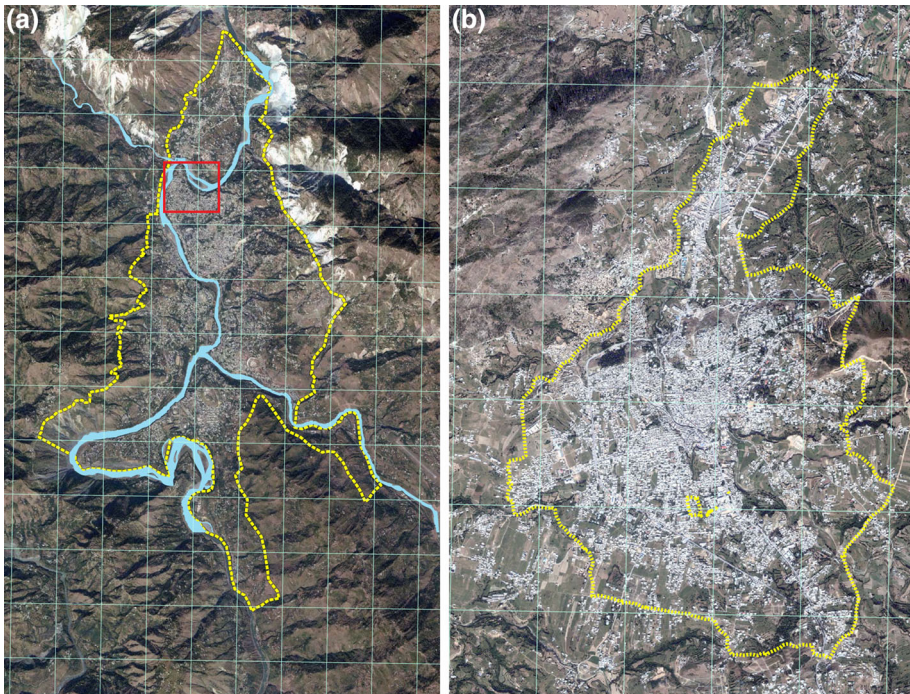


Fig. 2 Boundary of the cities surveyed for damaged buildings **a** Muzaffarabad, **b** Mansehra, UNDP-ERRP (2008)

Cooperation Agency (JICA) study team in March 2006 within the 17 km² area shown in Fig. 2a. In this survey a total of 16,823 buildings, were examined for damage by dividing the area under investigation into 30 zones. Among the total surveyed buildings, 40 % (6736) were completely collapsed, 44 % (7323) were damaged partially and 16 % (2764) remained undamaged.

The Mansehra district of the Khyber Pakhtunkhwa (KPK) province, Pakistan is located around 40 km from the epicenter also suffered significant building damage with 32,293 fully damaged and killing around 24,511 people (ADB-WB 2005). The damage survey of the Mansehra city (located within Mansehra district) has been conducted under UNDP-ERRP (2008) project for 11,202 buildings within a 9 km² area, as shown in Fig. 2b.

A view of the building damage distribution on the bank of Nilum river in the Muzaffarabad city is shown in Fig. 3. This building damage area is highlighted with the square block in Fig. 2a. Red represents collapsed buildings whereas yellow is for partially damaged and green for slightly damaged buildings.

The detailed building inventories used in the current study for Muzaffarabad and Mansehra city were prepared under Earthquake Risk Reduction and Preparedness (ERRP) project executed by National Disaster Management Authority (NDMA), Pakistan with the financial and technical support by UNDP-ERRP (2008). The building inventory of these cities includes structures of different construction types like RC, brick masonry, stone, adobe and block masonry with the details of building height, location, age, usage and building configuration. The author was granted permission by United Nation Development Programme (UNDP), Pakistan to use the RC building inventory damage data for the vulnerability assessment study (Ahmad 2011). Moreover, limited RC buildings data have been gathered from the survey reports (Nisikawa et al. (2005), Stegemeier (2008), Naseer et al. (2006), ERA-PERRA (2007)) for the Abbottabad city. The details and statistical analysis of the damage data for the Muzaffarabad and the Mansehra city is discussed in the following section.

2.1 Details and statistics of the observed damage data

The database consist a total of 4846 RC buildings from the Muzaffarabad and the Mansehra city. Buildings having few RC columns and beams were also considered to be in

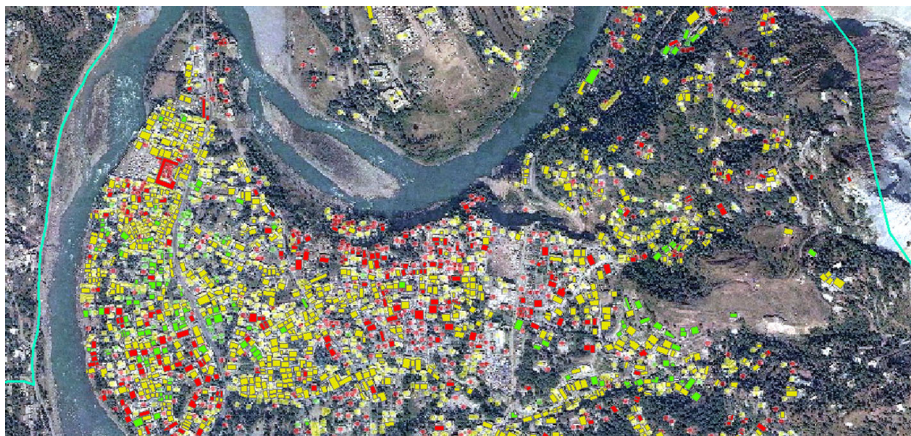


Fig. 3 A view of damage distribution of RC buildings on bank of river Nilum in the Muzaffarabad city after the Kashmir earthquake (2005), JICA (2006)

non-engineered RC structures category during survey. A typical example is shown in Fig. 4.

These RC frame buildings generally had very weak brick or block masonry infill panels, which did not have adequate connection with the frame and did not contribute much towards the lateral load resistance. The data includes buildings with different usage such as residential, commercial, educational and health institutes, government and private offices/banks, industrial, recreational and others. The height of buildings varies from 1 to 5 storeys, most comprising 1 and 2 storey buildings, as shown in Fig. 5. These buildings can be divided into two heights: low-rise (1–3 storey) and mid-rise (4–7 storey) in accordance with HAZUS (1999). Variations in construction practices due to different building height category may exist, but considering the non-engineered approach adopted and damage observed (Duranni et al. 2005; Naseer et al. 2006; Peiris et al. 2005) in this region, all these buildings appear to have behaved in a same manner.

The buildings in the region were constructed at different times before the Kashmir earthquake and their age is divided in three ranges: 1–10, 10–50 and 50–100 years old. The buildings have been assigned three different damage states namely: slightly damaged (SD) (10–40 %), damaged building (DB) (50–70 %), and destroyed or heavily damaged (HD) (80–100 %). Age and height wise damage distribution with respect to their damage state is shown in Fig. 6 (for 1–3 storey buildings) and Fig. 7 (for 4–5 storey buildings). A clear bias of frequency is observed in Figs. 6 and 7 towards the moderate damage state (DB) for building age ranges 1–10 and 10–50 years for both building height categories. The percentage given for each damage state corresponds to the degree of damage used by HAZUS (1999). In the building damage survey in Muzaffarabad a tagging procedure was adopted



Fig. 4 Damage of typical non-engineered structure after Kashmir earthquake (2005)

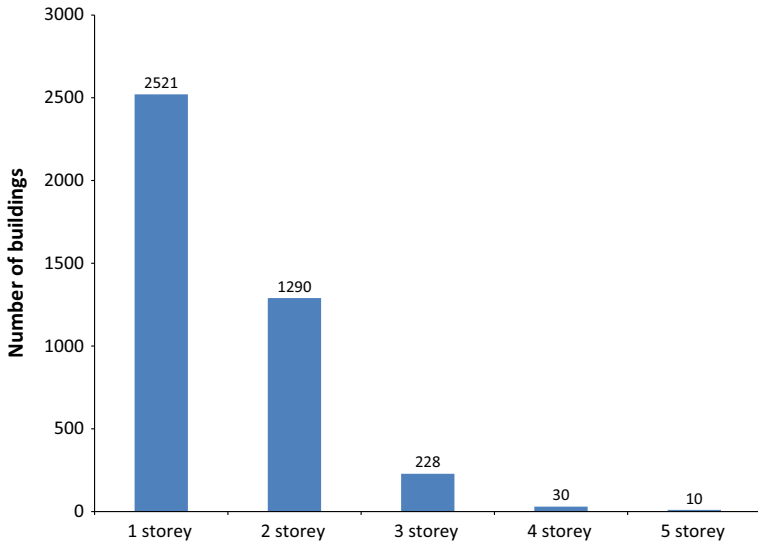


Fig. 5 Height wise distribution of the RC buildings (Muzzaffarabad and Mansehra)

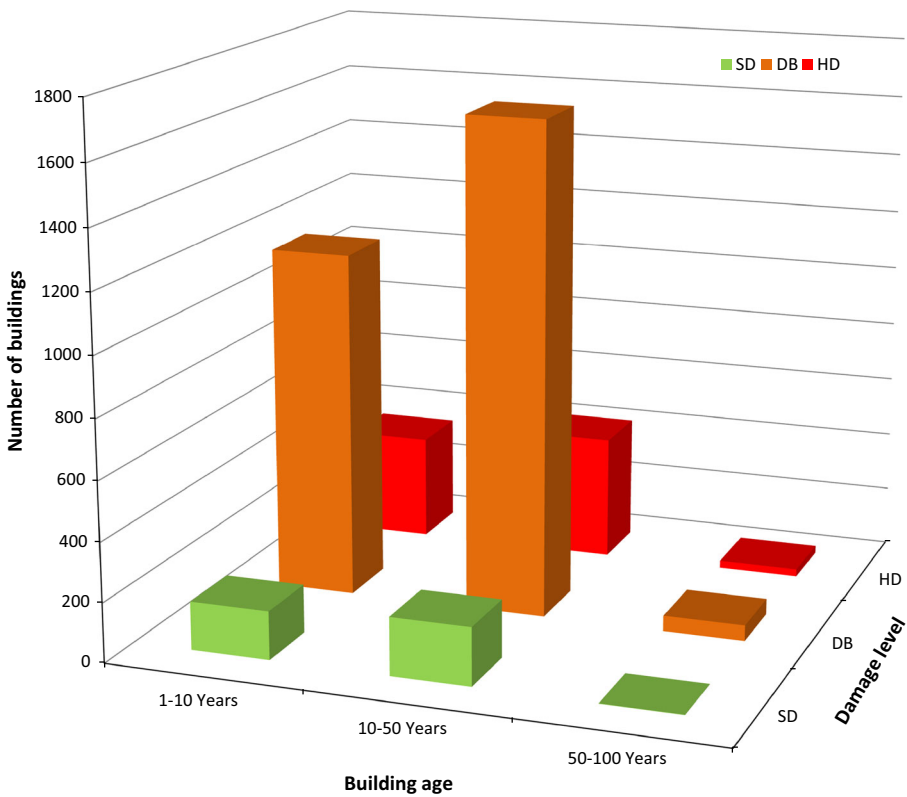


Fig. 6 Age wise distribution of 1–3 storey RC buildings with different damage levels

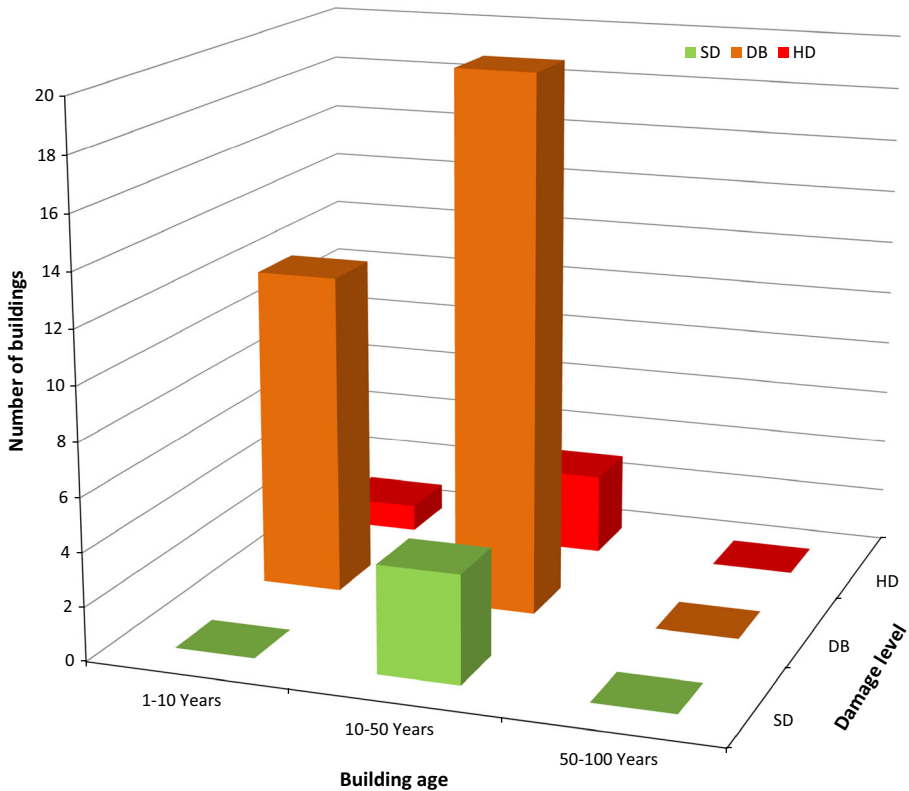


Fig. 7 Age wise distribution of 4–5 storey RC buildings with different damage levels

and the detailed damage descriptions were not available. However, for the Mansehra city the damage descriptions for few RC buildings were available by UNDP-ERRP (2008), and these were used to characterize RC buildings damage in Mansehra. Figure 8a–d shows few examples of the different damage level caused to RC buildings during the Kashmir earthquake.

For the Abbottabad district, ERRA-PERRA (2007) reported the extent of building damages in different sectors. For the current study, the damage statistics of health, education and governance sectors are utilized, since most of the buildings in these sectors had RC frame structure or have at least few beams and columns and can be included in the category of NERC structures. These statistics are given in Table 1 and used for developing the DPM elements for Abbottabad.

3 Method for the development of empirical vulnerability curves

The DPM technique by Whitman et al. (1973) is adopted in this study to develop empirical vulnerability curves. The repair cost per meter square (Table 2) associated with different damage grades of the adopted damage scale is obtained from the local contractors. Initially these values were acquired in 2008 but for updated vulnerability estimates, the inflation

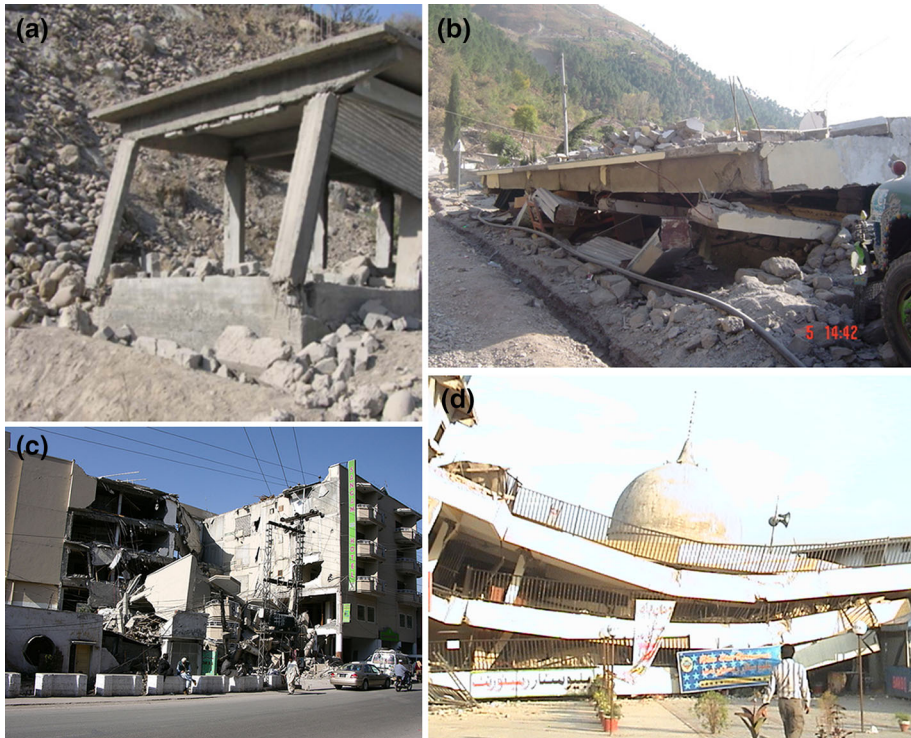


Fig. 8 Various damage states of buildings in different Kashmir earthquake affected cities **a** damaged building (DB), **b** heavily damaged (HD), **c** heavily damaged (HD), **d** heavily damaged (HD)

Table 1 Sector wise building damage extent in the Abbottabad city (ERRA-PERRA 2007)

Sector	Total buildings	Partially damaged	Fully damaged
Health	53	13	12
Education	1614	736	295
Governance	145	82	63

Table 2 RC building repair cost for each damage grade

Damage grade	SD	DB	HD
Rs./m ^{2a}	2125	10,626	66,102
Rs./m ^{2b}	2374	11,872	73,856

^a Values in 2008–2009

^b Values including inflation (2009–2010)

trends also needs to be considered for the repair costs. Consumer Price Index (CPI) values can be used as an inflation indicator. The year wise inflation pattern in Pakistan for the year 2009–2010 according to Federal Bureau of Statistics (FBS) is shown in Fig. 9. An inflation

of 11.73 % is considered for year 2009–2010. The inflated repair costs for the year 2010 are also given in Table 2.

The replacement cost of an average RC structure in the affected areas, which also includes the demolition cost of the structure is Rs. 66,102/m² as obtained through a personal communication from Camp Dresser and McKee Inc (CDM), Islamabad, Pakistan. This replacement cost is extremely high, since the reconstruction areas were located close to active faults and new shear wall RC frame structures are designed and detailed according to modern seismic codes. This is an unrealistic value to use for intermediate damage level buildings, since the existing building stock is worth much less. Hence, the replacement cost based on the average price of a typical RC structure will be used in this study for evaluating Damage Ratio (DR) corresponding to SD and DB and is taken as Rs. 27,000/m². The DR values corresponding to each damage state is given in Table 3 and these values can be used for empirical vulnerability generation as discussed in the following section.

4 Empirical vulnerability curve generation

4.1 Evaluation of PGA

PGA values corresponding to each RC building in the surveyed city are required and were obtained using the hazard framework developed by Khan (2010). The deterministic event of Kashmir earthquake ($M_w = 7.6$) was used and the “Epicentral Fault Line” (EFL) size which depends on the fault rupture length was calculated using equations by Wells and Coppersmith (1994). In this framework, the EFL was oriented parallel to the direction of fault traces found in that particular seismic source zone. Geodetic coordinates of the centroid of each building footprint were used to find the closest distance between the EFL

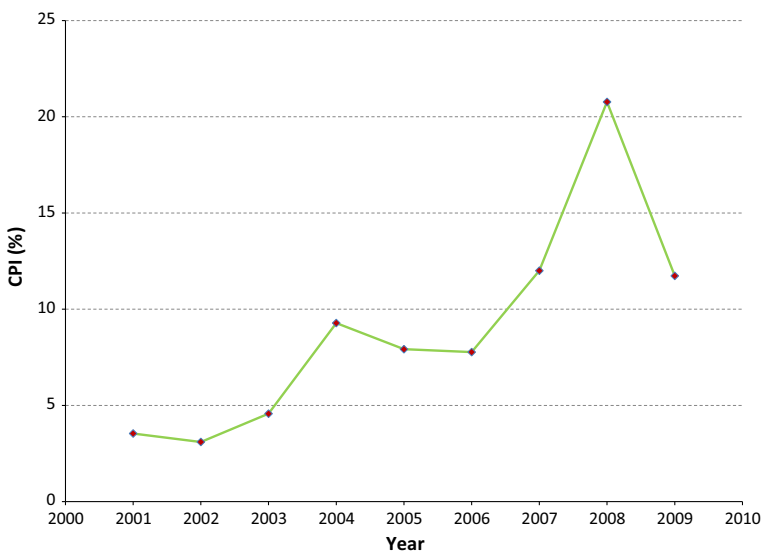


Fig. 9 Year wise inflation estimate in Pakistan, FBS (2010)

and the site. The Ambraseys et al. (2005) attenuation relation was used in this hazard model to evaluate the deterministic PGA. The iso-seismals of the Kashmir earthquake (2005) event in the radius of 150 km generated using Khan (2010) hazard framework are shown in Fig. 10. The PGA value very near to the fault line ranges between 0.21 and 0.71 g and is estimated to be 0.06 g for Islamabad city located around 105 km from epicenter.

4.1.1 Soil conditions

Realistic soil characteristics are very important for reliable PGA and spectral values. The site characteristics (in Table 4) are defined from soil maps and the findings of different researchers for PGA calculation.

4.2 Evaluation of DPM

The next step is to prepare the DPM which contains the percentage of buildings reaching different damage states at a particular PGA level. In the current study, the buildings in the database already have a defined damage state (SD, DB, HD) and only the percentage of buildings in different damage states and PGA level for group of buildings need to be

Table 3 RC building damage ratio (DR) for each damage grade

Damage grade	SD	DB	HD
DR (%)	8	39	100

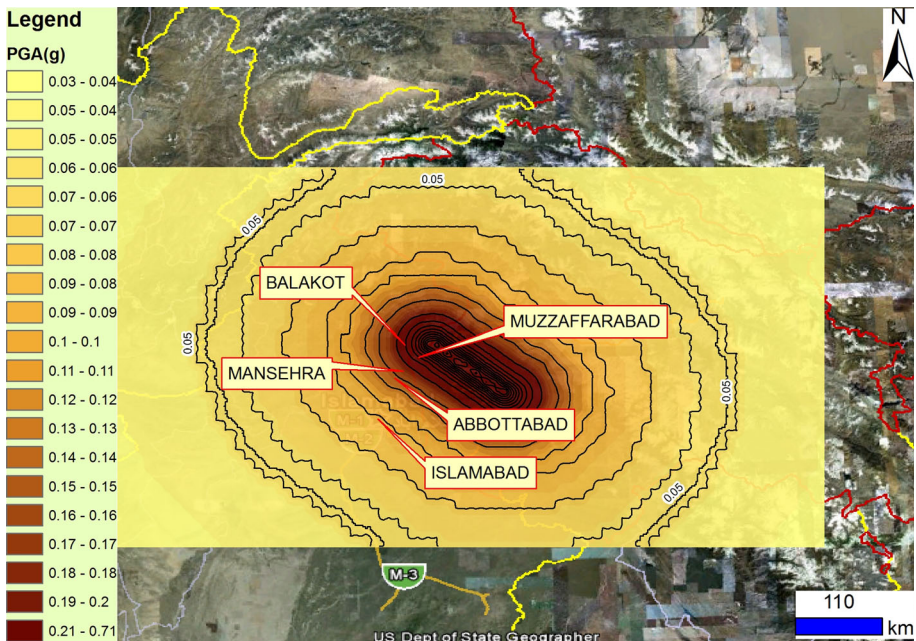


Fig. 10 Iso-seismals of the Kashmir (2005) earthquake event with location of different cities

Table 4 Site soil conditions according to different studies

Cities	References	Soil type
Muzzaffarabad	Peiris et al. (2005), JICA (2007), SSP (2006)	Rock
Mansehra	Monalisa (2008), GSP(2006), Ahmad(2008)	Rock
Abbottoabad	Kim and Elnashai (2009)	Soft soil

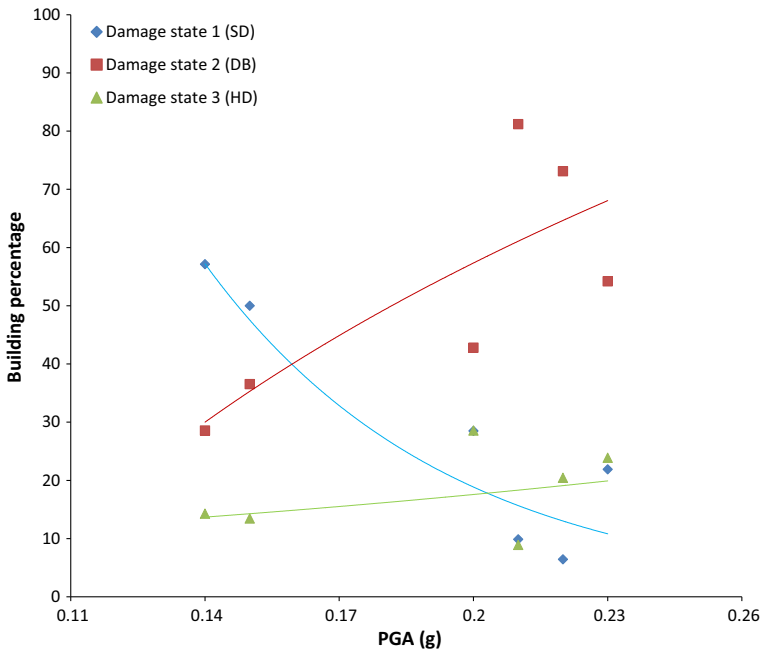


Fig. 11 Building percentage in three different damage states at different PGA levels

determined to form a DPM. The percentage of buildings in a particular damage state at different PGA levels is shown in Fig. 11.

4.3 Evaluation of MDR

Once the DPM is formed, the MDR, which is a vulnerability measure, can be calculated using the DPM elements and the DR values evaluated for each damage state. The expression used in calculating the MDR corresponding to each PGA is given in Eq. 3.

$$MDR_i = \sum_{j=1}^n DR_j = DR_j (\% \text{ of damage buildings})_j \tag{3}$$

where, DR_j = damage ratio in percentage corresponding to each damage state (Table 3). Subscript 'i' refers to varying range of PGA in DPM whereas 'j' is associated with different DR values.

The DPM elements and the MDR evaluated from the Kashmir earthquake data are given in Table 5, and the empirical vulnerability curve is shown in Fig. 12.

In Fig. 12, the MDR evaluated using the RC building damage data from the Kashmir earthquake is compared with the MDR evaluated by Kyriakides (2008) using the RC building damage data from Cyprus. In comparison to the Cyprus damage data, the NERC building damage data from the Kashmir earthquake show a higher and abrupt increase in damage with increasing PGA. The R^2 of the curve shown in Fig. 12 is 0.85 which is good for an empirical vulnerability curve, but this is due to the small quantity of available data at a narrow range of PGA.

5 Comparison with existing empirical and judgemental vulnerability curves

A comparison of the generated empirical vulnerability curve is made with existing relevant curves from literature. Using the “Global Earthquake Safety Initiative” (GESI (2001)) method, an empirical vulnerability curve for NERC buildings was developed. The score of the building is evaluated and an appropriate vulnerability curve is assigned to a building class. Other curves included in the comparison are by Schnabel (1987) for substandard constructions in the Cyprus. In the Schnabel (1987) curves, intensity on the MMI scale was used as an earthquake severity parameter and this was converted to PGA using the relationship of Theodulidis and Papazachos (1992).

A comparison of ‘GESI’ and ‘Schnabel’ curves with the generated empirical curve is shown in Fig. 13. Although the extent of the generated empirical vulnerability curve is limited, its pattern indicates a faster accumulation of damage with increasing PGA. The gradient of the curve increases very rapidly, which indicates that early brittle failures will be achieved similar to those observed in the post-Kashmir earthquake surveys. The Schnabel (1987) curves for substandard structures are found to be lower as compare to the GESI and derived empirical curve.

A comparison of the probability of the buildings exceeding the selected damage states (SD, DB, HD) is made with the general and class specific empirical fragility curves developed by Rossetto and Elnashai (2003) considering six different damage states. In the class specific curves, the one specifically developed for the pre-seismic code was used in comparison. The function used for plotting these curves is given by Eq. 2. For comparison with the general curves, PGA is used as the ground motion parameter, since the coefficients for Eq. 2 were available from both Rossetto and Elnashai (2003) and the DPM in Table 5.

For comparisons between the DPM data with the pre-seismic curves, coefficients for spectral displacement ($S_{d,5\%T_{elastic}}$) as a ground motion parameter from Rossetto and

Table 5 DPM in % for the non-ductile buildings typical of Pakistan

Damage grade	Peak ground acceleration (PGA)					
	0.14 g	0.15 g	0.2 g	0.21 g	0.22 g	0.23 g
SD	0.571	0.5	0.286	0.099	0.064	0.219
DB	0.286	0.365	0.429	0.812	0.731	0.542
HD	0.143	0.135	0.286	0.089	0.205	0.239
MDR (%)	32	34	51	45	53	50

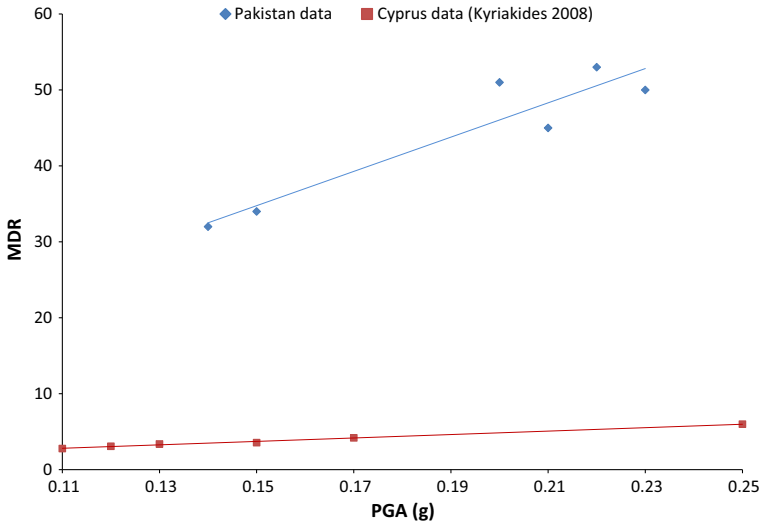


Fig. 12 Comparison between RC buildings MDR values obtained from the Kashmir and Cyprus earthquake damage data

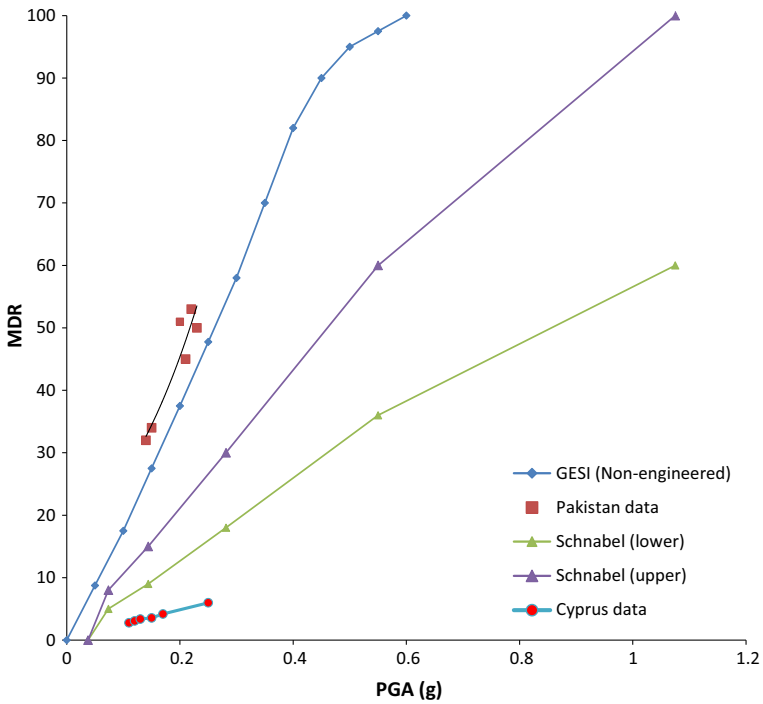


Fig. 13 Comparison of the generated empirical vulnerability curve with the existing empirical curves for substandard construction

Elnashai (2003) were available. Due to this reason, the elastic spectral displacement demand was obtained for each building in the dataset. Since the height of each building in the dataset was known, the elastic time period is determined using the EC8 relation given in Eq. (4).

$$T = C_t H^{\frac{3}{4}} \tag{4}$$

where, T = elastic time period of RC building, $C_t = 0.075$ for the moment resisting frames. H = building height [typical average storey height was taken to be 3.3 m (10.82 ft)].

The EC8 (2004) design spectrum in terms of spectral acceleration (S_a) was evaluated for each building using the evaluated PGA values and site soil type. S_a was then converted to spectral displacement (S_d) for each building using the following relation;

$$S_d = S_a \left(\frac{T}{2\pi} \right)^2 \tag{5}$$

The comparisons of general and class specific curves with the DPM data using PGA and spectral displacement as ground motion parameters are shown in Figs. 14 and 15, respectively.

The mean general and mean pre-seismic curves by Rossetto and Elnashai (2003) completely under-predicts the Kashmir earthquake damage data. The 90 % confidence (upper bound) general curve in Fig. 14 also under-predicts damage in all the damage states. This further endorses the observation made by Rossetto and Elnashai (2003) regarding the poor comparison of the general curves with the Bhuj earthquake, India (2001) damage data, because of the poor quality structures. The 90 % confidence (upper bound) pre-seismic curves in Fig. 15 associated with moderate and partial collapse damage state showed some correlation with the Kashmir earthquake damage data in DB and HD damage states. The reason for this agreement is because these curves were developed from structures predominantly failing in soft storey. In general, the available damage data show a more abrupt trend than the predictions by Rossetto and Elnashai (2003). The 90 %

Fig. 14 Comparison of the Kashmir earthquake building damage data with Rossetto and Elnashai (2003), 90 % confidence (upper bound) general empirical curves

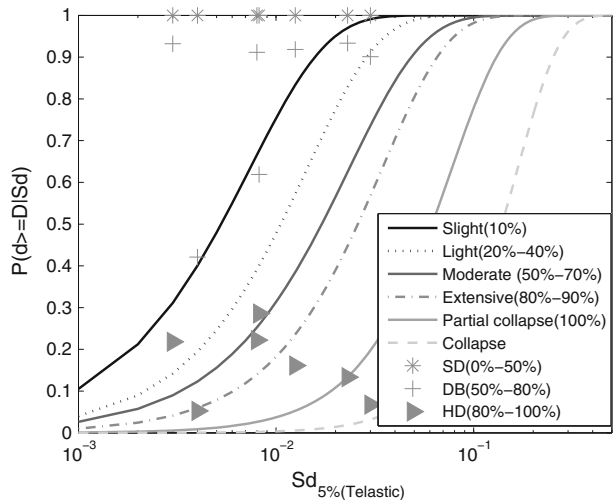
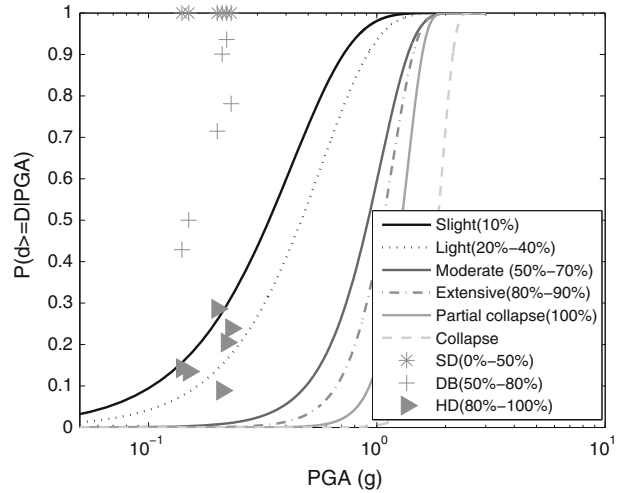


Fig. 15 Comparison of the Kashmir earthquake building damage data with Rossetto and Elnashai (2003) 90 % confidence (*upper bound*) pre-seismic code empirical curves



confidence (*upper bound*) pre-seismic curves can be of some relevance for the NERC structures.

6 Conclusions

Limited damage data for NERC structures from the 2005 Kashmir earthquake are presented and analyzed to generate the empirical seismic vulnerability curve by using the DPM technique. The majority of the damaged RC buildings from the Muzaffarabad, Mansehra and Abbottabad cities were low-rise and most of them suffered intermediate damage state DB (50–70 %). The age of these buildings ranges 1–10 and 10–50 years.

The degree of damage associated with the three damage states used by the JICA study team for characterising damages of building stock are related to the HAZUS (1999) damage states. All existing damage scales, which are associated with a physical parameter, are not calibrated according to the experimentally observed data from NERC structures, and further research is required in this area. The DPM technique was chosen because of the limited data over a small PGA range and the assumption that the buildings with similar structural system will behave in a similar way.

The Schnabel (1987) curves for RC buildings were found to be conservative for poor quality structures of developing countries. The Rossetto and Elnashai (2003) 90 % confidence (*upper bound*) pre-seismic curves showed some agreement with the empirical curve predictions using the Kashmir earthquake damage data. The GESI non-engineered vulnerability curve agreed well with the MDR evaluated from the current data and can be used for brittle structures in risk assessment studies, but since the curves are not validated over a large PGA range, an analytical vulnerability assessment is required for non-ductile structures from this region.

Due to the uncertainties and lack of NERC damage data, there is need for a more detailed analytical vulnerability assessment of RC structures with special emphasis on NERC structures. This study was conducted by the authors and is presented in a separate paper (Kyriakides et al. (2014)).

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References

- ADB-WB (2005) Preliminary damage and needs assessment—Pakistan 2005 earthquake, prepared by Asian Development Bank and World Bank, Islamabad, Pakistan, November 12, 2005
- Ahmad N (2008) Development of a seismic risk/loss model for Mansehra City, Pakistan. Masters Thesis, Universit_A Degli Studi Di Pavia
- Ahmad S (2011) Seismic vulnerability of non-ductile reinforced concrete structures in developing countries. The University of Sheffield, UK, Department of Civil and Structural Engineering, Ph.D Thesis
- Ambraseys NN, Douglas J, Sarma SK, Smit PM (2005) Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the middle east: horizontal peak ground acceleration and spectral acceleration. *Bull Earthq Eng* 3:1–53
- ATC-20 (1989) Procedures for post earthquake safety evaluation of buildings. Publication of Applied Technology Council, Redwood City
- Braga F, Dolce M, Liberatore D (1982) A statistical study on damaged buildings and ensuing review of the MSK-76 scale. In: Proceedings of 7th European conference on earthquake engineering, Athens
- DiPasquale G, Orsini G, Romeo RW (2005) New developments in seismic risk assessment in Italy. *Bull Earthq Eng* 3(1):101–128
- Dolce M, Masi A, Marino M, Vona M (2003) Earthquake damage scenarios of the building stock or Potenza (Southern Italy) including site effects. *Bull Earthq Eng* 1(1):115–140
- Duranni AJ, Elnashai AS, Hashash YMA, Kim SJ, Masud A (2005) The Kashmir earthquake of October 8, 2005, a quick look report. Mid-America Earthquake Center. University of Illinois at Urbana-Champaign
- ERRA-PERRA (2007) Earthquake reconstruction and rehabilitation authority. Government of Pakistan-Provisional Reconstruction and Rehabilitation Agency, Government of Khyber Pakhtunkhwa (KPK)
- FEMA154 (2002) Rapid visual screening of buildings for potential seismic hazards: a handbook, 2nd edn. Earthquake hazard reduction series 41
- FBS (2010) “Monthly review on price indices” federal bureau of statistics, ministry of economic affairs and statistics. Government of Pakistan
- GESI (2001) Global earthquake safety initiative (GESI). Pilot project, GeoHazards International (GHI), UNCRD
- Grünthal G, Musson RMW, Schwarz J, Stucchi M (1998) European macroseismic scale 1998. Centre Européen de Géodynamique et de Séismologie 15, Luxembourg
- GSP (2006) Geological map of Mansehra quadrangle, District Mansehra, NWFP. Geological Survey of Pakistan, Peshawar
- HAZUS (1999) Earthquake loss estimation methodology, technical manual. Report prepared for the Federal Emergency Management Agency, Washington, DC, under a contract with NIBS
- JICA (2006) Detailed building damage distribution map (right bank of Neelum river)
- JICA (2007) The urgent development study on rehabilitation and reconstruction in Muzaffarabad city in the Islamic Republic of Pakistan. Final report 1: Volume 2: Main report
- Khan S (2010) An earthquake risk assessment framework for developing countries: Pakistan a case study. Phd Thesis, The University of Sheffield
- Kim SJ, Elnashai AS (2009) Characterization of shaking intensity distribution and seismic assessment of RC buildings for the Kashmir (Pakistan) earthquake of October 2005. *Eng Struct* 31:2998–3015
- Kyriakides N (2008) Seismic vulnerability assessment of RC buildings and risk assessment for cyprus. Phd Thesis, The University Of Sheffield
- Kyriakides N, Ahmad S, Pilakoutas K, Neocleous K, Chrysostomou C (2014) A probabilistic analytical seismic vulnerability assessment framework for substandard structures in developing countries. *Earthq Struct* 6(6):665–687
- Miyakoshi J, Hayashi Y, Tamura K, Fukuwa N (1997) Damage ratio functions of buildings using damage data of the 1995 Hyogoken-Nanbu earthquake. In: Paper presented at the ICOSSAR 1997, Kyoto, Japan

- MonaLisa (2008) Seismic hazard assessment of Mansehra. Department of Earth Sciences, Quaid-e-Azam University (QAU), Islamabad
- Naseer A, Ali SM, Hussain Z (2006) Reconnaissance report on the 8th October, 2005 earthquake Pakistan. Earthquake Engineering Centre, Department of Civil Engineering NWFP UET Peshawar, Pakistan National Disaster Management Authority (NDMA). Government of Pakistan
- Nisikawa T, Nakano Y, Tsuchiya Y, Sanada Y, Sameshima H (2005) Quick report of damage investigation on buildings and houses due to October 8, 2005 Pakistan earthquake. Japan Society of Civil Engineers (JSCE) and Architectural Institute of Japan (AIJ)
- Orsini G (1999) A model for buildings vulnerability assessment using the parameterless scale of seismic intensity (PSI). *Earthq Spectra* 15:463–483
- Peiris N, Rossetto T, Burton P, Mahmood S (2005) EEFIT Mission: October 8, 2005 Kashmir earthquake. The Institution of Structural Engineers, London
- Rossetto T, Elnashai AS (2003) Derivation of vulnerability functions for European-type RC structures based on observational data. *Eng Struct* 25:1241–1263
- Rota M, Penna A, Strobbia C (2006) Typological fragility curves from Italian earthquake damage data. In: Proceedings 1st European conference on earthquake engineering and seismology, Geneva
- Schnabel WE (1987) The accumulation of potential in Cyprus. In: number 13: earthquake risk and insurance—e.g. in Cyprus. Nicosia, Cyprus, pp 87–130
- SSP (2006) Azad Jammu and Kashmir soils and landforms: map prepared at soil survey of Pakistan regional office. Peshawar
- Stegemeier RJ (2008) Mitigating seismic risk in developing countries: a case study on the 2005 Kashmir earthquake. Rice University, Houston
- Theodulidis NP, Papazachos BC (1992) Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement. *J Soil Dyn Earthq Eng* 11:387–402
- UNDP-ERRP (2008) United Nation Development Programme (UNDP), Pakistan-earthquake risk reduction and preparedness (ERRP) project. Muzaffarabad city's Earthquake Scenario
- Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull Seismol Soc Am* 84:974–1002
- Whitman R, Reed J, Hong S (1973) Earthquake damage probability matrices. In: Paper presented at the proceedings of the fifth world conference on earthquake engineering, Rome