SURFACE DEFORMATION AND MASS MOVEMENTS CAUSED BY THE 2005 KASHMIR EARTHQUAKE, NORTHERN PAKISTAN

Allah Kausar[1*], Dave Petley[2], Simon Sadiq[3]

ABSTRACT

The 2005 Kashmir earthquake with magnitude of M_w 7.6 accompanied fault ruptures over a length of approximately 79 km from immediately north of Balakot to northwest of Bagh with a northeast-side-up vertical separation of up to 7 m. The surface rupture is subdivided into northern, central and southern geometric segments separated by small steps. The location of the hypocenter suggests that the rupture was initiated at a deep portion of the northern-central segment boundary and propagated bilaterally to eventually break all three segments. We tentatively estimated the earthquake recurrence interval and shortening rate on the Balakot-Bagh fault to be 1000-3000 yr and 1.4-4.1 mm/yr, respectively.

This earthquake triggered numerous landslides and slope failures, with most of them being located on the hanging wall of the fault. These include deep-seated failures, shallow, disrupted landslides, rock-falls, and cut-slope failures. Many of these failures are still active and loose fractured material is moving down the steep slopes even under the gravity. The largest landslide occurred close to the town of Hattian Bala, approximately 3 km from the fault trace in a side valley of the Jhelum valley system. Here a pre-existing landslide has been reactivated, the resultant debris avalanche has blocked two valleys to a depth of over 100 m, and two lakes are currently forming on the upstream side of these obstructions.

The most notable aspect of the impact of the earthquake is the occurrence of cracking across very large of the slopes within about 5 km of the fault. Monitoring of these cracks during the successive summer monsoons suggests that the cracks did show some displacement as the slopes become wet. Therefore, the presence of these cracks over many hillslopes in the area affected by the earthquake identifies potential areas for future landslides by increasing infiltration and generation of pore water pressures.

Keywords: Pakistan, Earthquake, Landslides, Surface rupture, Cracking, Deformation

INTRODUCTION

The M_w=7.6 Kashmir Earthquake occurred 03:50:38UT on 8th October 2005 as a result of rupture on the NW-SE orientated Bakakot-Bagh Fault. The epicentre of the Kashmir earthquake was located at latitude 34.493^0 N, longitude 73.629^0 E with a focal depth of c. 20

[1] Visiting Professor, Faculty of Earth&Environmenral Sciences, Bahria University, E-8, Islamabad, Pakistan (*Corresponding author, Tel; +92515708784, Fax: +92519255136, e-mail: kausar_20001@yahoo.com)
[2] Professor, International Landslide Center, Depart. Of Geography, University of Durham, Durham, UK (d.n.petley@dur.ac.uk)
[3] Geological Survey of Pakistan, Plot 84, Street 3, H-8/1, Islamabad, Pakistan (simonsadiq@yahoo.com)

km (Purnachandra Rao et al. 2006) within the western transpressional margin of the Indo-Asian collision zone and occurred as a result of reactivation of known thrust faults and extends for approximately 79 km from immediately north of Balakot to northwest of Bagh with a northeast-side-up vertical separation of up to 7 m (Figure 1). This portion of the margin, the Hazara-Kashmir syntaxis, is structurally more complex than to the east, where the margin is marked by a simple arcuate curve that extends for more than 2000 km across India and Nepal. This was the deadliest earthquake in South Asia's recent history, with > 86,000 fatalities, > 69000 people injured, > 32000 buildings destroyed and 4 million people left homeless in Pakistan (Peiris et al. 2006; USGS, 2006). The largest cities affected by the earthquake were Muzaffarabad (capital of Azad Kashmir), Bagh and Balakot. The largest intensities were in Kaghan, Neelum, and Jhelum valleys, where landslides, rockslides, rockfalls, earthflows, and debris flows were triggered, some of them temporarily damming rivers. In India, > 1300 people were killed, > 6000 were injured, and many buildings were extensively damaged (Vinod Kumar et al. 2006). The loss of life is mainly attributed to collapsing structures due to poor building materials and architectural design. The devastation was exasperated by the many thousands of mass movements that were triggered by the earthquake, which resulted in ~ 1000 direct fatalities and many more indirectly due to the disruption of communication links (Kamp et al. 2008). In the period from Novemebr 2005 to date the Government of Pakistan along with the International Community has been transforming its efforts in the affected areas from rescue and recovery to reconstrution.

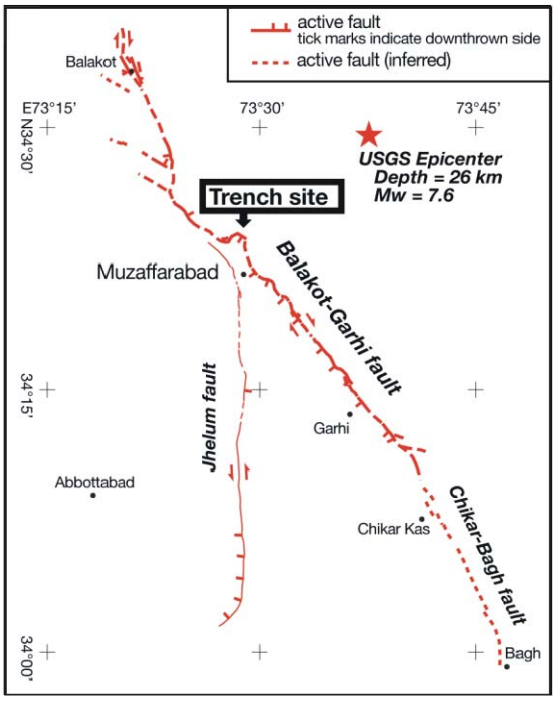

Fig. 1. Location of the active faults in the source area of October 08 2005, Pakistan Earthquake (modified from Kumahara and Nakata, 2005).

Several lines of evidence suggested that the earthquake had produced surface ruptures along the Balakot-Bagh fault. Mapped surface rupture trace shows that neither the Main Frontal Thrust (MFT) nor the Main Boundary Thrust (MBT) is responsible for the earthquake, but three active faults or fault segments within the Sub-Himalaya, collectively called the Balakot-Bagh fault make up the causative fault. Using satellite data and fault modelling, various researchers found that high crustal deformation has occurred along the known active faults stretching northwest and southeast from epicenter (Nakata et al. 1991), with northeastern part moved upward.

The present earthquake triggered hundreds of landslides and slope failures including debris slides and debris flow throughout the region but also put the slopes under tension, leading to the formation of cracks indicating incipient slope failure. Many of these failures are still active and loose fractured material is moving down the steep slopes even under the gravity. There are tension cracks particularly well developed in the vicinity of the fault where they have developed high density arrays with a complex interlocking pattern with both bedrock and colluvium (Petley et al. 2006). Slopes have continued to move since the earthquake as evidenced by the formation and widening of tension cracks. Some slopes have failed even in the exceptionally dry conditions prior to, and since the earthquake. Their presence is a clear expression of fracturing of the ground surface under tension due to perturbation of the dynamic stress field (Sarkar, 2004). The purpose of the present research is to report the landslide distribution, their relation to the fault surface ruptures and to identify a number of slopes that are in danger of failure witin the next few years (Petley et al., 2006). This will allow prediction of possible sequences of landslide development by identifying which slopes are extending under horizontal strain. Such slopes will be potentially unstable and likely to fail either en masse or as a series of integrated progressive slope failures that will eventually affect entire slopes during this post-seismic phase.

GEOMORPHIC AND GEOLOGIC SETTING

The area affected by this earthquake is located in the Lower Himalaya and drained by the Jhelum River and its tributaries, the Neelum and Kunhar Rivers. These rivers flow westward forming deep antecedent valleys before flowing southwards along broaders valleys to the Indo-Gengetic Plain. Transversal profile of the Jhelum Valley shows two types: one is a wide valley floor type in the down stream from Naushara and another is a deep gorge type in the upper course from Naushara respectively. Such topographic variation is presumably caused by difference of expression of active faulting. The Balakot-Bagh fault runs along the right bank of the Jhelum River from Muzaffarabad to Naushara and crosses the Jhelum River to the left bank. It is a reverse fault with slight dextral component of which fault plain dips to northeast. Active faulting causes up-throw of the upstream side of the Jhelum Valley from Naushara. Consequently the up-thrown side inevitably undergoes subsequent river incision and forms a deep gorge, on the contrary, river floor is relatively stable in the lower course from Naushara, down-thrown area.

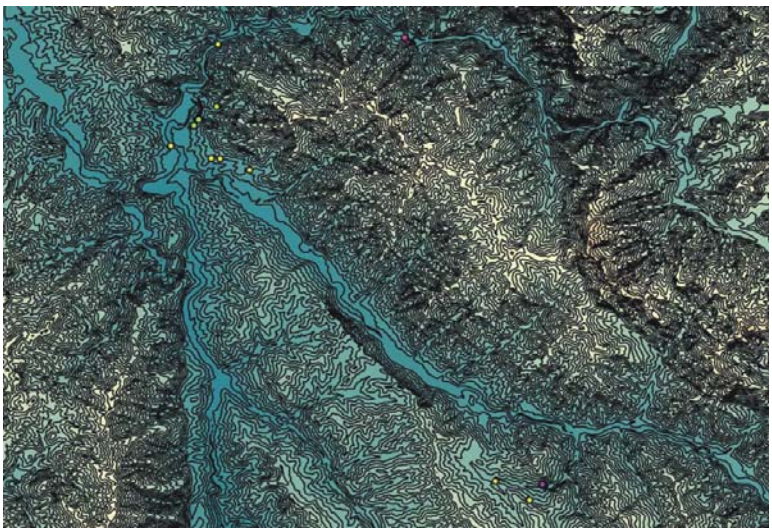

Fig. 2. Digital elevation map of the Neelum, Jhelum and Kaghan valleys derived from NASA SRTM data.

The mountains reach elevation > 3000 m a.s.l between the Jhelum and Neelum river valleys with highr values > 5000 m. The landscape is deeply incised by the river network giving topographic relief of c. 3000 m that reflects fluvial erosion with landslides forming an important geomorphic component of sediment flux and landscape development (Figure 2). The intense fluvial incision by the Jhelum River has produced steeper low valley slopes that exceed 50^0 and is observed along its left bank. Above these lower steep valley slopes, the hill slopes become less steep ranging from 10 to 20^0 before being replaced by steeper (> 50^0) high glaciated summit slopes (Kamp et al. 2008). Elevation of river floor in the upper stream from Naushera ascends from 800 to 1000 m a.s.l. The river terrace of the last glacial age develop as if it had once buried the Jhelum Valley, however, it has been incised deeply and the relative height from the river floor is about 100 m. Lower river terraces of several levels are observed below the last glacial terrace.

Structurally, the study area forms a major anticline termed the Hazara-Kashmir Syntaxis (Calkins et al. 1975) reflecting part of the complex structural situation which defines the western termination of the Himalayan arc. This is a place where the MBT veers by about 170^0, surrounding a “finger” of strongly folded, Miocene, red sandstones of the Murree Formation. The outer parts of the syntaxis are formed of older Pre-Cambrian metasedimentary rocks and metamorphic rocks of the Indian Shield and which are now in fault contact with the younger Murree Formation (Figure 3). The western side of the syntaxis is complicated by the existence of the Muzaffarabad anticline (Calkins et al. 1975). The Balakot-Bagh fault has an opposite sense of movement to the MBT and has moved south-westwards brining Neo-Proterozoic Muzaffarabad Formation dolomites over the Murree Formation. Along the thrust fault, these rocks are highly fractured with many discontinuities.

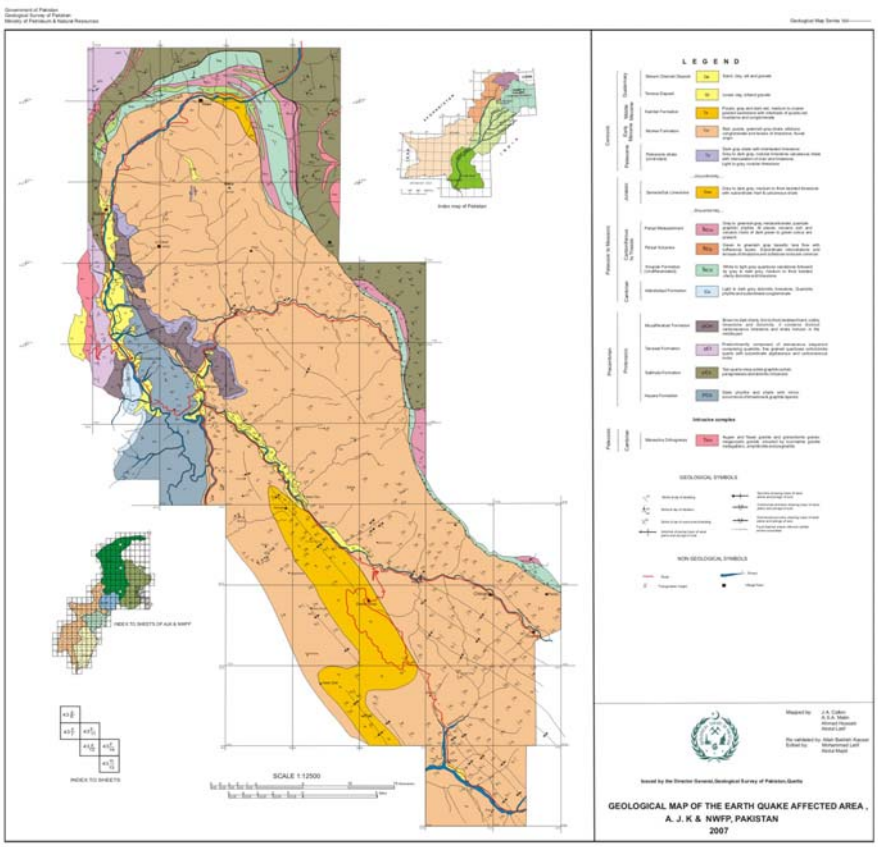

Fig. 3. Geological map of Hazara Kashmir Syntaxis and its surroundings.

Seismic movement during 2005 Kashmir earthquake occurred along the NW-SE trending Muzaffarabad fault, north of Muzaffarabad and the Tanda fault which is the continuation of this fault in a south-easterly direction within the Jhelum Valley (Nakata et al. 1991). General strike of the active fault is NW-SE and occurs along the MBT as a western wing of the Hazara-Kashmir Syntaxis. Trace of the fault shows a step jog at Chela, north of Muzaffarabad, forming a small scale syntaxis. And it continues southeast from the west of Chela to the south crossing Muzaffarabad city. It is the middle segment of the active fault (Jhelum fault) trending N-S and is southern continuation of the MBT along the Jhelum River. It is also an active fault, because it dislocates Pleistocene terrace in the south of Domel, forming east facing scarp. Maximum displacement for the fan surfaces due to active faulting ranges 30-50 m since the last glacial age. The fault line crosses the Jhelum River at Naushara and enter the mountains near Chikar Kas. Field investigations suggested that the typical geomorphology of the fault zone is a scarp with compressional features at the base and tension cracks along the cracks with maximum ground displacement of up to 7 m occurred on the hanging wall of the northern segment of this fault during this earthquake (Kaneda et al. 2008). It would appear that there may be different types of cracks on these hillslopes reflecting direct tectonic processes associated with the physical breaking of the slopes by the thrust and fractures assiciated with high ground acceleration in the near field situation.

LANDSLIDE DISTRIBUTION

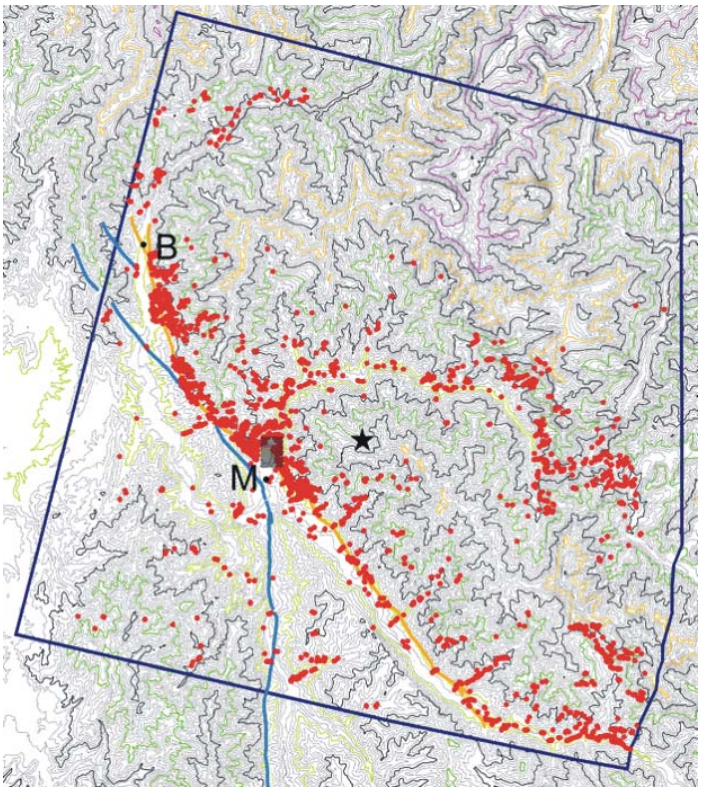

Fig. 4. Landslide distribution of coseismic landslides interpretted from SPOT-5 imagery (Sato et al. 2006).

Unsurprisingly in the light of previous studies of landslide occurrence in large earthquakes (Keefer, 1984), the incidence of slope failure during Kashmir earthquake occurred extensively. The most detailed map (Sato et al. 2006) on the distribution of landslides has been derived

from mapping from 1 m IKONOS and 2.5 m SPOT imagery resulted in approximately 2,424 landslides over an area of 55 x 51 km (Figure 4). This total does not include slopes showing signs of progressive failure. However, based on our's own visit we consider that this total needs to be revised upward to over 3000 landslides. The distribution of landslides is not clustered around the epicentral point, but instead appears related to proximity to the surface expression of the fault rupture, particularly hanging wall slopes of the northwestern half of the fault trace. This seems due to hanging walls comprising highly of fractured dolomite and limestone above the Balakot-Bagh fault. Landslide types included deep-seated failure; shallow, disrupted landslides; rockfalls; and cut-slope failures. The Kashmir earthquake involved slope failures in both bedrock and superficial deposits, with landslides occurring on many natural slopes and artificially cut slopes, particularly along transport routes (Owen et al. 2008; Petley et al. 2006). Kamp et al (2008) observed nearly 90 % of all landsliding occurred at elevations below 2000 m a.s.l., with nearly half of all landsliding being at elevations from 1000-1500 m a.s.l. Only 10 % of the landsliding occurred at elevations between 2000 and 3000 m a.s.l. Furthermore, landsliding was scare at high elevations above 3500 m a.s.l.

High resolution satellite imagery show that most slopes failed by rock fall and shallow failure on steep slopes leading to the formation of numerous talus cones. Field observations have however shown that it is not simply a matter of plotting the fault trace from a colour of the landslide debris. There are thick colluvial gravels composed of white dolomite clasts overlying the red Murree sedimentary rocks on many slopes due to previous slope processes, particularly debris flows. These plus the in situ fragmentation of the slopes has resulted in a high increase of available sediment which . During heavy rains of monsoon, this loose material combined with water moves as debris flows in the deeply incised creeks and hit the in habitants. These creeks directly pass through the Muzaffarabad city and feed the Neelum River flowing southward immediately at the western end of the city. People living in the valley along these creeks are seriously effected by the debris flow with there houses half or full buried (Figure 5).

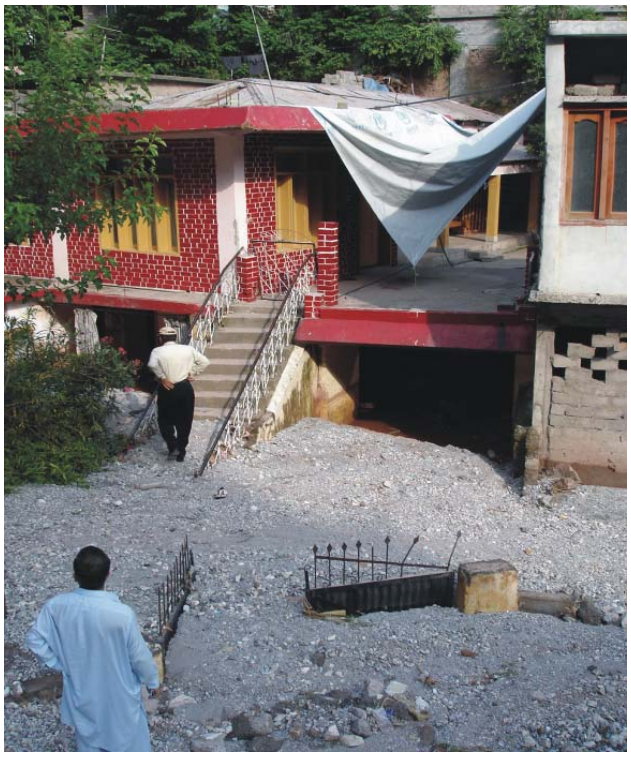

Fig. 5. Houses half burried in debris flow.

Fig. 6. Hattian Bala landslide on the left bank of Karli stream.

The largest landslide, known as the Hattian Bala Landslide, as it is close to the town of Hattian Bala, is located in a tributary of the Jhelum Valley in the Murree Formation, approximately 3 km from the fault trace (Harp and Crone, 2006; Owen et al. 2008). Its scar is > 1 km long, > 200 m wide, and > 20 m deep and sloping northwards between 60-70^0 (Owen et al. 2008). Here, about 80 million m^{3}of material slid in the form of a debris avalanche over a total crown to toe distance of about 2 km (Figure 6). The landslide was clearly structurally controlled, with the slide plane being defined by a plunging syncline. The debris crossed the valley, was ~ 130 m thick, and two lakes subsequently formed. By 2008, both lakes have increased in size and depths, and in both cases mitigation was undertaken through the construction of spillways, both of which have since had flown across them. Trommler et al. (2008) modeled the clear-water peak discharge of such a flood to be 8000 m^3/s causing a 12 m high flood wave immediately below the dam and 9 m high wave at the confluence of the Karli and Jhelum rivers near the village of Hattian.

ON-GOING SLOPE DISASTER

The major on-going slope disaster resulting from the Kashmir earthquake are still related to slope stability and our preliminary results demonstrate a direct relationship between rainfall and landslide movements. The earthquake changed the slope stability conditions throughout the Kaghan, Neelum and Jhelum valleys, and that there is very high risk in these areas of substantial landsliding occurring during monsoon. This risk is from both shallow and deep landslides. These represent different types of hazard with large deep-seated catastrophic landslides posing potentially the greatest threat. We further believe that the slopes damaged in the earthquake-affected area have created a long-term hazard and that landsliding will be common during successive monsoons until slopes obtain a new equilibrium state. Many slopes along the road system remain in an unstable condition having been over-steepened both in the process of road construction and by the earthquake. The road network will continue to be affected by rock fall, translational failures of slopes over which the roads have been constructed and destruction, particularly of bridges, by debris flow activity within different slope gullies. The possibilty of floods and their impact on slope stability must also be considered for this area.

Fig. 7. A cracked slope in colluvium in the Jhelum River valley. The orientation of the cracks varies according to local topographic controls.

Most extensive slope failures are also likely to occur as existing landslides continue to enlarge by retrogression of back and lateral scarps. The presence of tension cracks on many slopes with a pattern that mirrors the configuration of the scarp allows the pattern of development to be proposed. However, there are other areas of hillslope that have not failed but have a high density crack array (Figure 7). These cracks occur on both the hanging wall and footwall blocks, but with the highest concentration occurring on the footwall side. It is suggested that these two are likely to fail as a series of deep seated failures on parts of slopes. It is more difficult to determine whether whole hillslopes may fail, such as the Botha-Khilla slope. However, should this scenario arise, this would be a major disaster affecting this part of the Jhelum valley.

The major slope system on which the Botha and Khilla sites occur, is a series of disjointed slope failures at present. The upper slopes of this area are marked by large failures associated with a number of large gully systems. The large gully systems to the east of the Botha site are also highly active with a number of individual slope failures in Murree rocks leading to back scarp retreat. Slope failures are also occurring at the toe of this slope with a number of active landslides in terrace gravel; these were also probably initiated by the earthquake. As these enlarge they are likely to coalesce increasing the area involved with slope failure. Given the number of houses still occupied on such slopes means that this will be a major disaster in terms possible fatalities.

CONCLUSIONS & RECOMMENDATIONS

The most obvious geomorphic response to teh earthquake has been the generation of a large number of landslides encompassing a wide range of size and styles. These are most clearly expressed where white dolomites of the Muzaffarabad Formation have failed in conjunction with the red Murree Formation siltstones and sandstones. The overall number of failures documented has been reported as being less than would be expected from the earthquake magnitude of this event based on previous studies. Also, many landslides that blocked the road network were quickly removed by engineers maintaining access. Apart from the Hattian rock avalanche, most of the landslide distribution appears to be of a shallow translational

origin in both rock and colluvial slopes. Collapse of steep rock slopes to form talus cones is well examplified on the each bank of the Neelum at Makri due to fragmentation of the dolomite. At other places along the dolomite outcrop, shallow rock slope failures have introduced a high volume of rock debris into the stream system where it is currently being reworked.

Co-seismic generated landslides may also develop crack patterns around the crown and lateral scarps in association with localised tensional stress due to the removal of mass in the landslide. These tend to occur parallel to the existing scarp and indicate areas that will be incorporated into future failure of these slopes. The consequence of an increase in landslide occurrence will be a marked increase in the production of sediment from the slopes. Downstream of the landslides there will be increased sediment on the slope that is now disturbed and has started reaching the fluvial system. The downstream consequences of increased sediment transport could be severe.

The large gully systems are also highly active with a number of individual slope failures in Murree rocks leading to back scarp retreat. As these enlarge they are likely to coalesce increasing the area involved with slope failure. Given the number of houses still occupied on such slopes means that this will be a major disaster in terms of possible fatalities. Therefore, the whole area needs to be assessed in detail to identify areas of high risk from future landslide and debris flow hazard.

REFERENCES

Calkins, A.J., Offield, W.T., Abdullah, S.K.N. and Ali, S.T. (1975). Geology of the southern Himalaya in Hazara, Pakistan and adjacent areas. *U.S. Geological Survey Professional Paper,* **716-C**, Denver, Colorada, 1-29.

Harp, E.L. and Crome, A.J. (2006). Landslides triggered by the October 8, 2005, Pakistan earthquake and associated landslide-dammed reservoirs. *U.S. Geological Survey Open-File Report,* **2006-1052**, 1-10.

Kamp, U., Growley, B.J., Khattak, G.A. and Owen, L.A. (2008). GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. *Geomorphology*, **101**, 631-642.

Nakata, T., Tsutsumi, H., Khan, S.H. and Lawrence, R.D. (1991). Active faults of Pakistan, map sheets and inventories. *Special Publication no.* **21**, Research Center for Regional Geography, Hiroshima University, 1-141.

Owen, L.A., Kamp, U., Khattak, G.A., Harp, E.L., Keefer, D.K. and Bauer, M.A. (2008). Landslides triggered by the October 8, 2005, Kashmir earthquake, *Geomorphology,* **94**, 1-9.

Petley D.N., Dunning S.A., Rosser N.J., Kausar A.B., (2006). Iicipient landslides in the Jhelum Valley, Pakistan following the 8th October 2005 earthquake. In: Marui, H. (Ed.), Disaster mitigation of debris flows, slope failures and landslides. *Frontiers of Science Series,* vol**. 47**. Universal Academy Press, Tokyo, Japan, 47-56.

Purnachandra Rao, N., Kumar, P., Kalpana, Tsukuda, T. And Ramesh, D.S. (2006). The devastating Muzaffarabad earthquake of 8 October 2005: New insights into Himalayan seismicity and tectonics. *Gondwana Research,* **9** (4), 365-378.

Sarkar, I. (2004). The role of the 1999 Chamoli earthquake in the formation of ground cracks. *Journal of Asian Earth Sciences,* **22(5)**, 529-538.

Sato, H.P., Hasegawa, H., Fujiwara, S., Tobita, M., Koarai, M., Une, H., and Iwahashi, J.

(2006). Interpretation of landslide distribution triggered by the 2005 Northern Pakistan earthquake using SPOT 5 imagery: *Landslides*, v. **DOI 10.007/s10346-006-0069-5**.

Trommler, N., Huggel, C., Korup, O. And Schneider, F.J. (2008). Assessing post-failure geomorphic impact of an earthquake-triggered landslide dam, Jhelum River, Pakistan. Geophysical Research Abstracts 10 EGU2008-A-00622.

Vinod Kumar, K., Martha, T.R. and Roy, P.S. (2006). Mapping damage in the Jammu and Kashmir caused by the 8 October 2005 M_w7.3 earthquake from the Cartosat-1 and Resourcesat-1 imagery. *International Journal of Remote Sensing*, **27**, 4449-4459.