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ORIGINAL ARTICLE

An investigation on Balakot, Muzaffarabad (Pakistan) earthquake, 8 Oct. 2005, Mw 7.6; geological aspects and intensity distribution

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Abstract In this paper, the investigations on seismotectonic and intensity evaluations of epicentral and meizoseismal regions in Muzaffarabad earthquake—8 Oct. 2005, Mw 7.6—are summarized using The European Macroseismic Scale (EMS-98). The observations are compiled based on the field investigations and isoseismal map. The results show that the isoseismals are elongated parallel to the reactivated Muzaffarabad fault, and the attenuation is high in the direction normal to the fault compared with the direction parallel to it. The geotechnical investigations in Muzaffarabad Valley have helped the authors to assign intensity values in the localities where some huge landslides are observed. Finally, the empirical laws, previously developed for intensity attenuation in Iran in EMS-98 scale, are compared with the intensity observations here. The results are roughly consistent with the general form of attenuation laws. However, it is found that the intensity attenuations are different in the directions normal and parallel to the fault.

Keywords Balakot · Muzafarabad · Intensity · Damage · Engineering seismology · Iran · Attenuation · Pakistan

1 Introduction

On 8 Oct. 2005, at 8:50:40 A.M. local time (3:50:40 GMT), an earthquake of magnitude Mw = 7.6 occurred in the NE of Pakistan. Its epicenter was located at about 10 km in the east of Balakot and 19 km in the northeast of Muzaffarabad in Pakistan-administered Kashmir. The earthquake caused heavy life and property losses in Pakistan-administered Kashmir, Pakistan's North-West Frontier Province, western and southern parts of Kashmir on the Indian side, and eastern parts of Afghanistan. The People in Srinagar (Indian Kashmir), Kabul (Afghanistan), and Islamabad (Pakistan) experienced violent shaking and ran outdoors; in Pakistan, Balakot City was totally destroyed, and Muzaffarabad, Bagh, and Rawalakot were severely damaged; in Mansehra and Abbottabad, many modern constructions were damaged, and a 10-story building (a block of the Margala towers) collapsed in Islamabad; the phone network

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was either down or jammed in the epicentral region. More than 80,000 persons were killed according to the official report. The affected region is a mountainous area with high landslide potential. A series of landslides were triggered by the earthquake, which blocked and damaged roads and power transport lines. Small houses located in the slopes were buried under the debris of landslides. Unstable and traditional structures enhanced damage in the epicentral region. The event effects were observed up to Lahore (Pakistan) in the south of epicenter zone where several stores collapsed. Even in Rawalpindi (few kilometers south of Islamabad) and in Srinagar region (capital of Kashmir in India), severe damage was reported.

2 Seismotectonics

The study area is a part of the NW Himalayan Fold and Thrust Belt (Kazmi and Jan 1997), seismically very active (Fig. 1). Some researchers (e.g., Verma and ChandraSeckhar 1986; Sercombe et al. 1998; MonaLisa et al. 2002, 2004, 2008; MonaLisa 2008) have contributed to the seismicity/tectonics understanding of this seismically very active region of the world and studied the ongoing collisional processes of Indian plate with Kohistan Island Arc. They also recognized transpression features as a result of this convergence in addition to the N–S compression. This fold and thrust belt form an area between the Main Mantle Thrust (MMT) and Salt Range Thrust with the

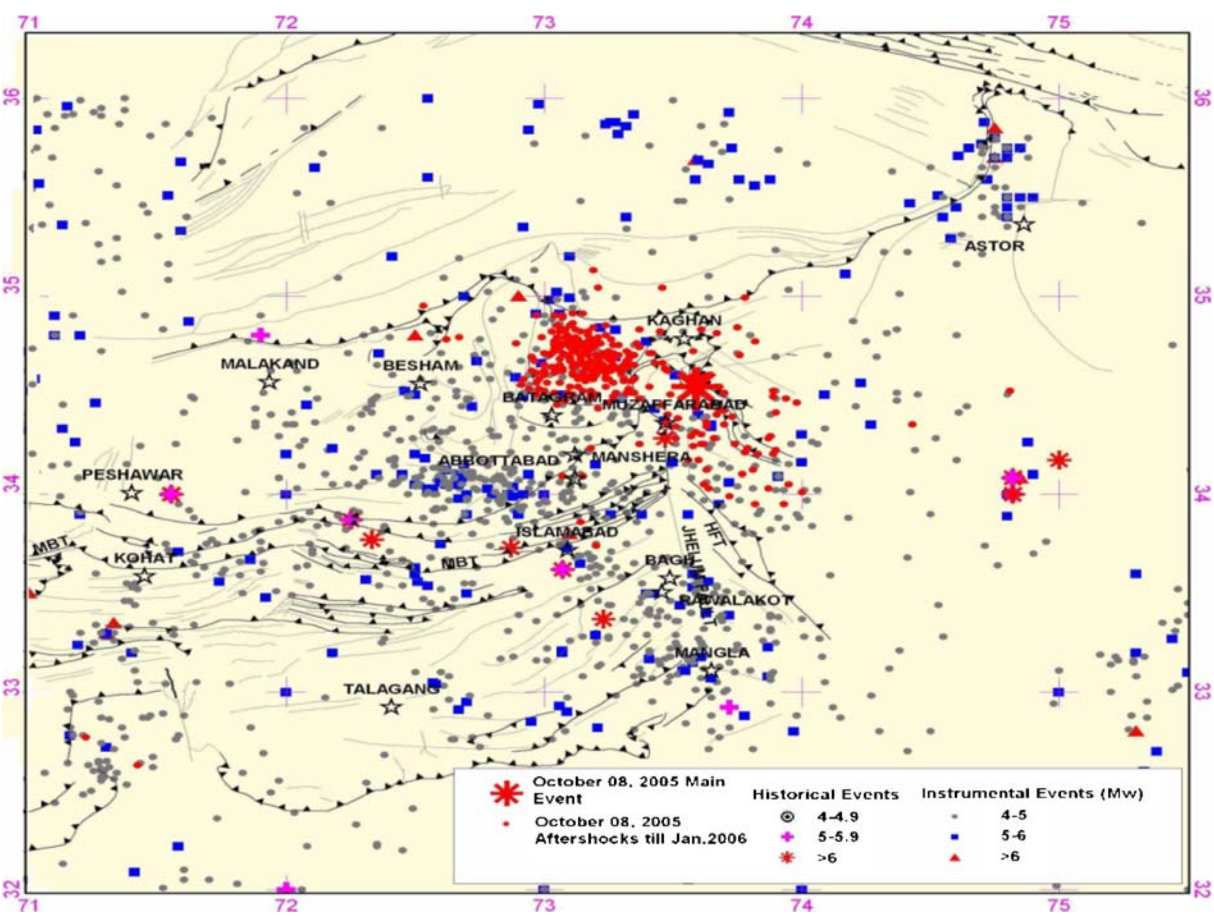

Fig. 1 Seismotectonic setting of the area of the 8 Oct. 2005 earthquake (modified after MonaLisa et al. 2004). The *red dots* are the aftershocks of the mainshock

westward extensions (Surghar, Marwat, Bhittani, and Manzai ranges). According to Gee (1980) and next researchers, the southern sides of the ranges are also marked by thrusts. Tectonic domains of Hazara-Kashmir Syntaxis (where the earthquake on 8 Oct. 2005 occurred) and Nanga Parbat Haramosh Massif form its eastern border. In the hinterland zone, mostly crystalline rocks are represented by Proterozoic to Mesozoic metamorphic and igneous rocks occur. Shearing and imbrication are ended in a complex deformation pattern. Basement is also involved in thrusting (Armbruster et al. 1978; Seeber and Armbruster 1979). Treloar et al. (1989) identified six nappe zones (Mohmand-Swat, Besham, Hazara, Banna, Kaghan, and Nanga Parbat-Haramosh massif), separated from each other by prominent shears and thrust faults. According to Kazmi and Jan (1997), uplift rates in different blocks of the nappe zones also vary, and the crustal shortening of more than 470 km has taken place in the area between Mansehra Thrust and MMT. It is an active tectonic feature, characterized by uplift rates of 7 mm/year (Zeitler et al. 1982), high seismicity (Yielding et al. 1984; and this study), and active faulting (Madin et al. 1989; Treloar et al. 1989; Khwaja et al. 2003).

The epicentral location of this earthquake lies in the northwestern portion of Himalayan Frontal Arc. Between 1897 and 1952, along the Himalayan convergent plate margin, 14 major earthquakes ($M \geq 7.5$), including five great earthquakes of $M \geq 8$, occurred.

3 Muzaffarabad earthquake, 2005: source parameters

The epicenter of Balakot, Muzaffarabad earthquake—8 Oct. 2005—was located at 110 km in the north of Islamabad and 175 km northwest of Srinagar. The focal mechanism determined by Avouac et al. (2006), using sub-pixel correlation of advanced spaceborne thermal emission and reflection radiometer (ASTER) images, indicates thrust faulting on a N138° striking fault having dip towards NE with significant strike-slip component of slip. Similar focal mechanism was obtained by Parsons et al. (2006).

Forty-seven aftershocks of mb ≥ 5.0 occurred in the first month after the event. The fault plane solutions of these aftershocks show thrust motions similar to the mainshock.

The aftershocks distribution shows a concentration in the north and northwest of the epicenteral zone. The earthquake rupture on 8 Oct. 2005 reached the surface in many places, being referred to as "Muzaffarabad fault" and in the name of "Murree Fault" in geological map of the area (Geological Survey of Pakistan, 1:50,000 scale; Pathier et al. 2006). Furthermore, most surface ruptures are marked by landslides. The estimated focal depth is less than 10 km (Parsons et al. 2006).

4 Landslides

The earthquake occurrence accompanied by landslides made a lot of dust specially in Darebagh, Muzaffarabad, and Balakot. Such phenomena with huge stones falling destroyed the roads in different places (Fig. 2) and blocked the traffic, leading to extreme congestion.

Numerous landslides occurred in the meisoseismal region, and most of them were associated with the fault scarp where the rupture reached the surface. The landslides mostly occurred from the eastern parts of Darebagh to Muzaffarabad and Balakot (Fig. 3) which damaged or blocked roads and also induced some damages to the transport facilities such as tunnels, having no

Fig. 2 Islamabad–Muzaffarabad road destroyed by Balakot earthquake on 8 Oct. 2005

Fig. 3 An example of landslide south of Balakot along the earthquake fault rupture

halter or cover, and bridges in the south of Muzaffarabad. Some vertical and horizontal cracks and fissures have been observed on the south Muzaffarabad bridge. The bridge was barricaded, and the road was closed in the first days after the event. By reopening this tunnel, the connection between Islamabad and Muzaffarabad was resumed (Fig. 4).

5 Earthquake intensity

The isoseismal map for the 8 Oct. 2005 earthquake is prepared based on the total destruction of epicentral zone (Balakot and Muzaffarabad) and studying the reports of remote places such as Srinagar in India and Lahore in Pakistan (Fig. 5). This map is essentially based on field visits of International Institute of Earthquake Engineering and Seismology (IIEES) reconnaissance team. The visits took place less than 3 weeks after the epicentral mainshock. The maximum intensity was estimated to be around Balakot and along Muzaffarabad fault (Table 1), with a width of 10–15 km around the fault.

Fig. 4 Destruction of the tunnel opening on the road located in the south of Muzaffarabad

The greatest damage was observed in Balakot (Fig. 6) representing complete destruction (i.e., more than 1 m dislocation of the concrete bridge over Balakot River; Fig. 7). Balakot region is assigned intensity X [according to The European Macroseismic Scale (EMS-98) scale]. All buildings in this valley city were destroyed totally. Many landslides took place on the north and south sides of the valley, and they were more concentrated in the eastern hillsides. And all buildings, facilities and roads around Balakot were seriously damaged.

The city of Muzaffarabad is located on a river terrace. Based on damages seen in Ijaz Golab military hospital, an intensity of IX on EMS-98 scale is estimated. There are many large earthquake-inducing landslides along the hills around the city. The retaining walls were collapsed in some roads (Fig. 8). In Ijaz Golab hospital, the northern block fell down due to the first floor collapse (soft story), but other parts of the hospital show less damage. The daily life had returned to normal 18 days after the event when IIEES reconnaissance team visited the epicentral region.

Intensity in Abbottabad was estimated to be VIII (EMS-98 scale) derived from a hotel collapse. Due to the observed damage of residential buildings, VIII intensity is assigned to Mansehra (Fig. 9).

No damage was observed on the dam and the facilities upon the inspection of Tarbela earth-rock fill dam. However, mud was reported in the dam's reservoir due to the landslides.

To the SW of the epicenter, the landslides were observed in the region between Punjab and Jammu and Kashmir (India). This region is assigned an intensity of about VI.

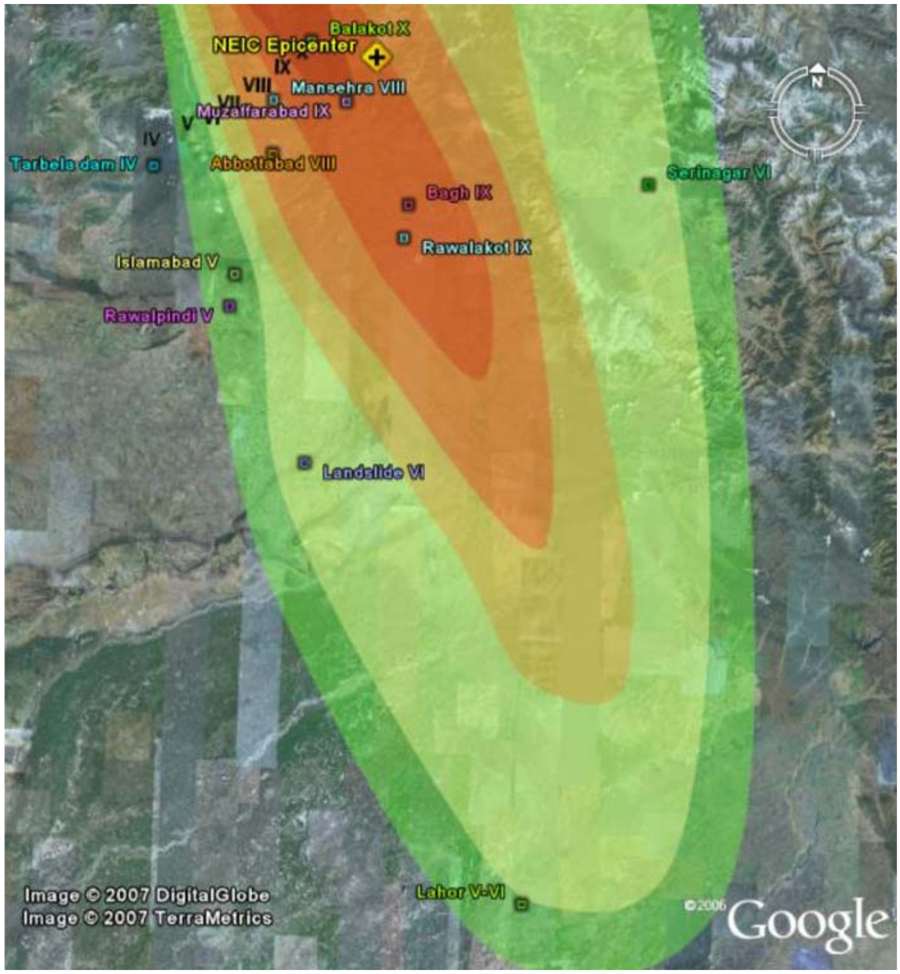

Fig. 5 Iso-intensity map generated by IIEES reconnaissance team (Dr. Eshghi and Dr. Zaré, Nov. 2005) on EMS-98 scale

While there was not as much damage in Islamabad, a Margala tower collapsed in the northwest of Islamabad (Fig. 10) because of its structural engineering and also the type of soil (grain alluvium with clay matrix).

In Balakot, Bagh, Rawalakot, Mansehra, Abbottabad, and Lahore, estimated intensities are similar to those reported by Geological Survey of India (Pande et al. 2006).

6 Comparing Muzaffarabad earthquake intensities and Iranian empirical intensity attenuation law

Empirical relationship for the attenuation of earthquake intensities, published recently in Iran, was presented by Zaré and Memarian (2003). It is based on EMS-98 intensities (Grunthal 1998) observed for Iranian earthquakes, the general form of which is:

$$I = a \times M - b \times X - cL_n X + \sigma \times p$$

where M is moment magnitude, X is the distance between epicenter and site, and I is intensity on EMS-98 scale. The obtained coefficients for this relationship are presented in Table 2.

According to the attenuation studies in Iran, at least two regions, Zagros and Alborz-Central Iran, might be distinguished with different attenuation rates. The coefficients of attenuation laws are obtained based on the regression analysis, Zaré and Memarian (2003), of the dataset selected

Table 1 Observed values of the intensities during the earthquake on 8 Oct. 2005

Region	Distance (km)	Structural damage	Landslide	Observed intensity EMS-98
Balakot	0	Dislocation of the concrete bridge over the Balakot River more than 1 m; all buildings in this city destroyed totally	Many landslides on north and south sides of valley took place	X
Muzaffarabad	0	Damages seen in Ijaz Golab military hospital		IX
Bagh	0	Major damage in residential buildings	Great landslide	IX
Rawalakot	13	Collapse of some residential buildings	-	IX
Mansehra	23	Damages in residential buildings	-	VIII
Abbottabad	35	A hotel collapsed	-	VIII
Islamabad	70	A public panic reported, cracks in buildings (Margala Tower collapsed)	-	V
Tarbela dam	75	No fissure observed (or reported) on the dam	Mud enters to dam's reservoir due to the landslides	IV
Rawalpindi	80	Panic reported	-	V
Serinagar	95	Damage in residential buildings	-	VI
Landslide in south of Rawalpindi	113	–	Landslide happened	VI
Lahore	275	Several stores collapsed	-	V–VI

for these two regions and an ensemble of the datasets (Table 2).

Comparing the results with the predicted intensities, based on the empirical intensity laws for Iran, indicates higher values of earthquake intensities in the Balakot earthquake, in comparison with the similar case in Iran.

Since the observations show two different attenuation intensity rates along the earthquake fault direction and in the fault-normal direction, we have dealt them separately and have tried to compare the data with the values from Iranian attenuation of intensity relationships.

Table 1 shows the observed values of the intensities during the earthquake on 8 Oct. 2005. Applying the observed intensity values, a regression is performed, and the intensities are assessed for a possible similar event in Iran. Using Iranian

Fig. 6 Panoramic photo of the destroyed city of Balakot

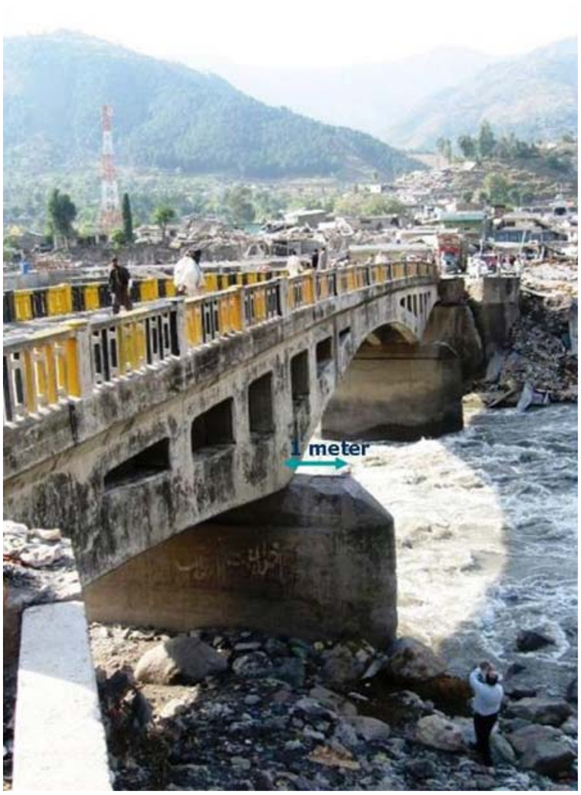

Fig. 7 About 1 m displacement in the abutment of Balakot southern bridge due to the earthquake mainshock on 8 Oct. 2005

intensity attenuation for Zagros and Alborz-Central Iran regions, a separate law developed based on a data ensemble. Here, the empirical

Fig. 8 Muzaffarabad: the retaining wall collapse due to Balakot earthquake mainshock on 8 Oct. 2005

Fig. 9 Destruction at Mansehra

intensity assessments (with Iranian laws) are compared with those obtained by the regression based on 8 Oct. 2005 earthquake data (Fig. 11).

According to this comparison:

- A major difference can be seen between the attenuation intensity rate of Zagros belt in Iran and that of the earthquake on 8 Oct. 2005 in Pakistan.
- The estimated intensity values, using Iran empirical relationship (developed based on all Iranian data), are quite in accordance with the earthquake intensity observations on 8 Oct. 2005 (Table 3).
- Due to the significant difference between observed intensity values in the fault-normal direction and those observed along the fault strike, a major scatter might be seen at the distances of 50 to 100 and over 250 km.

Fig. 10 Margala Tower collapse in Islamabad (Associated Press, Oct. 2005)

Table 2 Iranian intensity attenuation coefficients (Zaré and Memarian 2003)

Region	a	b	c	Sigma	R
Alborz model	1.127	0.0136	0.277	0.92	0.88
Central Iran-Zagros model	1.148	0.0214	0.131	0.73	0.54
Total Iran model	1.175	0.0140	0.227	0.88	0.77

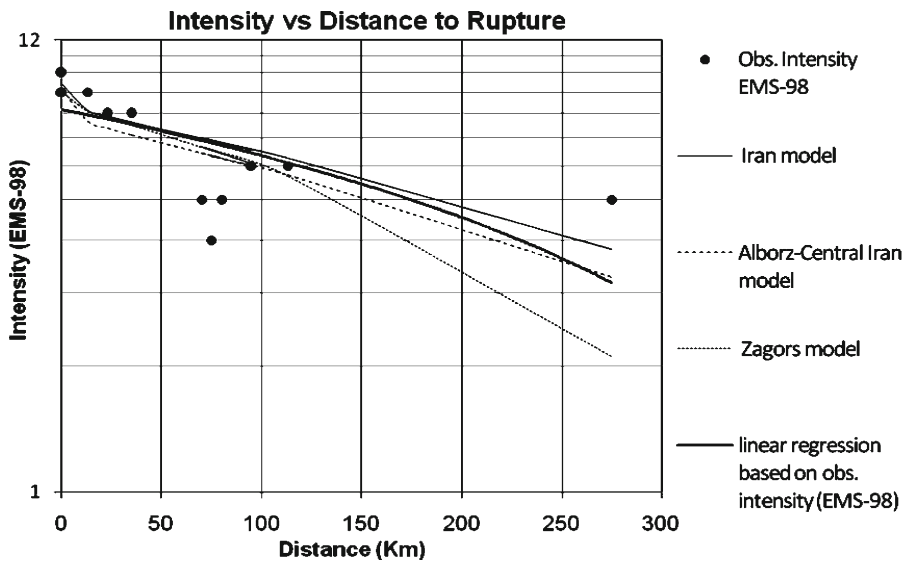

Fig. 11 The attenuation of intensities versus distance for Balakot earthquake on 8 Oct. 2005

Table 3 Comparison of observed and estimated intensity values using the Iranian empirical laws

Region	Distance	Observed intensity EMS-98	Iran model	Alborz-Central Iran model	Zagors model
Balakot	0	X	IX	IX	IX
Muzaffarabad	0	IX	IX	IX	IX
Bagh	0	IX	IX	IX	IX
Rawalakot	13	IX	VIII	VII–VIII	VIII
Mansehra	23	VIII	VIII	VII	VIII
Abbottabad	35	VIII	VII–VIII	VII	VII–VIII
Islamabad	70	V	VII	VI–VII	VI–VII
Tarbela dam	75	IV	VII	VI	VI–VII
Rawalpindi	80	V	VII	VI	VI–VII
Serinagar	95	VI	VI–VII	VI	VI
Landslide in south of Rawalpindi	113	VI	VI	V–VI	V–VI
Lahore	275	V–VI	IV	III	II

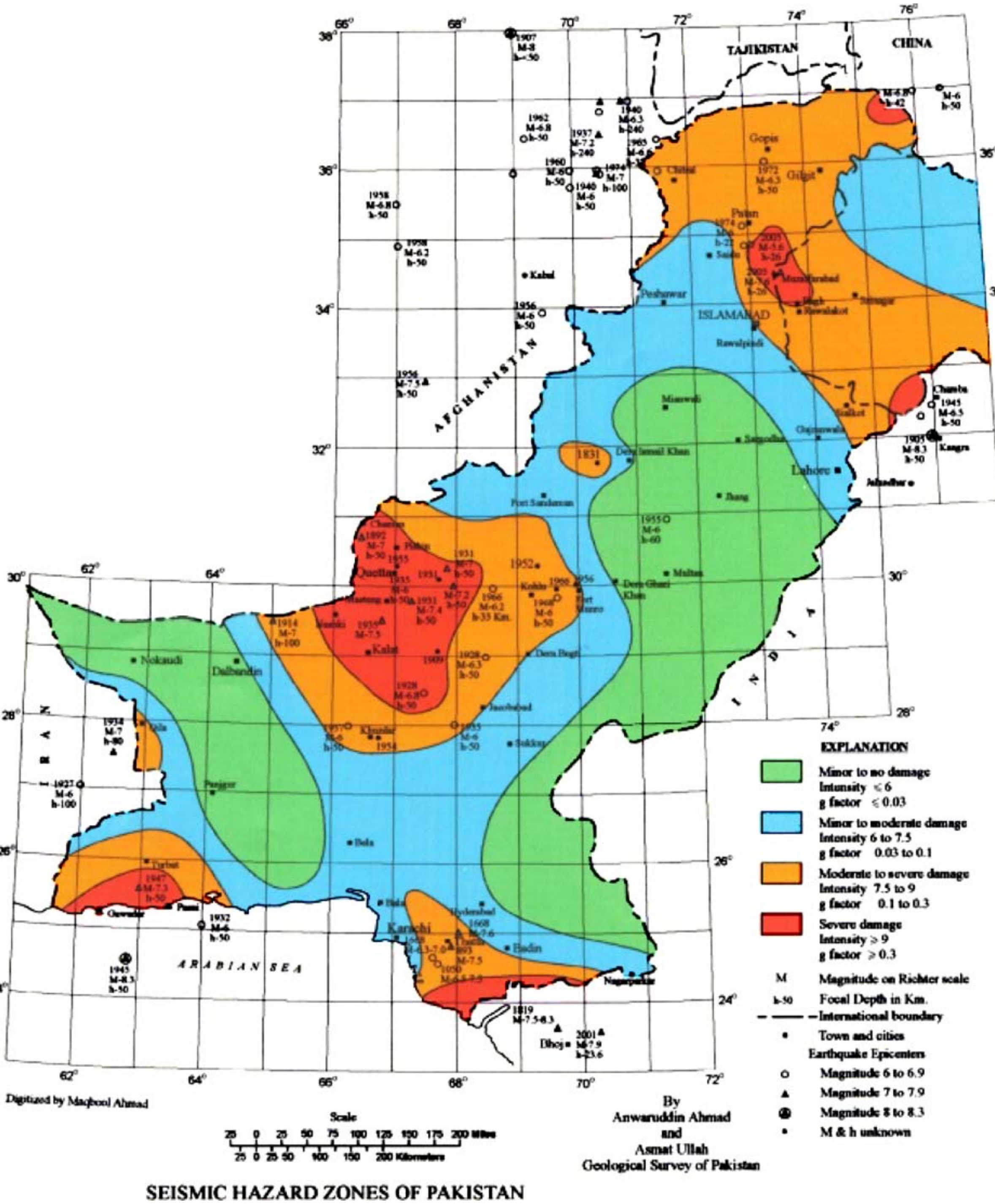

Fig. 12 Seismic hazard zonation map of Pakistan generated immediately after the earthquake of 8 Oct. 2005, principally modified by showing high hazard in Balakot (Geological Survey of Pakistan website, Nov. 2005)

7 Discussion

Based on the field observations in the epicentral area and the meisoseismal region of Balakot earthquake on 8 Oct. 2005, the following points are mentioned:

- The meisoseismal region is located in the Muzaffarabad Valley, and the most devastated area, Balakot City, was totally demolished. The observed damage was nearer to the southeast end of the fault (towards Bagh) that could be due to directivity effect along the fault towards northwest.
- The upward progress of the rupture plane might be the source of heavier damage in the hanging wall of the fault.
- The attenuation of strong ground motions was faster in the fault-normal direction, and therefore, the damage diminished rapidly towards the east and west of the meisoseismal region.
- The site effect might be a secondary source in Margala Tower damage, about 70 km from the rupture. However, the damage was limited due to the attenuation of strong motions (intensities) in Islamabad City.
- This earthquake has shown the importance of the landslides in the determination of earthquake intensities in the remote and sparsely populated mountainous areas. The great landslides, specially along Muzaffarabad Valley and near Bagh City, were major indicators of inferring isoseismal intensity.
- The earthquake occurred near the line of control between Pakistan and India. This has evidently prohibited the reconnaissance group from moving freely in the earthquake-affected areas and to access beyond the border. This may cause uncertainties in the assessment of the attenuation in the epicentral area.
- The attenuation of intensities regarding Muzafarabad earthquake on 8 Oct. 2005 shows a general accordance with the attenuation law for intensities already developed for Iran. However, this agreement might not be true concerning the differences in fault-normal and fault-parallel attenuations.

8 Concluding remarks

The Balakot earthquake of 8 Oct. 2005, with the magnitude Mw = 7.6, caused heavy life and property losses. The earthquake occurred along Muzaffarabad fault, and most likely, a part of the fault between Bagh and Balakot was reactivated. Strong ground motion caused severe damage especially in the east and northeast part of the epicenter. The direction of the strong movement mostly were northwest–southeast. As the occurrence time of the previous event on this fault segment is unknown, paleoseismological studies are required to infer the recurrence interval.

Islamabad City is located near the syntaxial bend where the tectonic process are more intense and complex. Therefore, the region has very high potential seismic hazard. The seismic hazard zonation map of Pakistan, produced by Geological Survey of Pakistan before 8 Oct. 2005, represented moderate hazard level in Balakot region. After the Balakot earthquake, the seismic hazard map of Pakistan has been revised (Fig. 12). Balakot and Muzaffarabad zones now lie in high seismic hazard zones. However, in order to update the seismic hazard zoning maps for Pakistan, incorporating major active tectonic units and assuming proper seismicity parameter are proposed for the input of seismic hazard map.

Besides using the attenuation laws applicable to Iran region, it is imperative to develop attenuation laws for Pakistan region. Furthermore, as the attenuations are different in the direction parallel and normal to the fault, the relations should be developed carefully. This will help in developing earthquake-resistant building codes in the region.

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References

Armbruster J, Seeber L, Jacob KH (1978) The northwestern termination of the Himalayan mountain front: active tectonics from microearthquakes. J Geophys Res 83:269–282. doi:10.1029/JB083iB01p00269

Associated Press (2005) web site http://www.ap.org/, October 2005

Avouac JP, Ayoub F, Leprince S, Konca O, Helmberger DV (2006) The 2005, Mw 7.6 Kashmir earthquake: subpixel correlation of ASTER images and seismic waveforms analysis. Earth Planet Sci Lett 249:516–528. doi:10.1016/j.epsl.2006.06.025

Gee ER (1980) Pakistan geological salt range series; (6 sheets, scale 1: 50,000). Directorate of overseas surveys, UK, for the Government of Pakistan & Geological Survey of Pakistan

Geological Survey of Pakistan (GSP) (2005) web site; http://www.gsp.gov.pk/, October 2005 to December 2005

Grunthal G (ed) (1998) European Macroseismic Scale 1998, http://www.gfz-potsdam.de/pb1/pg2/ems_new/INDEX.HTM

Kazmi AH, Jan MQ (1997) Geology and tectonics of Pakistan. Graphic, Karachi

Khwaja AA, MonaLisa, Khan SA, Chaudhry QZ, Rafiq M, Khan AT (2003) Recent seismic activity along the western margin of the Nanga Parbat Haramosh Massif, Pakistan. Islamabad J Sci 13(1): 18–27

Madin IP, Lawrence RD, Ur-Rehman S (1989) The northwestern Nanga Parbat-Haramosh Massif; evidence for crustal uplift at the northwestern corner of the Indian craton. In: Malinconico LL, Lillie RJ (eds) Tectonics and geophysics of the Western Himalaya, vol 232. Geological Society of America, Special Papers, pp. 169–182

MonaLisa (2008) Recent seismic activity in the NW Himalayan Fold and Thrust Belt, Pakistan: focal mechanism solution and tectonic implications. Geological Society of London, Special Publications (in press)

MonaLisa, Khwaja AA, Qaiser M (2002) Focal mechanism studies of Kohat and Northern Potwar deformed zone. Geol Bull Univ Peshawar 35:85–95

MonaLisa, Khan SA, Khwaja AA (2004) Focal mechanism studies of North Potwar deformed zone (NPDZ), Pakistan. Acta Seismol Sin China 17:255–261. doi:10.1007/s11589-004-0047-8

MonaLisa, Khwaja AA, Jan MQ (2008) October 08, 2005 Muzaffarabad earthquake: seismological investigations and probabilistic estimation of peak ground accelerations. Curr Sci 94(9):1158–1166

Pande P, Joshi DD, Kandpal GC, Joshi KC, Singh RJ, Singh BK, et al (2006) A geoseismological report on 8th October 2005 Kashmir earthquake. Geological Survey of India

Parsons T, Yeats RS, Yagi Y (2006) Static stress change from the 8 October, 2005 M = 7.6 Kashmir earthquake. Geophys Res Lett 33:LO6304. doi:10.1029/2005GL025429

Pathier E, Fielding EJ, Wright TJ, Walker R, Parsons BE, Hensley S (2006) Displacement field and slip distribution of the 2005 Kashmir earthquake from SAR imagery. Geophys Res Lett 33:L20310. doi:10.1029/2006GL027193

Seeber L, Armbruster J (1979) In: Farah A, DeJong KA (eds) Seismicity of the Hazara arc in northern Pakistan: decollement vs. basement faulting, in Geodynamics of Pakistan. Geol. Surv. of Pakistan, Quetta, pp. 131–142

Sercombe WJ, Pivnik DA, Wilson WP, Albertin ML, Beck RA, Stratton MA (1998) Wrench faulting in the northern Pakistan foreland. AAPG Bull 82:2000–2030

Treloar PJ, Rex DC, Guise PG, Coward MP, Searle MP, Windley BF, et al (1989) K-Ar and Ar-Argeochronology of the Himalayan collision in NW Pakistan: constraints on the timing of collision deformation, metamorphism and uplift tectonic. Tectonics 4:881–909. doi:10.1029/TC008i004p00881

Verma RK, ChandraSekhar CH (1986) Focal mechanism solutions and nature of plate movements in Pakistan. J Geodyn 5:331–351. doi:10.1016/0264-3707(86)90013-X

Yielding G, Khurshid A, Ahmad S, Davison I, Jackson JA, King GCP, Lin Ban Zuo (1984) The seismicity of northernmost Pakistan. Tectonophysics 109:209–226. doi:10.1016/0040-1951(84)90141-0

Zaré M, Memarian H (2003) Macroseismic intensity and attenuation laws: a study on the intensities of Iranian earthquakes: 1975–2000. In: Proceedings of the 4th international conference on seismology and earthquake engineering (SEE4), vol 1. CD-Rom. May 2003, Tehran, Iran, published by IIEES, 8 pp

Zeitler PK, Johnson NM, Naeser CW, Tahirkheli RAK (1982) Fission-track evidence for Quaternary uplift of the Nanga Parbat region, Pakistan. Nature 298: 255–257. doi:10.1038/298255a0