

# Landslide Environment in Pakistan after the Earthquake-2005: Information Revisited to Develop Safety Guidelines for Minimizing Future Impacts

Shahina Tariq<sup>1</sup> and Chandima Gomes<sup>2\*</sup>

<sup>1</sup>Department of Meteorology, CIIT, Islamabad, Pakistan

<sup>2</sup>Center for Electromagnetic and Lightning Protection, Faculty of Engineering, Universiti Putra Malaysia, 43400, Sardang, Selangor, Malaysia

## Abstract

The 2005 earthquake in Pakistan engraved one of the worst natural hazards in the history of mankind. The mass destruction caused by nature in several parts of Azad Jammu Kashmir is revisited to assess the public impact. Several visits were paid to the most affected areas of the region, especially Muzaffarabad, to collect data on debris flow patterns, loss of vegetation, instability of the surface structure and buildings, impacts on social structure etc. Influences of pre-slide activities, both natural and man-made, on the pattern of landslides and triggering factors were investigated. The major landslide catastrophe that took place in Attabad in January 2010 was discussed as a case study. Attempts were made to correlate observations elsewhere with collected data, pertinent to 2005 earthquake in Pakistan with the objective of proposing safety guidelines to prevent or at least minimize such human catastrophes in the future, in the case of such an event.

**Keywords:** Landslide; Debris flow; Earthquake 2005; Natural hazards; Safety guidelines

## Introduction

A condition and/or processes in the nature that give rise to economic damage or loss of human life (or injuries) is termed a natural hazard [1,2]. In the list of natural hazards, landslide is categorized as one of the most destructive phenomenon. The aftermath effects of landslides are in par with those due to floods, hurricanes and Tsunami and just below those due to earthquakes [3-5]. Typically, many natural hazards, especially those which were mentioned above, have direct impact on landslides but not vice versa. An earthquake of magnitude 7.6 occurred in south western slopes of Himalayas on 8<sup>th</sup> October 2005, around 8.50 in the morning. Although neighbouring India and Afghanistan felt the impact of the event, it was Pakistan-administered Kashmir (popularly known as Azad Jammu Kashmir or AJK) which was struck with the highest level of impact. The epicentre of the earthquake was about 20 km northeast of Muzaffarabad, the capital city of AJK. Many areas surrounding Muzaffarabad, Sehnsa-Kotli, Gilgit-Baltistan and Khyber Pakhtunkhwa province were severely affected [6-8]. Although, the official death toll stated by the Government of Pakistan was slightly above 87,000, many relief agencies estimated a figure of over 100,000 deaths [9]. The number of people that encountered serious injuries reached 138,000 by October 2005, while those who took refuge at various makeshift camps and shelters due to loss of home was over 3.5 million [10]. Among 19,000 child deaths, most of the victims were trapped in the collapsed school buildings. Furthermore a quarter million farm animals died by getting trapped in the debris of stone barns.

The earthquake was felt even in Islamabad, the capital city of Pakistan which is situated approximately 100 km away from the epicentre. Two blocks of a condominium, known as Margalla towers were collapsed killing over 150 people in Islamabad. Apart from this grossly highlighted incident, about 75 buildings in the city were totally collapsed incurring quite significant losses to the public. Murree and Abbottabad are the other major cities that have been severely affected. The main earthquake and after tremors gave rise to many landslides immediately after the event and continue to threaten the home-safety of

public even by 2012. Many landscapes in the earthquake affected region and even in neighbouring areas which were apparently unaffected by the event in 2005, show signs of future landslides. Satellite imaging also throws some light on the change of surface topography and vegetation due to landslides occurring since the earthquake. For an example, a landslide occurred in January 2010 in Attabad, a northwest village in Pakistan alongside Karakoram Highway, directed a huge mass of debris that contained soil, silt and rock in to Hunza River. The debris developed a natural dam which caused mass floods in the neighbouring villages and townships, destroying roads, bridges, buildings, agricultural fields and many other valuable properties in a vast area. NASA's Earth Observatory provided images of a large lake that has developed shortly after the landslide giving clear evidence of the impact of debris movement on the consequent floods. The location of the landslide is within about 100 km from the epicentre of 2005 earthquake. Figure 1 shows the epicentre of the earthquake and major cities in Pakistan that have been affected. The above observations emphasize the need of overall assessment of the landslide triggering effects aftermath the 2005 earthquake. Several studies done so far, pertinent to the landslides triggered by the 2005 event, focus on particular cases such as Hattian Bala rock avalanche [11]. However, it is a need of the hour to analyse the surface soil structure and vegetation in pre and post-earthquake stages in the affected areas in Pakistan and compare the information with landslide experiences in other regions. Such analysis will enable to develop a database that provides useful information to plan various

**\*Corresponding author:** Chandima Gomes, Center for Electromagnetic and Lightning Protection, Faculty of Engineering, Universiti, Putra Malaysia, 43400, Sardang, Selangor, Malaysia, Tel: +603-8946 6311; Fax: +603-8768 6327; E-mail: [chandima@upm.edu.my](mailto:chandima@upm.edu.my)

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**Figure 1:** The epicenter and major cities affected in Pakistan.

activities in land-slide prone areas not only in Pakistan but in other regions as well. In this paper we investigate various changes in surface geology that has taken place in earthquake affected areas and how they are related to landslide tendencies. In determining the factors that influence the triggering of landslides we compare the data obtained in the earthquake affected areas in other parts of the world with information of landslides that have been collected in this study.

This paper is targeted for a large spectrum of readers ranging from frontier scientists in the subject to non-expert personnel in the managerial capacity that possess the decision making authority. We expect the paper to be a triggering factor for a large relevant readership for taking necessary steps in minimizing adverse effects of landslide by sharing the experience of different regions and nations.

## Methodology

Three study visits have been made to Azad Jammu Kashmir (Pakistan controlled area of Kashmir) from 2008-2012, during which visible information and verbal information (interviews with people in the area) have been collected. The areas visited were pre-determined by considering the level of destruction due to landslides subsequent to the tremors. Attabad area was specifically selected due to a major landslide event occurred in the area in January 2010. The data and information collected in the Attabad disaster has been presented as a case study.

The following information has been collected during the study visits.

1. Visual observation of the loss of vegetation, soil stratification of exposed hill-gradients, features of landslide slopes, sizes and nature of rock debris, formation of lakes etc.
2. Important geological features of surface land masses and fault lines.

3. Locations and situation of buildings on grounds that have landslide tendencies.
4. Sociological aspects of the people that live in destructed areas.
5. Flow patterns and dam/blockade formation of Jhelum and Neelum rivers.

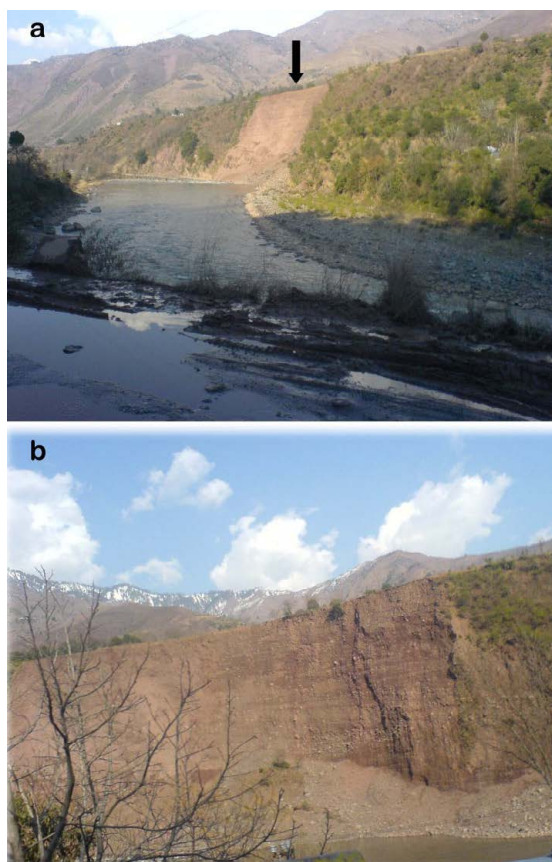
Information and data gathered were analysed to understand the current environment of the region. Furthermore, information has been collected from various published and unpublished resources on landslides in Pakistan after the earthquake especially, on the Attabad landslide which has been extensively discussed as a case study. The patterns of impact and outcomes of these extreme events observed in Pakistan have been compared with similar cases observed in other countries. The outcomes of information analysis were used to develop correlation between the pattern of landslides in Pakistan after the earthquake and that reported elsewhere.

## Information Analysis

### Observations in AJK, Pakistan

Seismic activities are prevalent in the Southern slopes of Himalayas due to compressive stresses between Indian and Eurasian tectonic plates. Collisions between the two plates cause the Indian Plate to move north-westward at a velocity of about  $5 \text{ cm yr}^{-1}$  [12]. Indian plate has been fractionalized in the Kashmir basin, due to the plate collisions. Such plate fractions de-stabilize the area especially Indian and Pakistan controlled Kashmir segments, some parts of Afghanistan and also territories run by tribal authorities, which are treated as no man's land. This unstable land mass is known as Indus-Kohistan seismic zone [13]. The earthquake in 2005 has occurred along the Balakot-Bagh fault in Hazara-Kashmir syntaxis of the Himalayan fold belt. The post-quake tremors and the torrential rain constantly trigger land mass movement

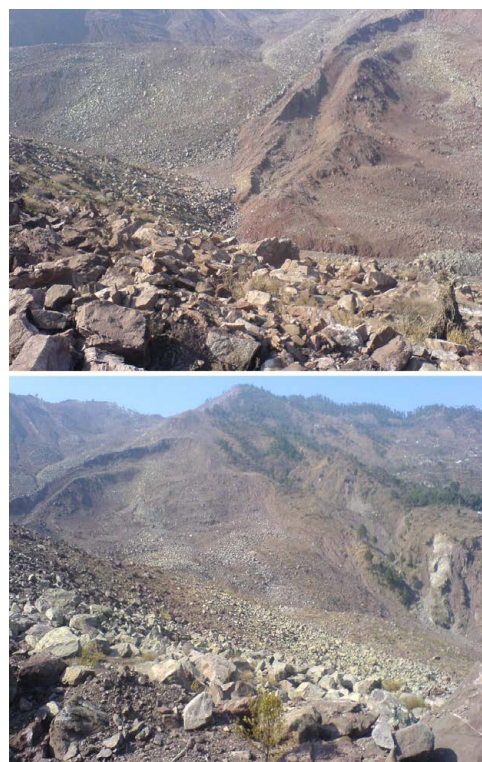
along the acute slopes as it could be observed even seven years after the earthquake-2005. The debris flows have most often narrowed the two major rivers Jhelum and Neelum that flow across the affected region. As it has been observed in 2008, slope failures in the scales of few hundred meters to few tens of kilometres in width have been recorded along the range of hills towards Muzaffarabad and Balakot. They were seen widening over the following four years. Figures 2 and 3 show such debris flow which hampered the natural flow of water in the respective rivers. The loosely bound unstable soil stratifications left by the debris flow which stands at almost  $90^\circ$  slopes (Figure 2b) hint that they may give up at any instant creating further catastrophe. The topography of the entire hill boundary along the two rivers showed this ready-to-flow feature as our observation team visited the area in 2012. The study visit made in 2008 showed that more than 75% of the hill gradients in the affected area with slope angle exceeding about  $60^\circ$  are deprived of vegetation. Even by 2012 the situation remained nearly the same in many parts while in some cases it has become worse as the light tremors and heavy rainfall has resulted further collapsing of loosely hanging soil layers that retained the vegetation. Figure 4 shows the large scale rock avalanche occurred in Hattian Bala which destroyed the vegetation in a vast area while killing over 12,000 within a period of about 10 minutes after the earthquake. The photographs in Figure 4 have been taken in 2008 after more than two years since the earthquake. Even by 2012 the vegetation did not show any signs of recovery. This may most often be due to the exposure of rock in the high elevations and covering of soil



**Figure 2:** (a) Debris flow into the River Jhelum close to Muzaffarabad observed in 2008, over two years since the earthquake. The arrow shows the debris flow area which is about 500-600 m in width. (b) The landslide in a close-up view.



**Figure 3:** (a) Debris flow has narrowed down River Jhelum in Muzaffarabad. (b) Debris flow has narrowed down River Neelum in Muzaffarabad.



**Figure 4:** Hattian Bala rock avalanche in two directions. The vegetation in a large area has completely been destroyed by the rock flow. Estimated number of 12,000 people has been buried in the debris.

in the lowlands by rock debris. At several sites where the rock has been exposed due to the down flow of soil masses, metal quarries have been started further eroding the surface. Figure 5 shows hill slopes in the vicinity of River Neelum in the backdrop of a metal quarry that harvest the exposed rock.

Irrespective of the known facts of large earthquake generation potential of the India-Tibet subduction region, the building structures; commercial, industrial and domestic; in the affected region have been designed without taking any measures on the earthquake effects. Furthermore, even as recent as in 2012 it has been observed that the new structures are put up in the region that may not withstand land movement and earth tremors, despite predictions of the possible occurrence of high end earthquakes (of which the magnitude may exceed 8.0) in the future [14]. Figure 6 shows the wreckage of a once a lively community on a hill slope in Muzaffarabad about 2 years after the earthquake-2005. The picture depicts the devastating effects of the tremor and consequent boulder-flow which has totally destroyed the buildings. Eye witnesses survived, with whom the inspection team has communicated mentioned that there were even concrete structures and beams were demolished by the tremor and debris flow. Arrows indicate the direction of debris flow.

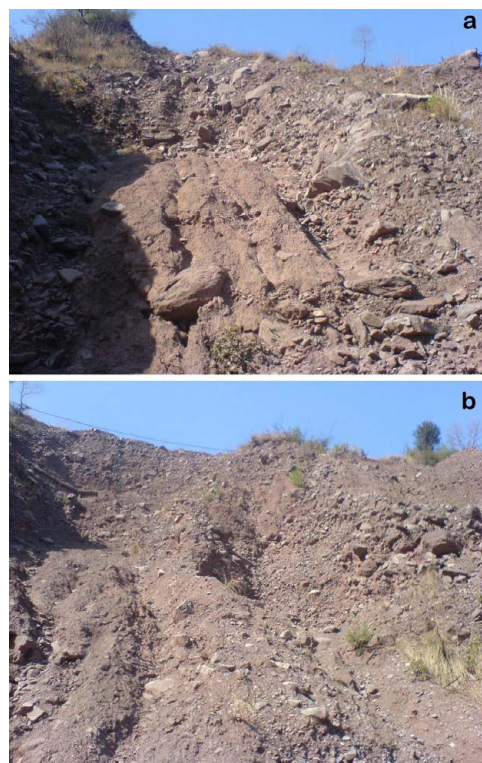
Frequent minor debris flow could be observed throughout the period of study even in built up areas. Figure 7 shows such locations close to the city centre in Muzaffarabad. The exposed soil profiles are characterised by soft bedrock type structure with fragmented and weathered unconsolidated rock debris in the basal subsoil. These localised debris flows are grossly neglected due to the large scale catastrophes looming over the area. The instability of slopes over small elevations (5-10 m) may affect many small houses and dwellings which shelter a sizable number of people. This relatively small debris flows most often move considerably large boulders down slope, of which the size sometimes exceed 1 m<sup>3</sup> (Figure 8). These boulders either end up in rivers causing damn formation or in highways or by roads causing traffic block. A number of new settlements could be observed on or



**Figure 5:** A metal quarry causing severe damage to the hills that are already stripped by the earthquake of its once beautiful lush greenery.



**Figure 6:** A village of over 500 houses wrecked by the tremor and the consequent boulder/debris flow. Arrows indicate the directions of material flow after the tremor.



**Figure 7:** Loosely hanging soil in the earthquake affected area (in built up area close to the city limits).

close to such unstable slopes. Most of these settlements are temporary or makeshift shelters; however, there were also few permanent structures. The increased human activities and the pore-water pressure generated during the prolonged rainfall may accelerate the slid-to-flow transition causing heavy casualties.

A majority of landslides of Muzaffarabad that have been activated during and after the earthquake, covering an area of about 7500 km<sup>2</sup>, was mainly attributed to the geology of the area, and climatologic/geomorphologic conditions [15]. Many of the slope failures included highly fractured carbonate rocks, Tertiary siliclastic rocks of monotonous fluvial sequence of red and purple clay, and interbedded greyish sandstones with subordinate intraformational conglomerate along antecedent drainage that traverse the Hazara-Kashmir Syntaxis;



**Figure 8:** Boulders of volume up to about 0.8-1.2 m<sup>3</sup> has moved down the slopes with debris. The presence of people provides an implication of the relative size.



**Figure 9:** A lake formed after the earthquake close to the Hattian Bala rock avalanche.

the most common forms of slope failure in southern Muzaffarabad. These slope movements pose a serious threat to the safety of Muzaffarabad-Kohala road and Kohala-Murree road and some residential places around the city of Muzaffarabad [16].

Several lakes have also been formed in the area aftermath the earthquake. One such lake that has been formed adjacent to the Hattian Bala rock avalanche is shown in Figure 9. A majority of these earthquake generated lakes were observed at isolated location, thus there were no human settlements developed in the neighbourhood by the time of conducting the investigation. As per our knowledge, until now there are no scientific studies that have been conducted to understand the lake environment such as bank stability, lake-bed structure, water quality etc. Hence, it is better prevent human settlements forming in the lake neighbourhood until such investigations are conducted.

The Hattian landslide, which was triggered by the 2005 Kashmir earthquake, formed one of the largest landslide dams in the world and it has posed a serious threat of flooding to people living in the lower reach of the Jhelum River. This landslide debris avalanche was measured around of approximately 80 million cubic meters volume within the Murree Formation of Miocene age comprising of mixed sandstone, mudstone, shale, and limestone. The avalanche deposit travelled approximately 1.5 kilometres downslope and 300 meters or more up on the opposite slope in the adjacent Karli stream drainage and also extended into the Tang stream drainage where the Tang stream joins the Karli drainage. The avalanche buried the village of Dandbeh and resulted in approximately 1,000 fatalities, according to

local residents. The landslide mass has impounded two lakes within the blocked drainages. The lake in the Karli drainage was approximately 800 meters long and 20 meters deep as of December 19, 2005. The lake in the Tang drainage was approximately 400 meters long and 10 meters deep as of this same date [17].

Konagai and Sattar [18] obtained the physical measurements; gradual deformation and slowly developing backward erosion using breach formation model that predict the outflow hydrograph generated by constant down-cutting of dam during a breaching event. A run-off analysis of the outflow hydrograph was done to evaluate inundation levels of flood waves in case the dam is breached. Hazardous downstream locations were identified near the junction of the Karli and Jhelum Rivers, suggesting a need for early warning system in order to avoid loss of lives.

The collision of Indian and Eurasian plates caused the compressional stresses in the core of Hazara-Kashmir Syntaxis [19]. Indus-4 Kohistan seismic zone is the wide region that is present around Muzaffarabad and during past few decades. Numerous earthquakes have occurred in this region. The Kashmir earthquake epicenter was located along the NW-SE trending Kashmir Boundary Thrust (KBT). According to Baig [20], the KBT was reactivated during the earthquake. KBT comprises of several fault which include Balakot, Bagh Fault, Jhelum and Muzaffarabad Fault. The Synthetic Aperture Radar (SAR) data analysis carried out by Fujiwara et al. [21] shown a 90 km long deformation belt along the KBT. MBT Jhelum Strike-slip fault and KBT are now tectonically more active which may be harmful for the multi-storeyed buildings and other construction works in the Muzaffarabad and its surrounding areas.

### A Case study: Attabad landslide

Attabad landslide, occurred on the 4<sup>th</sup> of January 2010, can be considered as one of the most significant natural extreme events, from a socio economic point of view, in the last 20 years in the Hunza area [22]. The region is particularly weak from a geotechnical point of view due to the tectonic structures passing in the area and intersecting rigid rocks typologies. This implies a continuous evolution in the slopes with devastating effects for the environment and on the inhabitants living there. It is evident from the minor debris movement observed for several years prior to the January 2010 event that the earth quake in 2005 is a major contributor to the triggering of Attabad disaster.

At least 20 people died in the landslide that blocked the Hunza River, creating a lake that gradually expanded 23 kilometres upstream, submerging four villages; Ainabad, Shishkat, Gulmit and Gulkin. The landslide also blocked the Karakoram Highway (KKH), a vital trade link to China, cutting off 26,000 people in Upper Hunza Valley, also known as Gojal Valley. The debris obstructed nearly three kilometres of the once fast-flowing river and a longer stretch of the highway.

Thirty five historical dam-burst flood events have been reported in the northern part of Pakistan in the last 200 years. Thirty glaciers have been identified to be advancing across major headwater streams of the Indus and Yarkand rivers [23]. For ice-dam failures with floods exceeding 20,000 cusec (9 events in 100 years), the apparent frequency is one event every 11 years. For floods exceeding 11,000 cusec (17 events in 100 years) the apparent frequency is one event every 6 years. The majority of recorded dam-burst flood events over the last 200 years have been glacial lake outburst floods. A few events have resulted from the failure of landslide dams, the most well-known being those of June 1841 and August 1858. Much smaller landslide dam failures

took place on the Gilgit river in 1911, and in Hunza valley in 1977 [24-28]. In recent years there have also been several minor flood events due to the sudden drainage of supra glacial lakes. Dam-burst events were relatively common during the period from 1833 to 1933. The most critical glacial lake outburst floods occurred in August 1929, June 1841, August 1885 (landslide), when the massive flood waves resulted in a significant rise in water levels [29]. About sixteen glacial lake outburst floods, damaging life and property occurred in Hunza valley alone (1830-1993), and approximately two smaller landslide dam failures are reported, one at Gilgit in 1911 and the other in Hunza valley in 1977. More than five glacial lake outburst flood events occurred in less than one year (2007- 8) in Gojal Teshil, Hunza river basin [30,31]. This historical record clearly depicts that the 2010 event was not very unexpected, though the relevant authorities or scientific community was not well-prepared for such debacle until the disaster struck the region

The Hunza valley is located astride two major faults, the Main Mantle Thrust (MMT) and Main Karakorum Thrust (MKT). North of Chalt along the Karakorum Highway and crossing the Main Karakorum thrust (MKT) Zone, one steps on the southern edge of the Karakorum block, to which the Kohistan Island Arc was accreted during late cretaceous time as a result of the northward drift of the Indo-Pakistan plate [32,33].

The Karakorum block extends from the Pakistan-Afghanistan border in the west to western Tibet in the east; its northwestern limit is marked by the Chitral Fault and the northeastern boundary is defined by the Karakorum fault. The upper Hunza fault is taken as its northern limit. The Karakorum Range is over 600 km long with an average of 150 km, forming a crescent-shaped belt convex northward. The Hunza valley zone to north of the Main Karakorum Thrust Zone (MKTZ) is composed of rocks mainly of brittle deformation, such as syn-metamorphic mylonites, metaconglomerates and foliated carbonaceous. Between Hini and Sarat, the Hunza valley exposes a complete section of the Karakorum Axial batholith as medium-grained granodiorite.

Focus Humanitarian Assistance (Pakistan) produced the first reconnaissance field assessment reports on the Active Landslide at Attabad in 2002, and subsequently in 2006, 2007. The 1974 Hunza earthquake and the 2002 Astor valley earthquake (6.5 Richter scale) produced some tensional cracks and displacements at points of contact between a rocky and overburdened slope (scree slope) and material of colluvial nature comprised of sub-angular to sub-rounded boulders, cobbles and gravel with sand and silt matrix at Attabad. These tensional cracks and ruptures in a vulnerable area remained unchanged for a long period of time. The downward movements observed along the main scarp were about 6 to 260 cm in 2002 [34]. These cracks became wider (1- 80 cm) when the earthquake on October 8, 2005 hit the entire region. With distant aftershocks, potential amplification effects, and torrential rains accompanying thunderstorms, a slope mass began moving downward in the form of slump and debris flow. However, due to lateral movement of slope, lateral gaps in tensional cracks and wedge failure, a strong downward movement of this vulnerable, threatened area was triggered, posing high potential disaster risk for the residents on 4<sup>th</sup> January 2010, at Sarat, Attabad. The Hunza River formed a landslide-dammed lake of about 10 km upstream of Sarat-Gogal Gulmit. The daily water level in this lake started rising continuously for several days. In 1858 a historically important Phungurh, Hunza landslide also dammed the Hunza River 35 kilometres upstream, from Salmanabad to Khabar in the Hunza region.

The slide debris mass in Attabad on 4 January 2010 fell for about 1.5 kilometres. The movement can be divided into four different phases:

- a. Rock fall of large boulders from the right hydrographic side which occluded part of the riverbed, squeezing the clay deposits derived from the lake created downstream by the event of 1858.
- b. The squeezed materials invested the opposite banks reaching an elevation of 2,460 m and collapsed over the previously deposited rocky material, covering it all.
- c. Another rock fall, again from the right side, submerged the previous one, running through it and giving the actual shape to the deposit.
- d. The material which squeezed through a mud flow reached 0.8 km upstream and 1.2 km downstream to the dam that had been created. The colossal amount of clay deposit is due to sedimentation caused by the blockage of the Hunza River by the ancient landslide. When the dam formed, a new lake was created.

The disaster affected several small settlements, mainly Sarat, Salmanabad, Attabad Bala, Payeen and Ayeenabad. Burial of villages under the debris flows and rock avalanches was followed by the loss of at least nineteen lives, with numerous persons injured or missing. Attabad, comprised of about forty-three houses, numerous cattle and thousands of fruit and timber trees, which were completely buried under the landslide rubble. In the aftermath of the major event, occupants of Sarat and Salmanabad villages were relocated due to continuous landslides in the area.

The materials of the debris flow consist of clay and silt size particles with some rounded fluvially-transported pebbles and cobbles. These materials have a very low permeability. The surface appeared quite dry and resistant with a thickness, in the dam area, of about 20 cm, underlain by material with high water content. The behaviour of this material is peculiar, as it deforms readily when loaded, without any break in the surface. The people who work in the area often walk on it, moving almost as if on a mattress.

Due to blockage of Karakorum Highway (KKH), the upper Hunza valley was completely cut off from the southern, downstream valley. Different sources have reported that approximately 20,000 people were at a risk of facing severe food, medicine, and fuel shortages, which have been confirmed later.

Shishkat, Ayeenabad, and Gulmit villages (6,000 people) along the banks of the river could be affected by the dammed water upstream. If the lake outbursts, it could affect another 18,000 people downstream, hence, spillway was dug to channel the river through the debris, to mitigate a potential disaster. About one hundred and ninety families have been affected by the extreme event.

Petley et al., analyzed the whole scenario based on monitoring reports studying various parameters of the massive landslide upstream and downstream along the Hunza river. The study proposed that the level of the hazard associated with a potential outburst flood from the landslide dammed water is higher than that can be considered tolerable. The downstream communities need to be protected since, although a flood is not inevitable, possibility is strong.

The four steps that define the event of 4<sup>th</sup> January 2010 created a particular sedimentary sequence that is compatible with the behaviour and positioning of the actual seepage points. It means that the water found a channel at a higher permeability compared to the clay matrix

widely present in the middle part of the neo-formation dam. Large boulders of granite and granodiorite compressed the lacustrine deposits and were covered by them, so that the permeability of the dam was not completely compromised. This allowed multiple seepage in four different positions.

The main part of the dam is formed by colluvial material of clay and fine sand matrix that isolates rocky boulders. The shape of the blocks was generally sharp and angular, ranging in size from a few centimetres to over 10 meters.

On the two slope sides of the valley, the deposits were found different. On the left side, there was a large rockslide deposit of large and very large boulders without any matrix support. On the right side, the matrix support was evidently observable. Over the main scarp, there was a thick glacial deposit mixed with debris deposit which could be easily remobilized. At the time of the survey, there were still several, frequent rock falls from the steep rocky slopes, which posed serious danger to the investigation team.

## Discussion

### Findings of AJK case study

The information given in the previous section clearly reflects the volume of disaster caused by the landslides that succeeded the earthquake 2005, immediately up to more than seven years since the event. It is evident that in the post-earthquake phase, the probability of land- mass movement is highly enhanced due to the loosening of bedrock and other stratified soil layers. Such loosely suspended land masses could easily be converted into debris flow by minor tremors and pore-water pressure due to heavy rainfall experienced by the region during rainy season.

The official reports reveal that in AJK alone there were 72,705 deaths, 68,157 injuries (without succumb to injuries), 454905 partially or fully damaged buildings and 4427 km of damaged roads after the earthquake (within first few days since the earthquake). In the event of a disaster of this scale it is unavoidable that resettlement and recovery of normalcy takes immense manpower, huge financial assistance and considerably long time. Thus, the inevitable outcome is the makeshift settlement (which in many cases extends to prolonged periods) in haphazard manner which may leads to even worse catastrophes.

The following list summarizes the observations that we have made during the study visits.

- a. The region in AJK which has been severely affected by earthquake 2005 suffers from looming threat of further land-mass movement.
- b. Natural causes that may trigger landslides are mild tremors, pore-water pressure and exposure of loosely bound bedrock due to the removal of vegetation cover.
- c. Man-made triggering effects such as vibrations and explosions caused by industrial activities such as that in metal quarries may also worsen the situation.
- d. The recovery of vegetation takes a long time since the soil layers that favours plant growth have been slid-off from the slopes and covered with rock debris in the lowlands.
- e. Frequent debris flow, even comprised of large rock boulders forms semi-dams in the two main rivers causing anomalies in the

water flow pattern. Similar debris flows regularly hamper the traffic movement in the highways.

f. Both damn formation in rivers and slit formation in solid land give rise to spread water masses. Scientific investigation on the properties and characteristics of such newly formed lakes are yet to be conducted.

g. Fault lines that spread over the affected region may provide vital information regarding future events. However, such continuous investigations or monitoring of variations could not be detected.

h. Settlements developed on extremely fragile slopes or in the vicinity of such slopes pose a serious threat to the safety of residents. The threat is equally high for people that reside both on the top of the slopes and at the base of the slopes.

### Lesson learnt from other regions

**Europe:** In general, landslides are caused by a set of preparatory and triggering factors. The movement of land-masses starts when the combination of these factors and the contributory intensity of each factor reach a perfect level of blend. Many researches that have modelled the landslides in Europe, especially those occur in the Alpine region could understand the quantitative rolls of these factors, thus prediction of location; frequency and magnitude of landslides are somewhat feasible [35-38]. The main contributory factors that they have figure out are the long and short term changes of topology, geology and hydrology in connection with the land utilisation, effects of other man-intervened processes such as forestation and deforestation, soil fixation, soil erosion, pore-water flow management and civil constructions [39-41].

**Malaysia:** Our investigation regarding the landslides in Malaysia, a country that experienced intensive damage and loss of life through small to medium scale landslides in the recent past, reveals that similar to Europe, man-intervened activities combined with heavy rainfall have mainly contributed to the disasters.

Many townships in Malaysia have been subjected to rapid urbanization during the last three decades. A major part of this urbanization process is the development of land for constructing residential schemes, most often sky scraping condominiums. A majority of these land development projects select hill tops and hill slopes due to one primary reason and several secondary reasons that enhance the property value. Being a country with one of the highest rainfall in the word, Malaysia frequently encounters flooding problems. Being in a hill top or hill slope one may rarely find flooding as a key problem. This is the primary reasons for Malaysians to opt for highly elevated sites for their residence. Secondary factors are, the panoramic views from high elevations, better ventilation and lightning, lack of land at lowlands for residence (as most of them are used for industrial and commercial installations) and beliefs based on superstition (Good luck of being at high elevations).

Due to the above mentioned reasons and also due to rapid development of highway system, hill slopes of Malaysia are rapidly been cleared and converted into built up sites. This rapid development has given way to frequent catastrophes as both hill top and hill base residents encounter heavy losses when the land masses trigger downward movement, sometimes taking skyscrapers also along with. Hulu Kelang, a suburb of the capital Kuala Lumpur, is one the worst landslide affected area in Malaysia which records 28 major landslides during the period from 1990 to 2011 [42,43]. All most all of these events have occurred at land-development related sites on or slopes of hills;

the collapsing of Highland Tower, a 20 story residential apartment block, in 1993 which killed 48 people [44] being the most significant.

Investigations that have been carried so far, in Hulu Kelang area reveal that the major preparatory factors of land slides are inadequate design of retaining structures and slopes improper design and construction methods and haphazard flow of rain water along near underground paths during excessively high rainfall experienced by the region almost throughout the year [45,46].

Several studies done on the Highland tower collapse concluded that the basic triggering factor of the tragedy is the pore-water pressure developed at the site due to topological changes that took place in the neighbourhood due to further development processes. It is evident as per our investigations that key triggering factors in Hulu Kelang landslides are pore-water pressure that rapidly enhance in the boundaries demarked by retention walls, building foundations, solitary rocks etc. during the intense heavy showers that followed prolonged periods of continuous rain. We also suspect lightning as a possible triggering factor for landslides as the mechanical forces exerted on the soil by lightning ground flashes due to high amplitude currents. Investigations are underway to find a quantitative estimation of force applied and pressure distribution on the surrounding soil by lightning protection grounding systems, especially when such systems are implemented by the building foundation or dedicated concrete chunks [47].

Apart from the development of residential buildings, highway construction has also triggered many isolated landslides scattered all over the country, both peninsular Malaysia and Sabah- Sarawak region. Many parts of highway system in Malaysia stretch over hilly terrains and rock slopes. Thus, in the highway development projects it is inevitable to excavate the hill slopes. Our investigations show that at many places soft rocks are cut almost in vertical planes. These excavations have become prominent triggering effect in landslides that frequently hamper the traffic flow in some highways due to debris flow [48-51].

**Sri Lanka:** Sri Lanka is an island in the Indian ocean of area approximately 65,000 km<sup>2</sup>. The country has a conical topology where the mid-country part has mountains which slopes towards the coastal line which is generally flat. The country experience sporadic landslides scattered over the elevated mid-country region and most often coincides with prolonged heavy rain. Our general observations as well as statistics provided by Sri Lanka National Report on Disaster Risk, Poverty and Human Development Relationship-2009, reveal that there is a marked increment of small-scale scattered landslides after the Tsunami in December 2004 which inflicted an unofficial figure of over 100,000 deaths along the eastern and southern coastal belt. It is expected to conduct further investigations in this regard to understand the causes of this prominent change in landslide pattern in the country.

Although not much information has been available in the published literature, our observations, personal communication and unpublished reports issued by several agencies reveal the following preparatory and triggering factors of landslides in Sri Lanka.

a. **Geomorphology of hill-country side:** Many parts of the peripheral slopes of upcountry hills in Sri Lanka are characterised by a non-homogeneous distribution of materials that forms an uneven stratification of fragmented rock-splits, weathering rock clumps, clay and sand. Sudden variation of temperature and pore-water pressure causes loosely bound rock fragments, weathering rock components etc. to separate from the stratified layers and move down slope due

to various transportation mechanisms. Thus mid slopes of the hills accumulate these overburden deposits known as colluviums over the time. Once the thickness of such colluviums is large enough, several triggering factors such as sudden gush of rainwater or mild tremors may lead to landslides in the form of debris flow.

b. **Heavy rain and flooding:** The western and south western slopes of the mid-mountain range get fairly large rainfall, during south-western monsoon, while the rainfall in other parts are also significantly high. Even few hundred millimetres of rainfall within day or two is not uncommon in the region. The rainfall pattern in this region is also characterised by sudden intense rain for a short period which follows a prolonged period of moderate rain. Such atmospheric condition is very conducive for a landslide.

c. **Construction of uphill reservoirs:** Being a country that is heavily dependent on hydroelectricity, Sri Lanka has many large reservoirs in the upcountry that are constructed by man-made dams across the rivers, in from 70s to 90s. These reservoirs, which have been built without taking the pressure gradients, they apply on the surrounding soil masses into account, may cause heavy stresses on the topology of downstream slopes. Furthermore, during the rainy season, the sluice gates of these reservoirs are frequently open to release excess water causing unwarranted pressures on the river banks. No proper scientific studies have been done so far in the country to understand the impact of these processes on the consequent landslides in the region.

d. **Heavy deforestation and improper vegetation:** The hill side of the country is rich with highly valuable timber, thus, the area is rapidly undergoing deforestation, exposing the soil directly to natural extreme events. To make the situation worse, many mountain caps of the region are now covered with advertently grown imported trees such as turpentine, willow and cypress tree. These trees do not have roots that can retain water and at the same time they prevent undergrowth causing significant soil erosion.

e. **Metal quarries:** A majority of landslides in hill slopes of the lowlands are caused by the soil instability induced by the activities at metal quarries. Rock blasting techniques used by many sites are not done according to national or international standards. Thus, sometimes, the debris-flows are triggered at locations few kilometres away from the blast site due to the minor tremors they generate in the hill.

### Safety measures for AJK region

The information analysed in the previous section shows that the landslide environment in AJK may or may not resemble the characteristics of the same in other countries. Hence, in the planning of safety and preventive guidelines for the region against the landslides, adoption of measures taken in other countries should be done with due care.

In many countries, man-intervened activities, especially land-development processes, play a key role in triggering landslides. However, in AJK most of the rock avalanches and debris flows are naturally triggered. The only man-intervened activity that we have observed is the metal quarry industry. On the other hand, the people in the region have put themselves into a great risk by making makeshift and even permanent settlements on the top, along the slopes and at the base of highly fragile mounds and hills. Although it is not yet started in large scale, the region will be urbanized sooner or later as the population multiplies. Hence, it is advisable to take precautionary measures from the early stages to prevent inevitable disasters in the future. As per the lessons learnt from other regions, we suggest the following guidelines

to restrict man-involved processes and natural causes that may provide preparatory and triggering factors for landslides in the region.

a. Rainfall pattern in the region should be analysed in detail to estimate possible flow water and pore-water pressure hotspots in the region. Settlements should not be allowed in the proximity of such locations.

b. A comprehensive and reliable methodology, using a physical-based model such as TRIGRS [52,53] should be applied to make slope stability analysis from highly localized pre-identified sites to regional-scale landscaping.

c. It is advisable to implement a region wide network of monitoring, predicting and early warning systems for rapid mass movements in vulnerable localities [54-56]. The best suited information platform and warning modes should be decided only after thorough physical and sociological survey [57].

d. In the locations where landslides may pose high risks of affecting human settlements (that cannot be shifted due to unavoidable reasons) or flow-water (rivers and streams), retention walls and other suitable structures should be built up well in advance. However, it should be noted that a poorly constructed retention wall may cause even worse damage in the event of a failure.

e. Re-settlement and new development projects should be allowed only if the construction/residential sites are on stable grounds. The stress applied by heavy building material load on the neighbouring landscapes should be evaluated and considered. Preventive measures should be taken to have not any adverse impacts of such stresses into the environment.

f. Irrespective of the purpose that it will serve, a dam in this region should be built only after detailed inspection and investigation of the aftermath effects of the reservoirs on the land stability in the region, especially downstream area.

g. It is extremely important to study the reaction of various soil types in the region in the presence of excessive water. As it is evident in the investigations of localized landslides that destroyed large buildings in Malaysia and elsewhere [58], surface soil layers with high sorption capacity may form slurry of mud once they are subjected to saturation in the event of a heavy downpour. They may easily shift even buildings of large volume for significantly long distance causing total collapse of the structure. Hence it is advisable to conduct a thorough survey on soil properties in the region before large scale development plans are implemented [59-63].

h. Industrial processes that directly affect the land stability should be controlled by the government or local authorities. Such processes are metal quarry industry, sand mining, mineral and metal mining, granite and graphite industry, timber industry etc. It is advisable not to allow such activities in landslide prone area, unless otherwise such activities are unavoidable.

i. The artificial forestation in the mountains that are deprived of vegetation due to earthquake triggered landslides should be done only after a scientific analysis. The type of soil and its stratification, the varieties of trees to be planted and their effects on the environment should be pre-assessed.

## Conclusions

In this paper we have done a thorough investigation and information analysis on the landslide environment in AJK, Pakistan after the

earthquake 2005. The data analysis leads to the recommendations to be adopted in preventing further disasters in the region.

The 2005 earthquake in Pakistan is one of the most affected natural hazards in the history of the country to both the nature and the habitants. The mass destruction caused by this event in several parts of Azad Jammu Kashmir, a north eastern part of Pakistan bordering India is visited several times by the team of investigators to collect data. These visits were pre-determined, targeting the most affected areas of the region, especially Muzaffarabad, to collect data on debris flow patterns, loss of vegetation, instability of the surface structure and buildings, impacts on social structure etc. Influences of pre-slide activities, both natural and manmade, on the pattern of landslides and triggering factors were investigated.

The most disastrous event in the post-earthquake era in the region was reported in January 2010 where a major landslide hit the already affected city, Attabad about, 100 km from the 2005 earthquake epicentre. This incident was investigated, analysed and presented in details as a case study.

In addition to the information in AJK Pakistan, we have also analysed the available data on landslides in Europe, Malaysia and Sri Lanka. Based on our study guidelines are proposed to prevent such disasters in the future and/or minimize property damage and loss of life in such an event.

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