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GEOTECHNICAL ASPECTS OF RECENT PAKISTAN EARTHQUAKES

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ABSTRACT

Geologically, Kashmir and northwestern areas of Pakistan are located in most active seismic zones of sub-continent. In Kashmir area, earthquakes had been triggered by a continuous subduction phenomenon of Indian plate under Eurasian plate; a collision zone that created Himalaya Mountain range and still giving it a rise of 1 cm each year. The Quetta earthquake occurred on part of the left-lateral Chaman Fault System and was measured 8.1 on Richter scale with focal depth of 17 km. The earthquake completely devastated the city of Quetta, leaving 35000-60000 dead and injuring thousands of people in affected areas.

The Kashmir earthquake was caused by the active Murree/ Muzaffarabad fault in Indo-Kohistan collision zone. The human loss was estimated to 80,000 dead and 600,000 injured. Almost all villages in and around cities of Muzaffarabad and Balakot were razed to the ground. Extensive slope failures and landslides severely damaged road and bridges. The landslides even temporarily blocked River Jhelum near Muzaffarabad City; due to blockade of two tributaries of the river, lakes were created and they are still intact. The slope failures also wiped off villages built on slopes and in foot hills. The aim of this research paper is to share information on geotechnical aspects of recent earthquakes in Pakistan. The paper enhanced the understanding of seismotectonics of seismically active areas of Pakistan.

INTRODUCTION

Pakistan is located between latitudes 23° in the south to 38° in north and 79° latitude in east to 63° latitude in the west. Situated on the tectonically active Indian plate, Pakistan has numerous earthquakes on its seismic inventory. Earthquakes in Pakistan have mostly occurred in the northern and western part of the country. Earthquakes of Quetta in 1935 and of Kashmir in 2005 are amongst the largest and most devastating in the history.

Besides larger magnitudes, enormous size of the devastation can rightly be attributed to lack of awareness of seismic hazards, geotechnical engineering, and poor construction practices. While not much lessons were learnt from 1935 Quetta earthquake, seismic hazard assessment and formulation of seismic building codes took roots only after the very recent 2005 Kashmir deadly earthquake. The paper encompasses geotechnical aspects of 1935 Quetta and 2005 Kashmir earthquakes.

GEOLOGY AND TECTONIC SETTING OF PAKISTAN

During the middle to late Eocene, Indian plate collided against Eurasian plate (Yoshida et al., 1997) and produced great Himalayan range and is still continuing at a rate of 5 mm annually (Patriat and Achache, 1984). The collision created numerous active folds and thrust wedges in Pakistan (see Figure 1). Major thrust planes in northern Pakistan starting from north to south are Main Karakorum

Thrust (MKT), main Mantle Thrust (MMT), and Main Boundary Thrust. North of MKT lies the Karakorum Range and Hindukush Range, south of MKT and north of MMT lies the Kohistan and ladakh Arcs . South of MBT lies the Salt Range-Potwar Plateau fold belt, Sulaiman fold belt, and Makran accretionary wedge in southwestward direction. As a result of this tectonic activity, Indus-Kohistan Seismic Zone (IKSZ) and Hazara Lower Seismic Zone (HLSZ) were produced in Kohistan and Ladakh Arcs. IKSZ is considered to be one of the most active seismic zones of the world (Hussain et al., 2008).

The areas of IKSZ and HLSZ have plenty of springs, streams, and rivers in the area. Major rivers are Indus, Neelum, and Jehlum. One of the biggest earthen "Tarbela Dam" also lies in HLSZ. The area is full of series of ridges and valleys. Major valleys and population centers in this area are Sakardu, Gilgit, Swat, Chitral, Dir, Mansehra, Abbotabd, Balakot, Muzaffarabad, Bagh, and Jammu. All valleys in the area are narrow surrounded by high ridges. A large size of the population lives in mud and masonry homes built in the bases, on the slopes, and terraces of mountains.

Geologically, north and north western block is mainly composed of intrusive and metamorphic rocks of pre-Cambrian, early Paleozoic, and Tertiary ages. Sedimentary and volcanic rocks of Quaternary and Tertiary ages also exist in the lower part of this block (Geological Survey of Pakistan, 2001). The nature of soil in this area is colluviums along the slopes, fluvial fans at mouths of streams, conglomeratic beds along the ridges, and alluvial plains with layered strata of alternating clayey, silty and sandy soils in the valleys.

EARTHQUAKE INVENTORY OF PAKISTAN

Pakistan due to its peculiar seismic-tectonic setting has experienced large number of earthquakes in the past. These earthquakes vary in magnitude and destructive effects. Most of the earthquakes occurred in the north and northwestern part of the country. Of all these, 1935 Quetta and 2005 Kashmir earthquake were the most destructive. Geological features and destructions caused by these two earthquakes have been discussed in more details while brief history of other recent earthquakes in Pakistan is given in Table 1.

Table 1. Earthquake Inventory of Pakistan.

Year	Location	Magnitude	Focal Depth	Losses
1931	Mach (Balochistan)	M 7.0	-	Several people were killed
1935	Quetta (Balochistan)	M 8.1	17 km	Details discussed in paper
1945	Off the Makran Coast (Balochistan)	M 7.9	25 km	2000 people were killed. Tsunamis as heigh as 12 m struck the Makran Coast
1974	NE of Malakand (N.W.F.P)	M 6.2	22 km	5000 fatalities were reported
1981	Gilgit Wazarat (Jammu & Kashmir)	M 6.1	33 km	220 people were killed, 2500 were injured & unconfirmed reports of surface faulting
1997	Near Harnai (Balochistan)	M 7.3	33 km	50 people were killed & Landslides blocked several roads and railway tracks in the region
2002	Gilgit-Astore Region	M 6.3	33 km	23 people killed in the Astore Valley & heavy damage in the area
2005	Muzaffarabad (Azad Kashmir)	M 7.8	10 km	Details discussed in the paper

GEOTECHNICAL ASPECTS OF 2005, KASHMIR EARTHQUAKE

In 2005 Kashmir earthquake, human loss was estimated to 80,000 dead and 600,000 injured. Almost all villages in and around cities of Muzaffarabad and Balakot

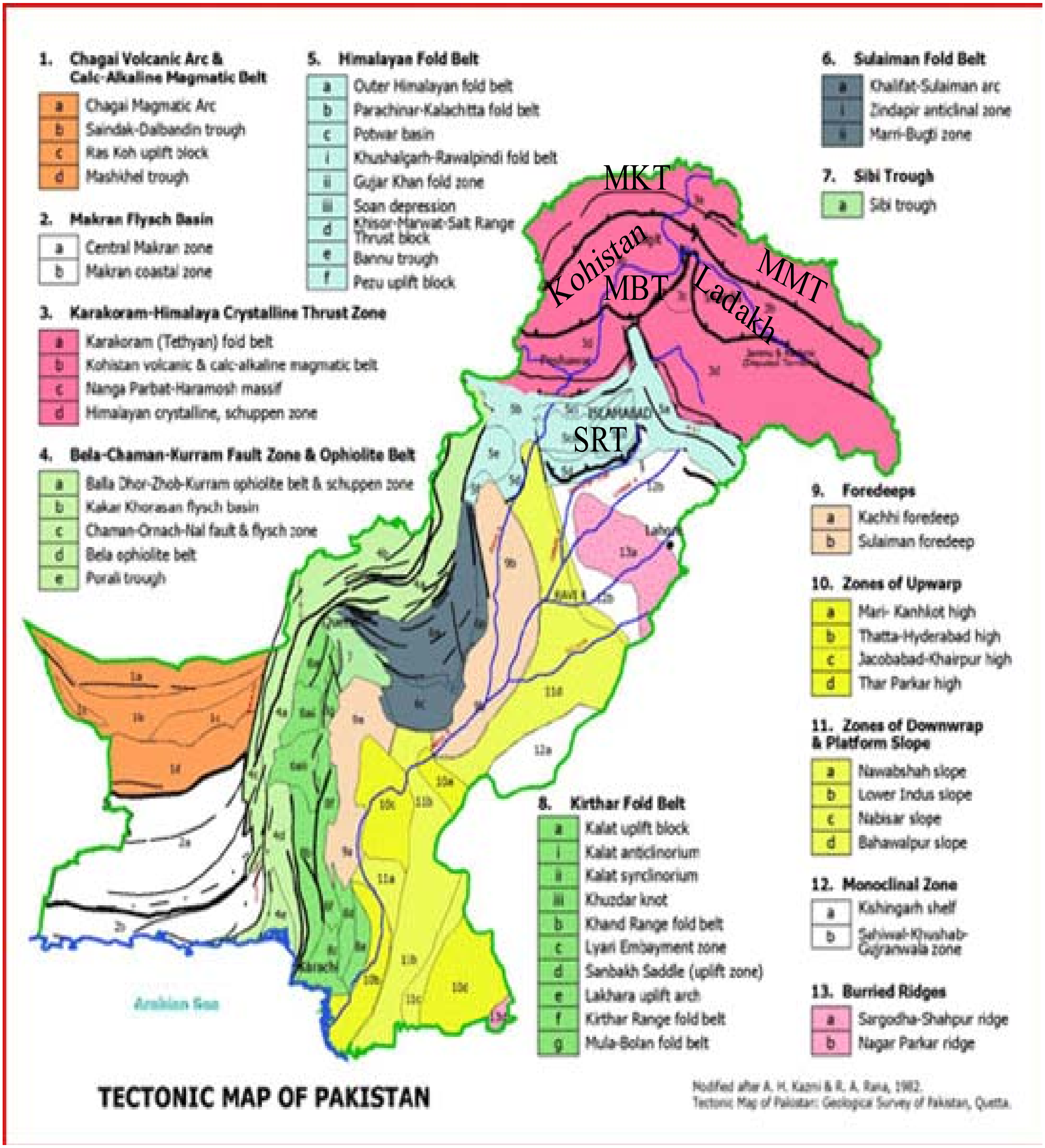


Figure 1. Map showing tectonic zones of Pakistan (Geological Survey of Pakistan, 2001)

were razed to the ground. Extensive slope failures and landslides severely damaged roads in the entire valleys. The landslides even temporarily blocked River Jhelum north of Muzaffarabad City. The slope failures also wiped off villages built on slopes and in the bases of hills.

Fault mechanism

This earthquake was triggered by a strike-slip, reverse faulting Muzaffarabad-Tanda fault, only 16 km of which was considered as active prior to 2005 Kashmir earthquake. The fault runs almost parallel and east of Jehlum River, crosses Muzaffarabad from the NE and runs almost straight towards Balakot (Figure 2), cuts across Hazara-Kashmir Syntaxis and is located in IKSZ. This fault is now termed as Balakot-Bagh Fault. The epicenter was approximately 16 km NE of Muzaffarabad and 95 km NNE of Islamabd. It was a first Himalayan earthquake that was accompanied with a surface rupture (Hussain et al., 2005).

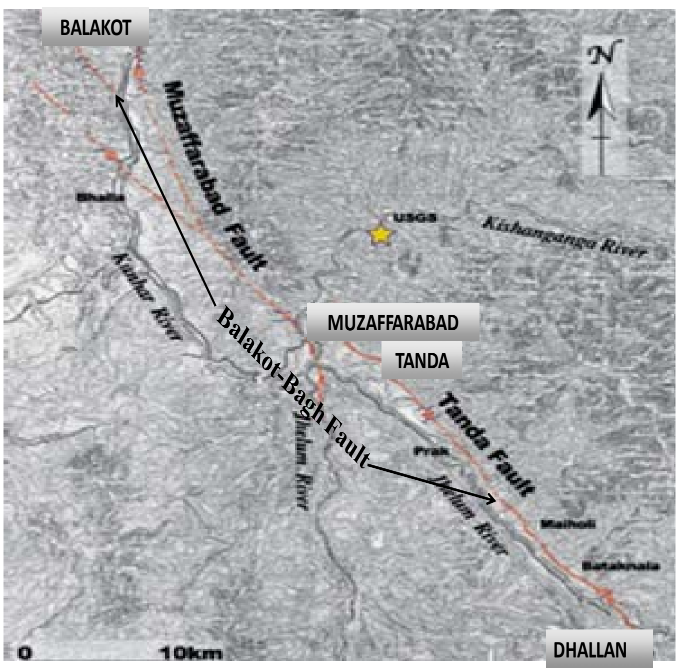


Figure 2. The causative fault; Balakot-Bagh Fault (Abeer, 2006).

Strong Ground Motions-Geotechnical

In Pakistan, strong ground motions of Kashmir earthquake were recorded at Abbotabad, Murree, and Nilore, located south of Muzaffarabad in the same sequence, see Table 2. Due to non availability of instrument, no data could be recorded in worst hit areas of Balakot and Muzaffarabad. Data obtained from Abbotabad is more reliable since it was recorded at a place where some damages were observed (MAE Center Report, 2005). The damage experienced near epicentral region when compared other earthquake indicate that much larger PGA would have occurred in the affected areas. This suggests a great care in selecting appropriate attenuation equation for back analysis with respect to site location and soil conditions.

Table 2. Peak Ground Accelerations (PGA) Recorded at various Locations.

Location	Peak Ground Accelerations (PGA)		
	East west (EW)	North south (NS)	Vertical
Abbotabad	0.231g	0.197g	0.087g
Murree	0.075g	0.078g	0.069g
Nilore	0.026g	0.023g	0.030g

Slope failures and landslides

The earthquake produced all kinds of slope failures and landslides ranging from rock fall to deep-seated slope failures, see Figure 3 and 4. This aspect was the most obvious and damaging. The earthquake also left many slopes in meta-stable state. During an aerial reconnaissance immediately after the earthquake, more landslides were noted on the hanging wall side than foot wall of the fault (Bilham et al., 2005). The concentration of the slides was much more along the mid slopes and on slopes which had roads built along them. A series of landslides noted from Balakot to southeast of Muzafarabad, indicate probable surface expression of the causal fault.

Figure 3. Views of slope failures in Balakot and Muzaffarabad affected areas.

Figure 4. Views of rock falls that blocked the roads at many places.

A massive slide blocked the Neelum River on northern side of Muzaffarabad, Figure 5. This posed a great danger to the city itself. A prompt breach if not done could have caused another catastrophe. Steep slopes on eastern side of the Neelum River are experiencing regular failures of varying nature. On western side of this river, slopes experienced numerous tension cracks. Most of the masonry and concrete structures on this slope were completely destroyed.

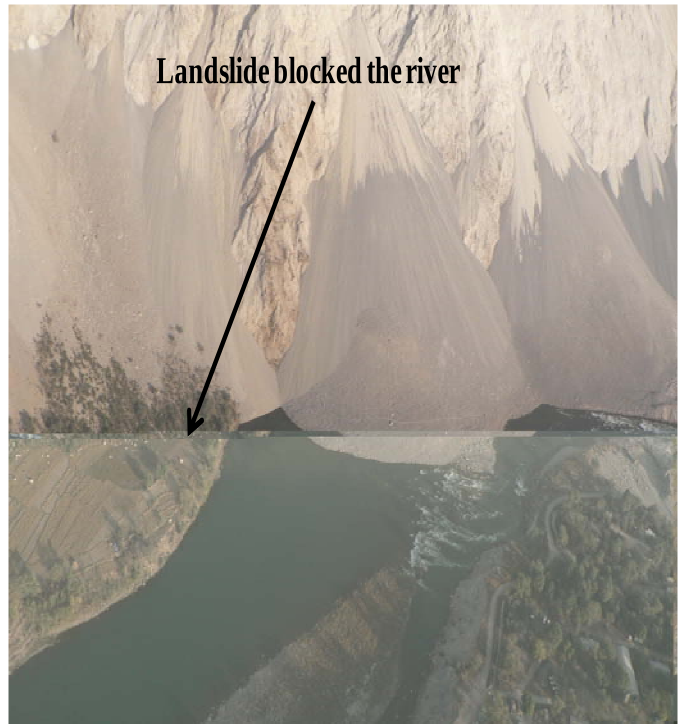


Figure 5. Views of slope failures that blocked Neelum River north of Muzaffarabad

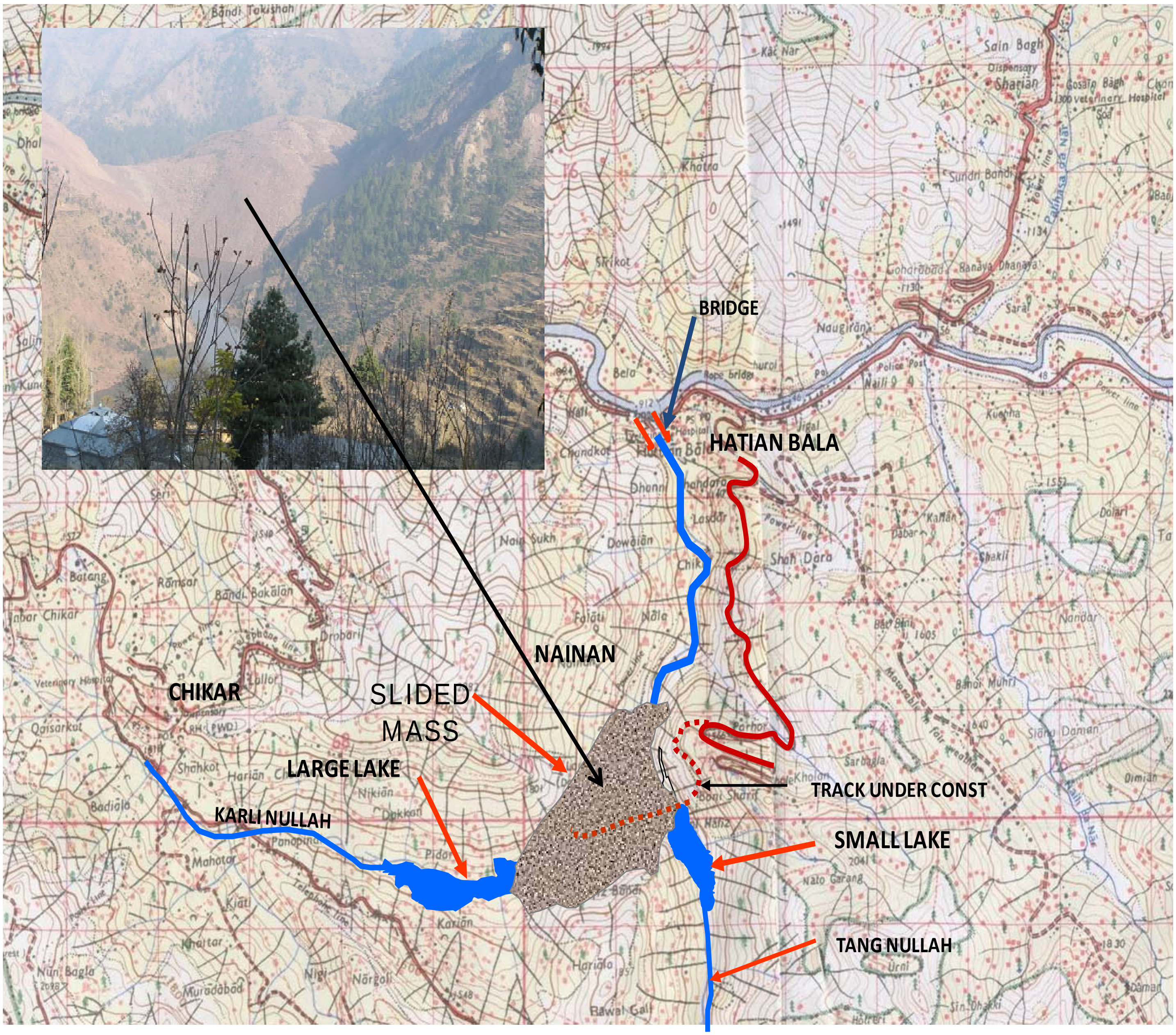
Near Hattian Bala, the biggest landslide occurred where two tributaries join Jhelum River, Figure 6. In this landslide, almost half of the Dana Hill situated 2080 meters above sea level (34° 09′ N / 73° 43′ E) moved down with such a speed that its over ran the mountain across the tributaries, (Fawad, 2007). The debris volume of this landslide was estimated to 85 million cubic meters. The villages with population of over 5000 on both the slopes were buried under this landslide. The landslide blocked the two tributaries and created two reservoirs. With constant inflow, the reservoirs posed a potential of flooding and damaging the population on the downstream.

Performance of shallow and Deep foundations (Masonry and Concrete Structures)

Ground shaking and deformation adversely affected the typical strip foundations in the entire area. Some concrete briged supported on pile foundations also suffered damages. In rural areas of earthquake affected area, houses were made of stone masonry with mud used as mortar and for plaster. Most of these houses did not have proper foundations. The roofs comprised of metal sheets laid over timber beams supported on stone masonry walls. From all aspects, all these buildings were liable to get collapsed under dynamic loads. In

Balakot area, almost all of the masonry and concrete structures were completely destroyed. In urban areas, most of the buildings were made with reasonably good foundations and with cement mortar and plaster.

Damage to structures was lesser around Muzaffarabad and least around Bagh area. Severity of damage to various types and quality of structures is shown in Figure 7 through 12.



Figurs 6. The largest landslide that blocked two tributaries of Jehlum River and formed two lakes (Abeer, 2006) in Balakot area.

Figure 7. Masonry buildings on slopes were razed to ground in Balakot area.

Figure 8. Concrete buildings with poor foundation and construction were collapsed in Balakot area.

Figure 9. Some buildings with relatively better construction though damaged but withstood the earthquake shaking.

Figure 10. Visible reinforcement; an indication of very poor construction practices.

Figure 11. A building displaced laterally but stayed intact; an evidence of good construction.

Figure 12. View of a collapsed multi storey building in Islamabad.

Performance of retaining structures

Most the roads in Kashmir area are made in cut. The slopes are maintained with the help of retaining and toe walls. Most of the retaining structures were razed along with the roads while at other places where roads were holding on, the retaining walls were severely damaged, Figure 13. At places, retaining structures were damaged due to rock falls. On many roads, longitudinal and transverse deep cracks were observed, Figure 14 and 15. Most of the culverts were either collapsed or partially damaged, Figure 16.

Figure 13. Damage to retaining walls in worst hit areas.

Effect on lifelines

When compared with other structures, the damage to bridges was minimal except at few places. Lateral displacement of bridges near Balakot and Muzaffarabad was observed, see Figure 17 and 18. Abutment of one of the bridge near Balakot moved almost 8 feet from its original position. Many bridges suffered damages at the joints due to improper joints. Suspension bridges suffered least damage except one located near Muzaffarabad. A landslide washed away its one of the towers along with its anchors, Figure 19. Electric supply lines were extensively disrupted in Balakot and Muzaffarabad, Figure 20.

Figure 14. Transverse cracks on roads showing tension cracks.

Figure 15. Longitudinal cracks on roads aligned parallel to slopes.

Figure 16. Most of the culverts in most affected area were damaged.

Figure 17. Though buildings on either side of the bridges were destroyed; the concrete and suspension bridge

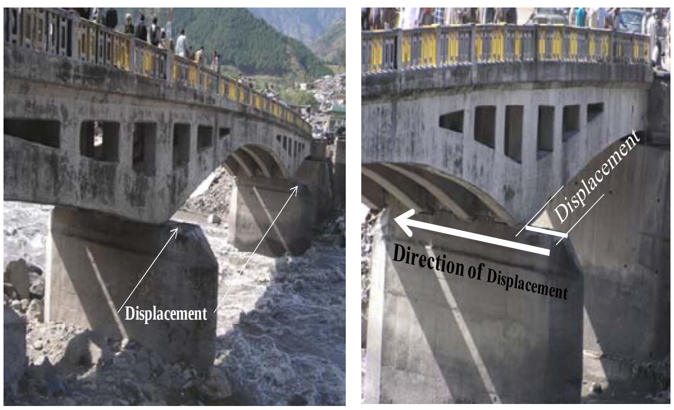


Figure 18. A laterally displaced bridge in Balakot.

Figure 19. Damage to suspension bridges.

Figure 20. Electric supply lines were severely disrupted.

Effect on dams and liquefaction

Tarbela, Khanpur, and Mangla are the three dams located in the vicinity of Kashmir area. The largest earth filled Tarbela dam in the world with height of 469 feet suffered no damage while other dams were also saved. No evidence of liquefaction was reported anywhere in the earthquake affected areas.

GEOLOGICAL AND TECTONIC SETTING OF 1935 QUETTA EARTHQUAKE

The Chaman Fault runs along Pakistan's western frontier with Afghanistan from Kalat, in the northern Makran range, past Quetta and then on to Kabul, Afghanistan (see Figure 1). This zone forms the boundary between the Arabian and the Iranian micro-plate, where the former subducts or dives beneath the latter. Thrust zones run along the Kirthar, Sulaiman and Salt ranges. There are four faults in and around Karachi and other parts of deltaic Indus, and Makran coast. The first is the Allah Bund fault that passes through Shahbundar, Jah, Pakistan Steel Mills, and runs through eastern parts of the city and ends near Cape Monz. This fault, in fact, has caused extensive damage in the past many centuries in the deltaic areas. The destruction of Bhanbhor in the 13th century and damage to Shahbundar in 1896 were caused by this fault. The other one emanates from the Rann of Kutchh. The third one is the Pubb fault which ends into Arabian sea near Makran coast and the last one is located in the lower Dadu district near Surajani and falls in the vicinity of Karachi. Tsunamis or tidal waves have also affected the coast of Pakistan. The worst case was in 1945 when an earthquake of magnitude 7.9 struck the Makran coast, waves as high as 12 meters were reported.

GEOTECHNICAL ASPECTS OF 1935, QUETTA EARTHQUAKE

On 31 May, 1935, an earthquake measuring 8.1 on Richter scale struck Quetta and its surrounding. The epicenter was located approximately 153 km west of Quetta, Balochistan at depth of 17 km. (Seeber et al., ND) The earthquake completely devastated the city of Quetta, leaving 35000-60000 dead and injuring thousands of people in affected areas. The entire infrastructure of Quetta city including roads, railway lines, residential buildings and other lifelines were completely disrupted, see Figure 21.

Figure 21. A view of Bruce market before (left) and after (right) the earthquake (Wikipedia.org).

LESSONS LEARNT

These earthquakes when compared with other earthquakes of similar magnitude around the world places them at much higher level of human and material damages. Lack of seismic awareness, absence and enforcement of seismic building codes can be attributed to such large scale devastation. The nation learned and is implementing following lessons.

- Re-evaluation of seismic hazard assessment and re-zoning.
- Formulation of seismic building codes and their enforcement.
- Re-location of population centers to safer areas.
- Establishment of national disaster management authority.
- Research on issues such as regional seismicity, tectonics, geotechnical and earthquake engineering.
- Assistance to local population in construction of earthquake resistant buildings.
- Well planned distribution of population with respect to medical and educational facilities.

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