

Geological and Seismological Aspects of Kashmir Earthquake of October 8, 2005 and A Geotechnical Evaluation of Induced Failures of Natural and Cut Slopes

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Abstract

On October 8, 2005 at 8:50 (3:50UTC), a large devastating earthquake occurred in Kashmir region of Pakistan. The depth of the earthquake was estimated to be about 10km and it had the magnitude of 7.6. The earthquake resulted from the subduction of Indian plate beneath Eurasian plate, and the earthquake was due to thrust faulting. Although there was no surface fracture as a result of the faulting, extensive slope failures observed along the expected surface expression of the causative fault. The main faults in the epicentral area are Muzaffarabad-Tanda fault and Panjal fault. Both of these faults are thrust fault. While Muzaffarabad-Tanda fault dips NE, the Panjal fault dips SW. The Oct. 8, 2005 earthquake occurred in a place, which may be regarded as a seismic gap. The computational results for crustal straining using GPS measurements indicated that Indian plate in Pakistan undergoing much higher straining as compared with that of India. The maximum ground acceleration for Balakot was inferred to be greater than 0.9g from overturned vehicles in the direction parallel to the axis of the valley. This probably represents the largest ground acceleration in the epicentral area. Balakot is situated on the hanging-wall side of the causative fault. In addition, some further analysis of overturned or displaced structures showed that maximum ground velocity could be more than 280kine, which is probably the highest value so far.

One of the most distinct characteristics of 2005 Kashmir earthquake is the widespread slope failures all over the epicentral area. The Kashmir earthquake of October 8, 2005 particularly caused extensive damage to housing and structures founded on sloping soil deposits. Extensive natural and cut slope failures occurred along Neelum, Jhelum and Kunhar valleys, which obstructed both river flow and roadways. Furthermore, many slope failures associated with highly sheared and weathered dolomitic limestone occurred along the presumed surface trace of the earthquake fault. The failures nearby Muzaffarabad were spectacular in both scale and their areal distributions. Slope failures caused Kashmir earthquake of October 8, 2005 may be classified into three categories, namely, 1) Soil slope failures, 2) Weathered and/or sheared rock slope failures, and 3) Rock slope failures. Soil slopes failures occurred in either plane sliding mode or circular sliding. Planar sliding modes are generally observed on soil slopes over the bedrock. Deep-seated circular type soil slope failures observed when the soil thickness was large. Some peculiar soil slope failures were observed in both Balakot and Muzaffarabad. These slope failures occurred in conglomeratic soil deposits with rounded large cobbles, which are products of the past glaciation's period. Since the slope angles were quite steep (60–80°), these slopes failed on surfaces involving partly vertical tensile cracks and curved shear plane. The epicentral area is a mountainous terrain and it is highly susceptible to slope failures and rock falls, which may be very catastrophic sometimes. Furthermore, the slopes are very steep and covered with fallen debris. With due considerations of topography and possibility of slope failures, several alternative routes involving construction of viaducts, tunnels and bridges would be desirable for the area in case of blockage of roadways by rock falls or slope failures.

Keywords: Kashmir, earthquake, Muzaffarabad, thrust fault, slope failure

1. INTRODUCTION

A large devastating earthquake occurred in Kashmir on Oct. 8, 2005 at 8:50 (3:50UTC) local time of Pakistan. The depth of the earthquake was estimated to be about

10km and it had the magnitude of 7.6. The earthquake killed more than 80000 people, most of which was on Pakistani side of Kashmir. About 2000 people were killed in Indian side of Kashmir. The earthquake resulted from the subduction of Indian plate beneath Eurasian plate, and the faulting mechanism solutions indicated

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that the earthquake was due to thrust faulting. Although there was no surface fracture as a result of the faulting, the valley between Bagh to Balakot through Muzaffarabad may be the location where the fault should have appeared. The largest city influenced by the earthquake was Muzaffarabad, which is the capital of Pakistani Kashmir region. Balakot town was the nearest settlement to the epicenter and it was the most heavily damaged. Valleys were filled by moraine and/or talus deposits resulted from post-glaciation, and they were cut through by fast-flowing rivers, resulting in very steep slopes, on which most of settlements were located. The earthquake caused extensive damage to housing and structures founded on these steep soil slopes. Furthermore, extensive slope failures occurred along Neelum valley, which obstructed both river flow and

roadways.

JSCE and AIJ jointly dispatched an investigation/technical support team to Pakistan from the 18th to 28th of November, 2005 (Figure 1). The author was one of the members of the joint team of JSCE and AIJ. The author also had the second chance to visit the damaged area as a member of the team dispatched by JICA during January 17-23, 2006. In the first part of this article, an overall view of the geological and seismological aspects of the Kashmir earthquake of October 8, 2005 is described. Then the characteristics of the failure of natural and cut slopes induced by the earthquake are presented and their implications on civil infra structures and site selection for reconstruction and rehabilitation are presented.



Figure 1. Routes of investigations

2. GEOLOGICAL AND SEISMOLOGICAL ASPECTS

2.1 Geology

In northern Pakistan the orogen is composed of three main tectonostratigraphic terrains (Najman et al. 2002) (Figure 2): the Asian plate to the north, the Indian plate to the south, and the Kohistan island arc sandwiched between. The Kohistan arc is separated from the Asian plate by the Northern or Shyok Suture and from the Indian plate by the Main Mantle Thrust (MMT). The Asian plate Karakoram can be divided into the Northern Sedimentary terrain of Palaeozoic and Mesozoic Formations, the Karakoram Batholith of Cretaceous to Miocene age, and the Kohistan arc consists of Late Cretaceous and Eocene plutonic belts, and pyroxene granulites, calc-alkaline volcanics, amphibolites, and minor metasediments. The Indian plate can be subdivided into three tectonic units: From north to south these are (1) an internal metamorphosed unit, (2) an external unmetamorphosed or low-grade metamorphic unit, and (3) the foreland basin sediments. The internal unit consists of cover and basement rocks. The basement rocks are predominantly high-grade gneisses; the cover rocks are predominantly greenschist to amphibolite grade metapelites and metapsammities metamorphosed during the Himalayan orogeny. The internal zone is separated from the external zone unmetamorphosed to low-grade metamorphic Precambrian sediments and dominantly Mesozoic to Eocene Tethyan shelf sedi-

ments by the Panjal Thrust (PT). Farther to the south, the Main Boundary Thrust (MBT) separates these rocks from the Tertiary foreland basin deposits. The Main Frontal Thrust (MFT) delineates the southernmost extent of the foreland basin fold and thrust belt.

The more than 8 km thick red bed Balakot Formation in the Hazara-Kashmir Syntaxis as a steeply north dipping, normal homoclinal stratigraphic succession, conformably overlying the Paleocene-aged shallow marine Patala Formation and Lockhart Limestone. The Balakot Formation is actually variably deformed and folded by a series of tight folds (wavelength and amplitude of 1 km). The Patala and Lockhart Formations unconformably overlie the Late Precambrian to Cambrian Abbotabad Formation, which forms the core of the Muzaffarabad anticline. The lower part the Balakot Formation is structurally imbricated and isoclinally folded with the Patala Formation, which in turn is in thrust contact with the overlying Abbotabad limestones. The entire package is complexly faulted, with systematic top to the southwest thrust shear sense. Therefore, in summary, the Balakot Formation red beds lie in thrust contact with the Paleocene aged shallow marine Patala Formation and Lockhart Limestone below, and are tectonically intercalated with an underlying dark gray marl formation.

2.2 Tectonics

Apparently, about 80 million years ago, India was located just south of the Asian continent, moving northward at a rate of about 9-m a century. Eventually India

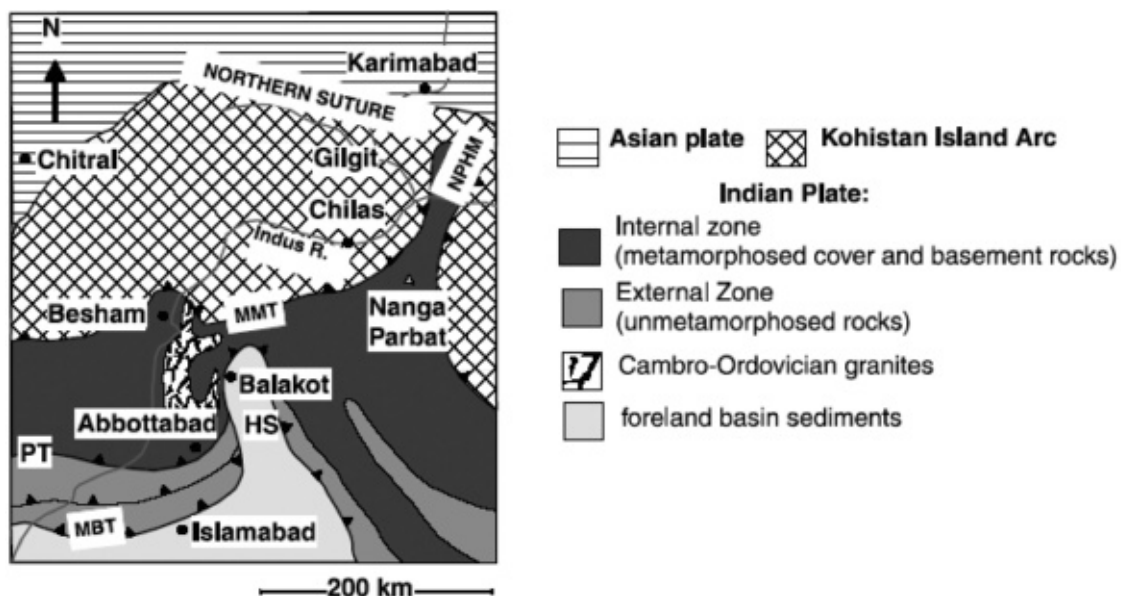


Figure 2. Regional Geology of Kashmir

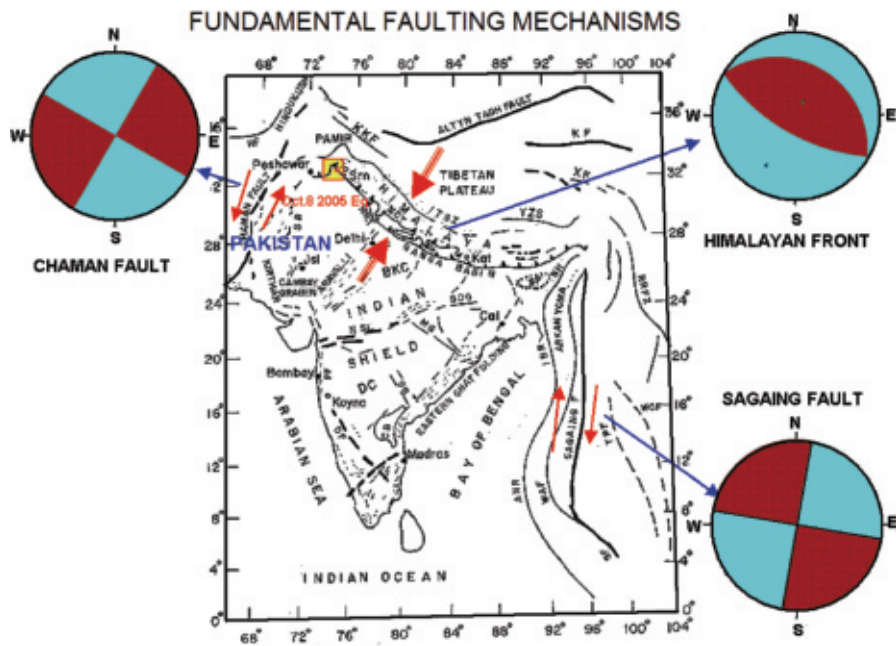


Figure 3. Tectonic features of Indian plate and its close vicinity

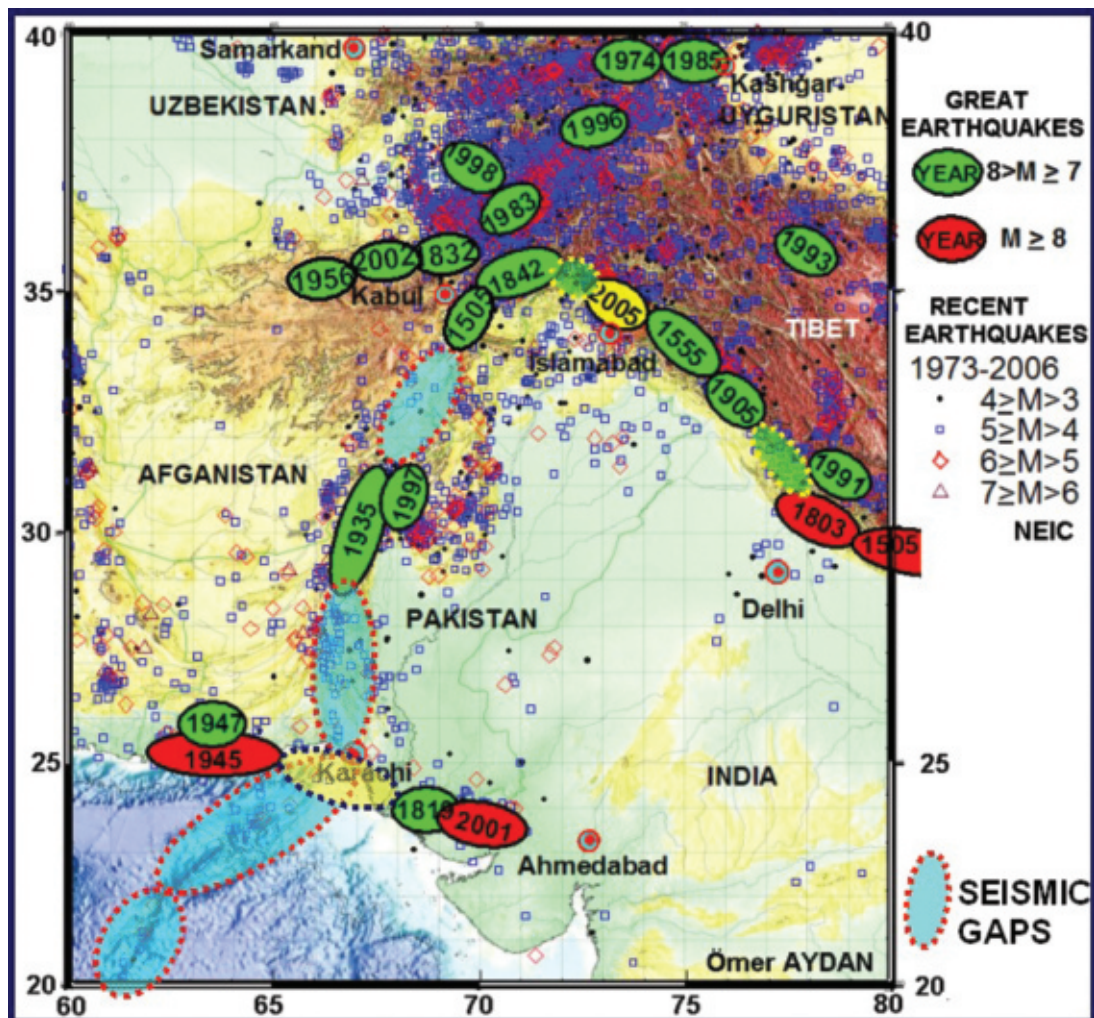


Figure 4. Locations of past earthquakes and seismic gaps around Indian plate

collided with Eurasia about 40 to 50 million years ago, and its northward advance slowed by about half. The Himalayas are also in continuous motion. They are growing by more than 1cm a year, which is a growth rate of 10 km in a million years. Although due to erosion and some subsidence of the whole area due to gravity, the effect of this growth is distorted. Himalaya mountain range constitutes the northern plate boundary of the Indian plate. Chaman fault in the west and Sagaing fault in the east is the transform plate boundaries. While Chaman fault is a sinistral fault, the Sagaing fault is a dextral fault. The indentation of the Indian plate into Euroasia resulted in the formation of Altin Dağ (Altyn

Tagh) and Karakoram faults in the central Asia (Figure 3).

The Jammu & Kashmir is the western most extension of the Himalayan mountain range in India. It comprises of the Pir Panjal, Zaskar, Karakoram and Ladakh ranges. The boundary of the Punjab plain and the mountains forms the Himalayan Frontal Thrust (HFT), which in this area is called Murree Thrust. The Main Boundary Thrust (MBT) underlies the Pir Panjal Range and is known as the Pir Panjal Thrust in the region. The Kashmir Valley lies between the Pir Panjal and the Zaskar thrusts. Northern parts of Jammu & Kashmir are heavily faulted. Along the Zaskar and the

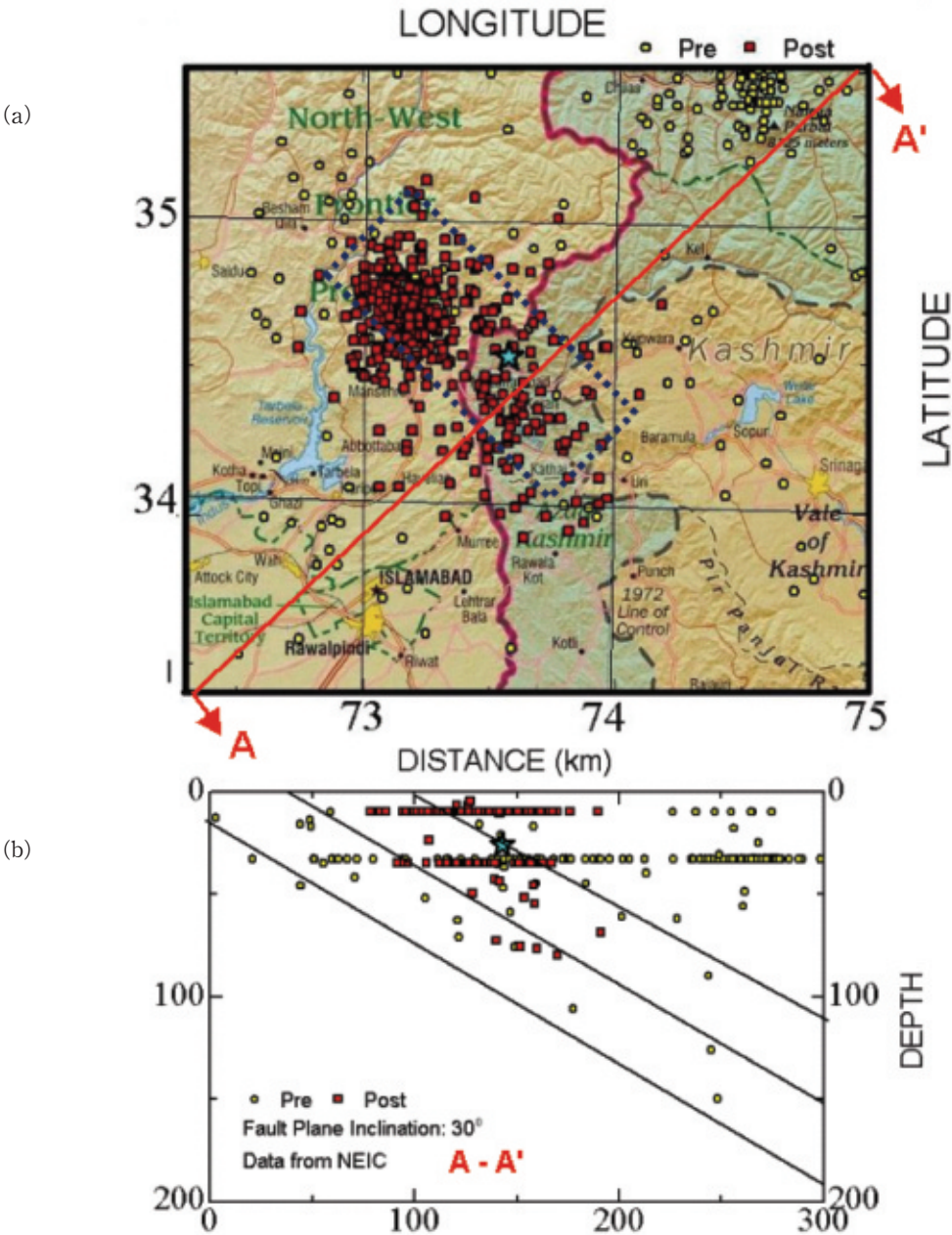


Figure 5. Pre-post seismicity of the epicentral area and cross sectional seismicity (A-A')

Ladakh ranges runs a NW–SE trending strike–slip fault, the longest in the Jammu & Kashmir area. The main faults in the epicentral area are Murree fault and Panjal fault. Both of these faults are thrust fault. While Muzafarabad–Tanda and Murree fault dips NE, the Panjal fault dips SW. These two faults may be conjugate to each other and they are in the footwall side of Main Boundary Fault (MBF).

2.3 Seismicity

The historical seismicity of the area was studied by several researchers. The earthquakes along the Himalayan front and their areal influences are shown in Figure 4 together with additional earthquakes along the western side of the Indian plate and inferred seismic gaps. In view of the earthquakes shown in Figure 4, the Oct. 8, 2005 earthquake occurred in a place, which may be regarded as a seismic gap. However, the gap is not fully ruptured and another earthquake having a similar magnitude may rupture in the region between the locations of 1982 earthquake and the 2005 earthquake. In addition, several seismic gaps exist along the entire Indian plate. If some of these seismic gaps rupture, it may produce earthquakes of M8 class. Figure 5(a) shows the pre–post seismicity of the epicentral area using the database of NEIC between 1973 and 2005. Before the Oct. 8 earthquake, there is almost no earthquake activity in the epicentral area, and a very high seismic activity has been taking place following the main shock. The high seismic activity is concentrated around the NW tip of the causative fault. Figure 5(b) shows the seismicity along a cross section perpendicular to the strike of the causative fault. It is interesting to note that the projections of the shocks imply that the fault plane should have the inclination of 30°.

2.4 Crustal Deformation and Strains

Crustal deformation measurements have been carried out to observe the motions of crustal plates by International GPS service. Although some local GPS networks seem to exist in both Pakistan and India, the measurements are intermittent. Therefore, it is presently difficult to know the variations of local strains and stresses in the vicinity of the earthquake area. A rough estimation of the crustal straining in the vicinity in Pakistan and India is carried out using the measured annual deformation rates of GPS stations, namely, BAHR (Bahreyn), IISC (India), KIT3 (Uzbekistan) and LHAS (Tibet). The deformation rates at these stations are given in Table 1 and computed strain rates given in Table 2. The illustrations of annual deformation rates and strains are shown in Figure 6. As noted from the computational results, Indian plate in Pakistan undergoing much higher straining as compared with that in India.

2.5 Faulting Characteristics and Surface Deformations

Various institutes worldwide estimated the fundamental parameters of the Oct. 8, 2005 earthquake and some of them are listed in Table 3. Furthermore, the fault plane solutions are shown in Figure 7. Although there are some differences among the parameters of the earthquake estimated by various institutes, the all solutions indicate thrust faulting with a slight lateral component except the one by USGS. As two fault planes are obtained from these solutions, the causative fault should be inferred from additional observations and seismic data. In view of the regional tectonics, after–shock activity, the fault plane dipping to NE should be the causative fault. If NE dipping fault is the causative fault, then the lateral strike–slip component of the faulting implies dextral motion of the fault, which is remark-

Table 1. Annual deformation rates measured (unit: mm)

Station	X (E+)	Y (N+)	UD (U+)
BAHR	32.10	28.76	0.94
IISC	42.89	33.66	0.93
LHAS	45.68	12.50	1.93
KIT3	28.02	3.75	−2.0

Table 2. Computed Annual strain rates

Element	$\Delta \epsilon_1$ ($\mu\text{s/year}$)	$\Delta \epsilon_3$ ($\mu\text{s/year}$)	θ (radian)
1	7.45044	−20.1116	−50.0149E−02
2	8.73246	13.3154	−22.4190E−02



Figure 6. Crustal deformation rates and strain rates in the vicinity of Pakistan

Table 3. Parameters of the earthquake estimated by different institutes

Institute	Latitude	Longitude	Depth(km)	Magnitude	Strike	Dip	Slip
HARVARD	34.37	73.47	12	Mw=7.6	NP1 333°	39°	121°
					NP2 116°	57°	68°
USGS	34.432	73.537	20	Mw=7.3	NP1 358°	29°	140°
					NP2 124°	72°	67°

ably similar to those of 2004 & 2005 Sumatra earthquakes.

Fault rupture propagation was inferred by various institutes such as BRI, IRD, USGS and ERI. The first computational results were released by Yagi of BRI (2005), which were followed by the others. Solutions by BRI, ERI and USGS estimated that maximum slip should be ranging between 8-13m, while the solution by USGS and IRD indicated that the slip should be ranging between 4 to 6m. Furthermore, this solution indicated that the maximum ground deformations should occur at the ground surface. The empirical relation proposed by Matsuda (1981) infers the relative slip to be 3.6m. Since there was no distinct surface rupture to confirm these estimations, it is very difficult to make further comments. Nevertheless, the inferred slips by BRI, ERI and USGS are somewhat overestimations.

Japan Geographical Surveying Institute (2005) inferred the ground displacement using SAR method. The maximum ground displacements are upward on the hanging wall side of the fault and the amplitude ranges between 4-6m. Although the solutions by this institute are quite similar to each other, they are diluted by topographical changes resulting from extensive slope failures on the hanging-wall side of the fault and the

result are quite disputable. The maximum upward ground deformation is estimated to be in Neelum valley in the north of Muzaffarabad. The post-earthquake configuration of the soil slope at this particular site was used to support the computational result of the GSI by some geologists. However, these disturbed slopes are simply soil slope failures and they are nothing to do with pop-up structures resulting in the folding of the upper soft layer in some thrust faulting events. The inferred trace of the fault is about 80-90km and its NW tip is located at Balakot. The inferred fault trace follows the line of Balakot town, Muzaffarabad city and Jhelum valley. Both aerial photographs and land surface observation along this line indicated numerous slope failures.

Except a surface rupture observation nearby Bagh by Geological Survey of Pakistan (2005), no distinct surface rupture was observed during the investigations in Balakot and Muzaffarabad and Jhelum Valley. However, there were numerous slope failures particularly on the NE side of the valleys. They were associated with the whitish 100m thick dolomitic limestone layer, which is a highly deformed and fractured rock unit (Figure 8). Figure 8 also shows a laboratory test on ground deformation in loose non-cohesive ground during thrust fault-

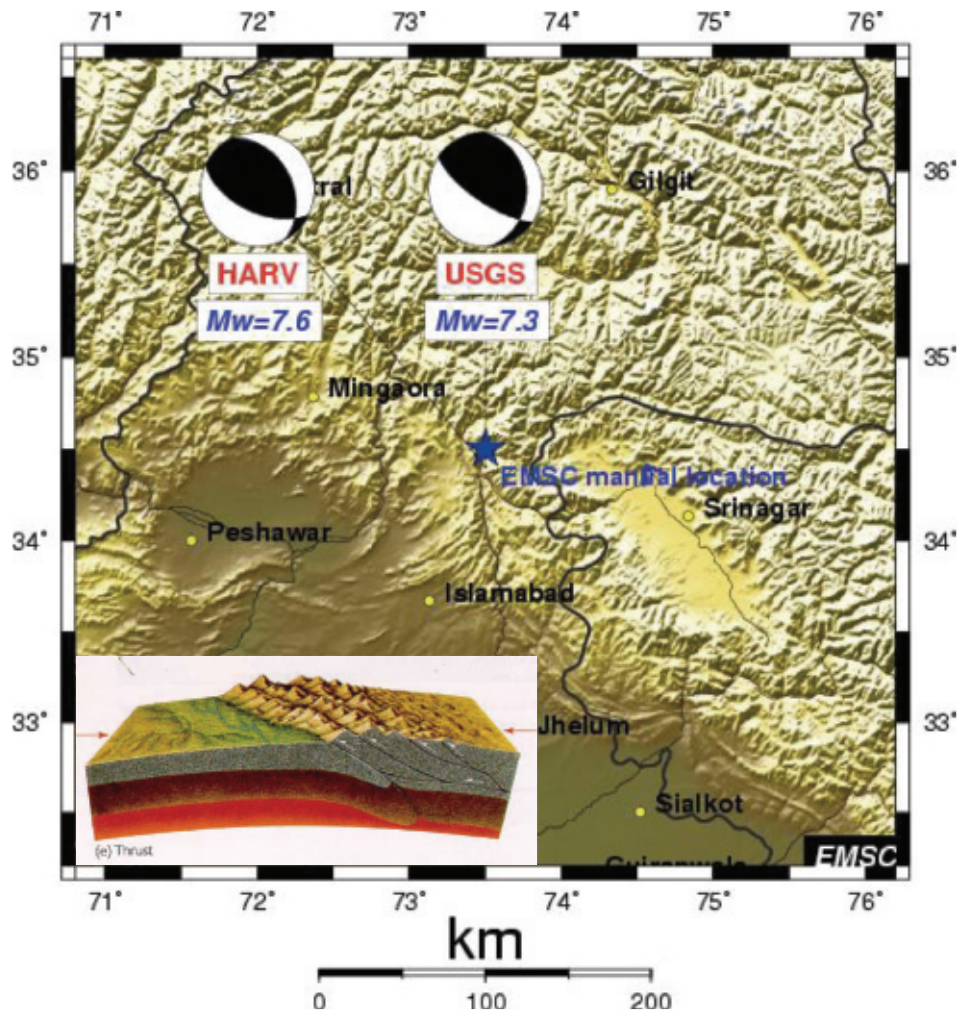


Figure 7. Fault plane solutions obtained by various institutes (modified from EMSC)

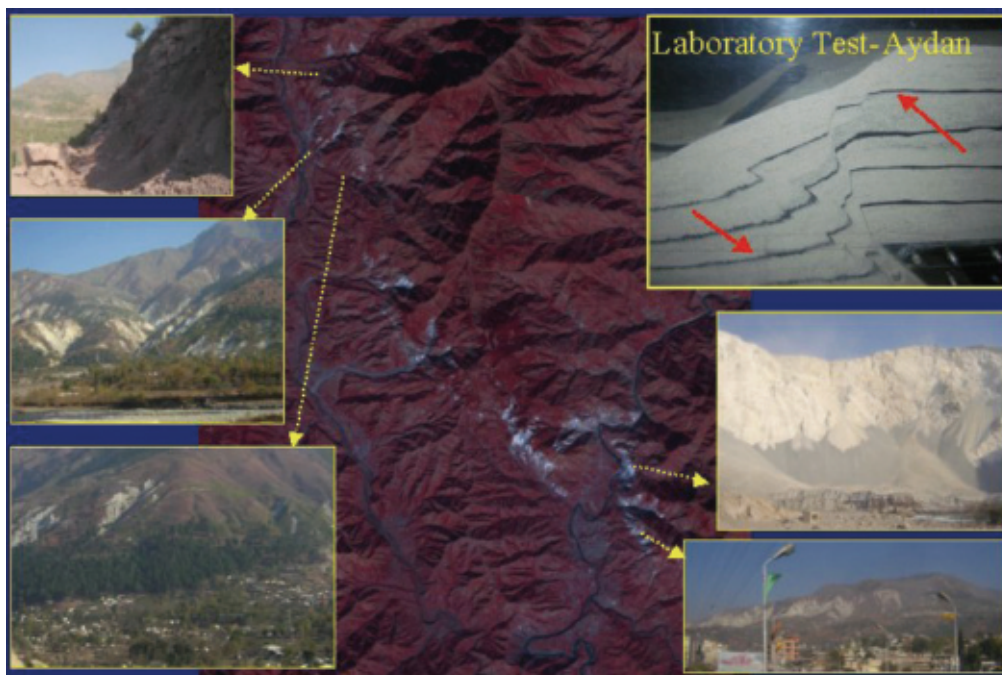


Figure 8. Slope failures observed in the regions of Balakot and Muzaffarabad

ing. As noted from the figure, in-spite of upward motion of the base-rock, some surficial slope failure (similar to small scale normal faulting or slope failures) occurs within the non-cohesive deposits. Furthermore, the thickness of deposits increases above the tip of the moving hanging wall as a rigid-body. Therefore the slope failures observed particularly on the hanging-wall side of the fault can be interpreted as the surface expressions of the earthquake faulting.

Following the main shock, an intensive aftershock activity was observed. Although the aftershocks distributed over a broad area, most of the aftershocks occurred to the north of the main shock. The faulting mechanisms of most of the large aftershocks are quite similar to that of the main shock. The seismic activity tends to decrease gradually. Nevertheless, from time to time, there are some large aftershocks with a magnitude greater than 5. However, it should be noted that the aftershocks of M6 class are very few for this scale earthquake.

During the investigations, the striations of the fault surfaces at three different locations were measured. In the close vicinity of Balakot on the SW side of the valley, two different faults striations on fault planes

having similar orientations were measured. While the events indicated thrust faulting with slight sinistral or dextral lateral component, some of events indicated almost pure sinistral or dextral movements. It is of great interest that the faulting mechanism of the thrust-faulting event at Balakot and Tundali bridge in Jhelum Valley, which are along the inferred causative fault, remarkably similar to the faulting mechanism of the main shock.

2.6 Strong Ground Motions

There are several strong motions networks operated by different institutes in Pakistan. The institutes are Pakistan Meteorological Agency, Pakistan Geological Survey and Pakistan Atomic Energy Center. The strong motions records from three stations, namely, Abbotabad, Murree and Nilore, of Micro Seismic Studies Program (MSSP) supported by Building Research Institute (Japan) for Pakistan are only available (Okawa, 2005). The nearest station to the epicenter is Abbotabad and its response spectra are very flat for the natural period of 0.4 and 1.5s. As the distance increases, the longer period components become dominant as observed in Nilore record. Murree strong motion is situated nearby the peak of the mountain and its response is

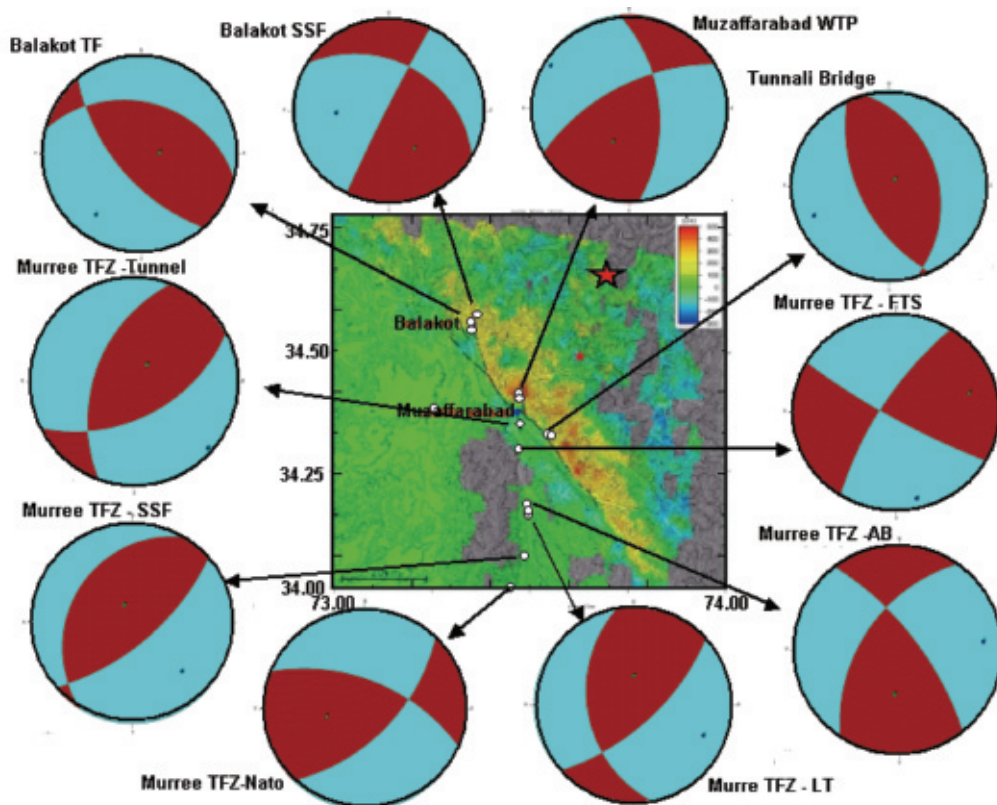
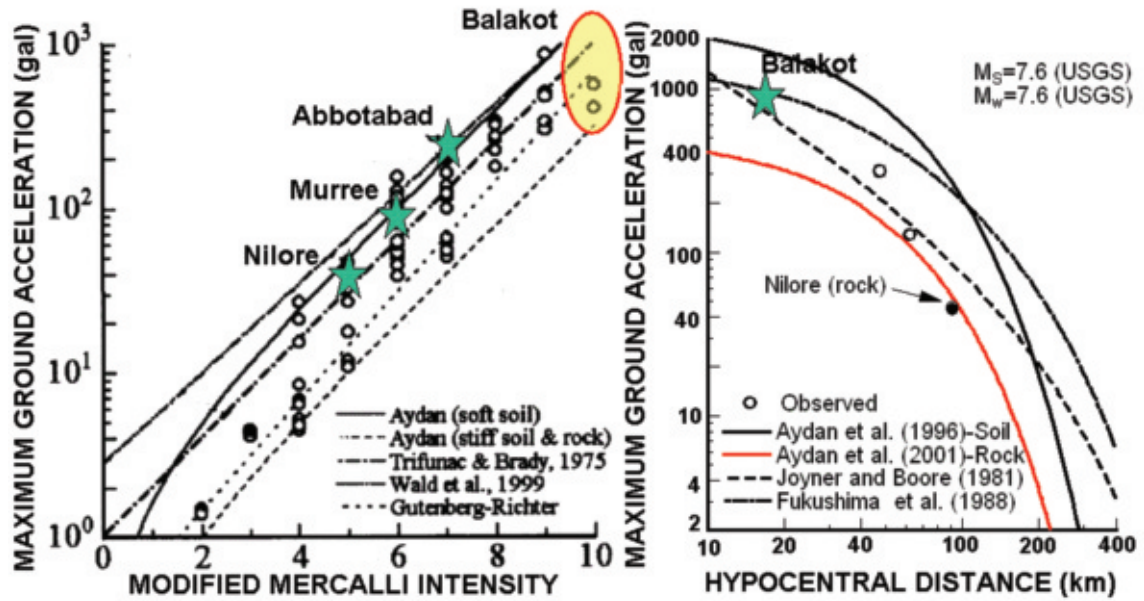


Figure 9. Faulting mechanisms inferred from fault striations



(a) Relation between Amax and MKS (b) Attenuation of Amax with distance
Figure 10. Relation between MKS and maximum acceleration and its attenuation

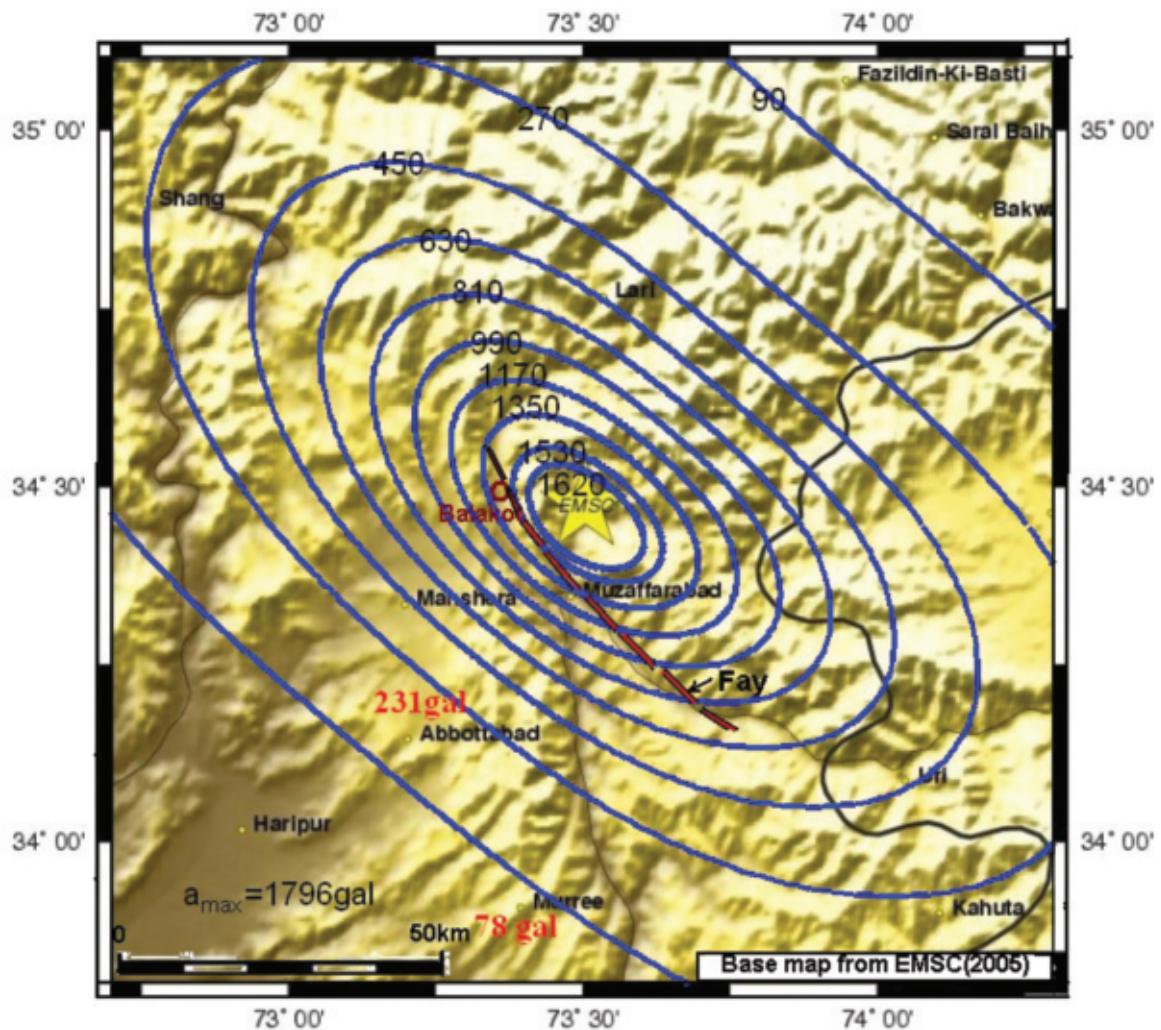


Figure 11. Estimated iso-acceleration contours for soft ground

likely to be influenced by the geometry and structure of the mountain. Compared with records of Abbotabad and Nilore stations, it seems that there is also a dominant natural period of about 0.2–0.25s. The acceleration record of a strong motion station on alluvium ground in Islamabad (according to the statement of an official from PAEC) is about 90gal. Since Nilore is nearby Islamabad, the ground amplification in Islamabad seems to be 3 times that on the bedrock.

Figure 10(a) compares the observed maximum ground acceleration (A_{max}) at three stations as a function of MKS Intensity together with some observations from past earthquakes. The maximum ground acceleration for Balakot was inferred as at least 0.9g from overturned vehicles in the direction parallel to the axis of the valley. This probably represents the largest ground acceleration in the epicentral area. Balakot is situated on the hanging-wall side of the causative fault. The attenuation of observed maximum ground accelerations are compared with some empirical attenuation relations in Figure 10(b). The contours of iso-acceleration on the ground surface for soft ground are shown in Figure 11. The ground acceleration on firm or rock ground would be 1/3 to 1/5 of those for soft ground. As noted from the figure, the maximum ground acceleration at the epicenter was estimated to be 1786gal. Although this value seems to be quite high, it should be

acceptable in view of the maximum ground accelerations recorded at Ojiya and Tokamachi during the 2004 Chuetsu earthquake. The surface extrapolation of the causative fault is also shown in the same figure. Furthermore, the maximum ground acceleration recorded at Abbotabad is in accordance with the estimated iso-acceleration contours.

In addition to the inference of maximum ground accelerations, maximum ground velocity are inferred from the displaced or overturned structures. Figure 12 shows the theoretical relations between maximum ground velocity and the displacement or size of the structure. In the same figure, the inferred results for the displaced Balakot Bridge and overturned bus next to the bridge are shown. The results indicated that the maximum ground velocity in the same location should have been more than 300kine. Additional back analyses for the failed soil slopes shown in Figure 14 by using the acceleration records at Abbotabad indicated that the maximum ground acceleration; velocity and displacement should be 1280gal, 289kine and 500cm, respectively. These results also agree with the previously inferred results using different techniques. There is no doubt that the strong motions at Balakot and Muzaffarabad were very high.

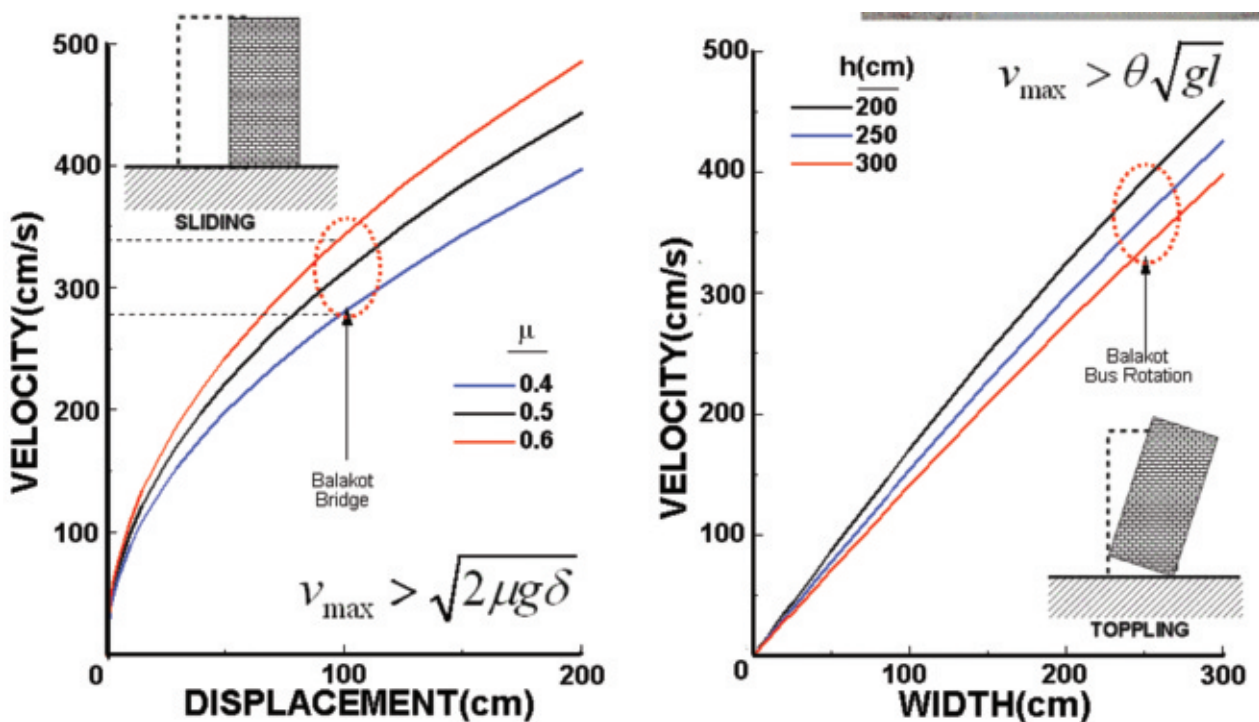


Figure 12. Theoretical relations between maximum ground velocity and displacement or size of structures

3. A GEOTECHNICAL EVALUATION OF INDUCED FAILURES OF NATURAL AND CUT SLOPES

One of the most distinct characteristics of 2005 Kashmir earthquake is the widespread slope failures all over the epicentral area. The Kashmir earthquake of October 8, 2005 particularly caused extensive damage to housing and structures founded on sloping soil deposits. Extensive natural and cut slope failures occurred along Neelum, Jhelum and Kunhar valleys, which obstructed both river flow and roadways. Furthermore, many slope failures associated with highly sheared and weathered dolomitic limestone occurred along the presumed surface trace of the earthquake fault. The failures nearby Muzaffarabad were spectacular in both scale and their areal distributions.

3.1 Classification and Examples of Slope Failures

Slope failures caused Kashmir earthquake of October

8, 2005 may be classified into three categories, namely, 1) Soil slope failures, 2) Weathered and/or sheared rock slope failures, and 3) Rock slope failures.

(a) Soil Slopes

Soil slopes failures occurred in either plane sliding mode or circular sliding. Planar sliding modes are generally observed on soil slopes over the bedrock. Deep-seated circular type soil slope failures observed when the soil thickness was large. Some peculiar soil slope failures were observed in both Balakot and Muzaffarabad (Figure 13). These slope failures occurred in conglomeratic soil deposits with rounded large cobbles, which are products of the past glaciation's period (Figure 14). Since the slope angles were quite steep (60–80°), these slopes failed on surfaces involving partly vertical tensile cracks and curved shear plane. The residual slope angles (repose angle) ranges between 40–45°, which may be considered to be equivalent to its friction angles (Figure 15). Some needle penetration tests were carried out at both Balakot and Muzaffar-



(a) Slope failure nearby Muzaffarabad



(b) Slope failure in Balakot

Figure 13. Soil slope failures nearby Muzaffarabad and at Balakot. (Note that the slope failure nearby Muzaffarabad misinterpreted by some geologists as a folding structure resulting from thrust faulting)

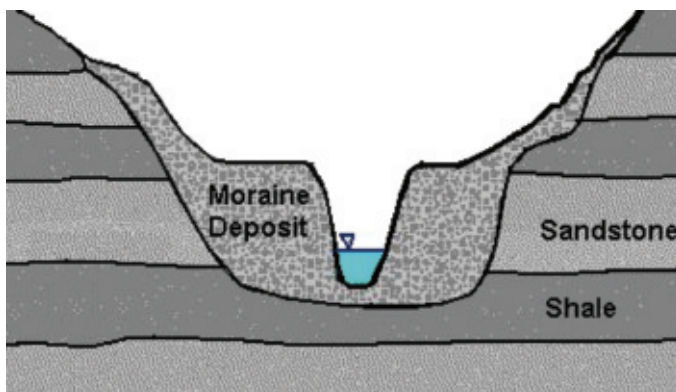


Figure 14. Illustration of steep soil slope formation and an example from Kashmir

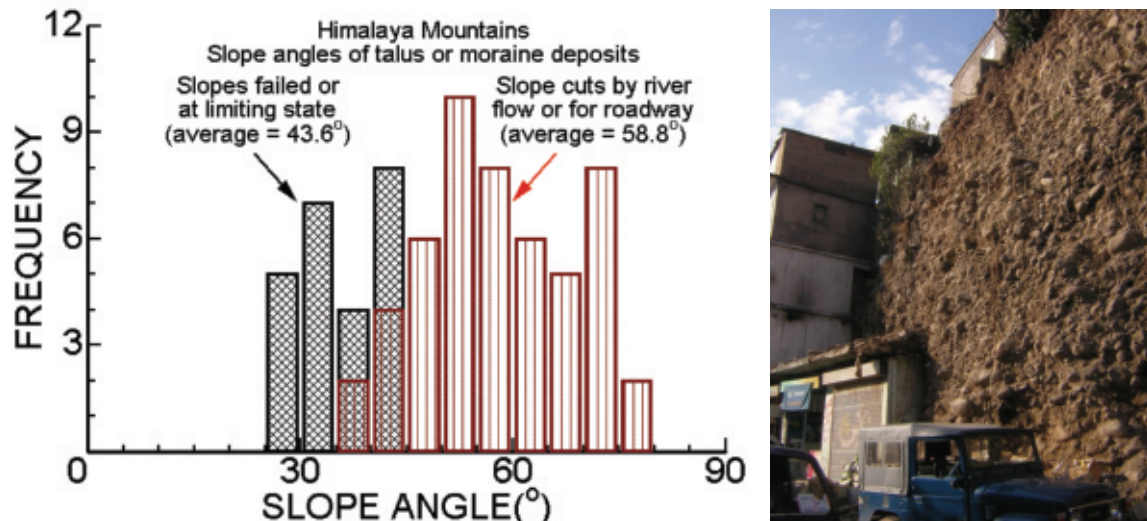


Figure 15. Relation between moraine slope angle and frequency and actual example

abad. The cohesion of soil matrix of the conglomeratic deposit is inferred from the needle penetration index tests to be ranging between 60–100 kPa.

(b) Embankment

The embankments of roadways failed along the rivers. Stone masonry or gabions are commonly used for supporting the embankments of roadways in steep terrain as well as along rivers. However, the embankments of roadways are not generally protected by retaining walls or gabions for a great length, which may make them prone to failures as a result of toe erosion due to fast river currents. They may also suffer from heavy rainfalls in long-term. No support or protection measures for most of slope cuts along roadways are undertaken. Furthermore, the slope cuts are generally very steep and there are no catchment pockets in case of rock falls and small-scale slope failures.

(c) Rock Slopes

Rock units in the epicentral area are schists, sandstone, shale, dolomitic limestone. Particularly red shale of Balakot formation is prone to weathering and the thickness of the weathered rock seems to be about 2–5 m. Dolomitic limestone rock unit is intensively sheared and this unit is thought to constitute the fault fracture zone. The surficial slope failures in dolomitic rock unit were spectacular and continued for several kilometers as they are clearly noticed in satellite images (Figure 8 and Figure 16(b)).

Except granite, all rock units have at least one

thoroughgoing discontinuity set, namely, bedding plane or schistosity plane. Since rock units had been folded, they also include joint sets and fracture planes as a result of tectonics movements. The rock slope failures are mainly planar or wedge sliding failure, flexural or block toppling failure (Figure 16(a,c,d)). Planar sliding failures were observed mainly in schists, sandstone and shale while flexural toppling failure was observed in intercalated sandstone and shale depending upon the inclination of bedding planes with respect to slope geometries. The inclination of layers ranges between 30–65°, which implies the sliding failure can be easily caused by a small intensity of disturbing forces resulting from such as earthquakes, heavy rainfall or the both.

Rock falls in the epicentral area generally resulted from the toppling of rock blocks due to excitation of the earthquake. Numerous rock falls were observed for a great length of roadways. Rock falls were particularly common in sandstone slopes. Some flexural slope failures were also observed in intercalated sandstone and shale formation with undercutting. The satellite images indicated that there was a large-scale slope failure nearby Hattian in the vicinity of the SE tip of the causative fault. The slope failure was at Hattian (Dana Hill) and it is an asymmetric wedge sliding type. The estimated wedge angle is about 100°.

3.2 Geotechnical Evaluation of Slope Failures

The most important issue is how to select the appropriate slope angle in relation to the geological features of slopes and slope height. For this purpose some empirical guidelines can be used as a preliminary assessment



(a) Flexural toppling failure



(b) Surficial failure of fractured dolomite



(c) Wedge sliding failure



(d) Planar sliding failure

Figure 16. Views of some rock slope failures

of the slope-cuts as they are outcomes of past records and case studies. However, it must be noted that the utmost attention must be paid to geological features of rock slopes, as the empirical guidelines may sometimes be mis-leading.

The epicentral area is a mountainous terrain and it is highly susceptible to slope failures and rock falls, which may be very catastrophic sometimes. Furthermore, the slopes are very steep and covered with fallen debris. With due considerations of topography and possibility of

slope failures, several alternative routes involving construction of viaducts, tunnels and bridges would be desirable for the area in case of blockage of roadways by rock falls or slope failures.

An example of stability analyses for failed slopes with cobbles observed in Balakot and Muzaffarabad is carried out using the planar sliding method. In the computations, the failure surface is obtained through the minimization procedure and computational results are plotted as a function of slope height and lower slope angle as

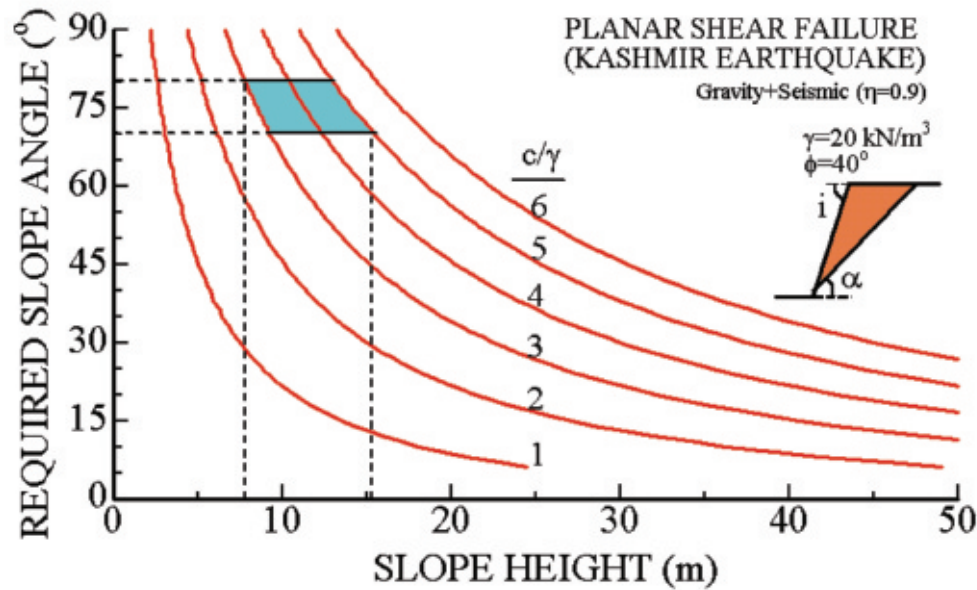


Figure 17. An example of slope failure and stability chart for soil deposits with cobbles

shown in Figure 17. In the computation, the friction angle is taken as 40° since the measured repose angle in-situ can be safely assumed to be equivalent to friction angle of failed soil. The normalized cohesion by soil unit weight was varied between 1 and 6 and the relation between slope height and slope angle for safety factor of 1 for a lateral seismic coefficient of 0.9, which is likely to be the ground acceleration levels at Balakot as well as at Muzaffarabad, is computed. The normalized cohesion of soil with cobbles was inferred from needle penetration index tests to be ranging between 3 to 5. For these parameters, the slope failures would be observed when the slope height was greater than 7.7m. This computational result implies that some restrictions on either slope angle or slope height in the re-development of settlements in sloping ground must be implemented. It is also recommended that geotechnical parameters of ground should be measured before the commencement of re-construction.

Many soil or surficial slope failures seem to be influenced by the inclination of the bedding plane of rock units. If the stability analyses to be performed for such slopes, the failure surface should be consisted of a failure surface parallel bedding planes and a curved failure surface from the toe of the slope to the bedding plane. Furthermore, the loads due to gravity, rainfalls and seismic forces should be considered in stability analyses since the epicentral area may further experience similar type earthquakes in the future.

The geometrical configuration of mountains in the

epicentral area is strongly influenced by geological folding process. The folding axis of the mountains generally ranges between N-S and NW-SE. The valleys are faulted and they may also correspond to either anticlines or synclines. As a result of these tectonic features, the mountain slopes are entirely governed by the thorough-going discontinuity set, namely, bedding plane. The measurements on the planes at several locations (nearby Balakot and along the route between Murree and Muzaffarabad) indicated that it ranges between 34 and 65° . The in-situ tilting tests revealed that the friction angle of bedding planes ranges between 30 – 40° , depending upon their surface morphology. The slope angle (lower part) of the natural mountain slopes of Himalaya mountains as well as Kashmir mountains are plotted in Figure 18 as a function of bedding plane, which may serve as guidelines for the long-term slope angle. The natural slope of mountains in the epicentral area ranges between 30 and 75° . When the bedding planes dip towards valley side, the natural slope angle of lower part of the mountain is almost equivalent to the inclination of bedding plane. This simply implies that the cohesion along the bedding planes is quite negligible. For the given height and tectonic features of rock mass, the natural analogy implies that the slopes would be resistant to pure shear failure or combined shear and sliding failure. However, when slopes are undercut, the planar sliding failure of bedded rock mass would be caused. Therefore, if the widening of present highways are to be carried out, the angle of slope cuts should be either parallel to the bedding plane or reinforcement by

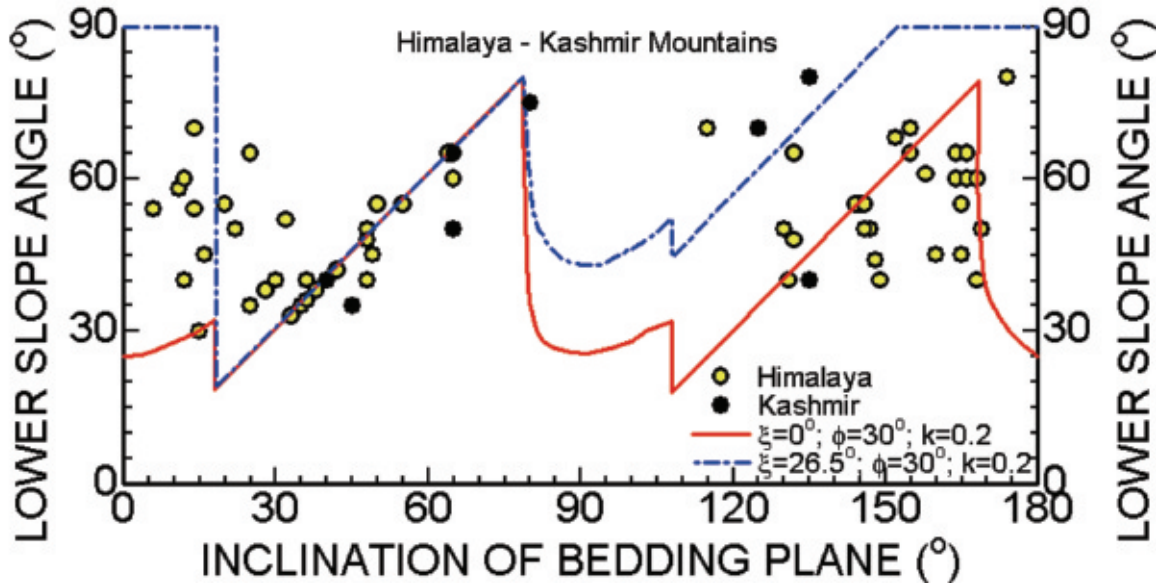


Figure 18. Relation between bedding plane inclination and slope angle for natural slopes

rockbolts or rock anchors will be required.

The mountains with bedding planes dipping into mountainside are more stable and the slope angle is generally greater than 40° . It seems that the natural slope angle (i) of high mountains in relation to the bedding plane inclination (α) can be taken according to the following formula

$$i = \alpha - 90 + \beta$$

Where β is the rupture angle with respect to the normal of bedding plane. Its value generally ranges between $10-15^\circ$ in view of both model tests and case studies. The value for the natural slope angle of mountains of the epicentral area ranges between 10 and 12° . This implies that if the angle of slope cuts for roadways is in accordance with the above formula, there is no need for any reinforcement measure in bedded rock mass.

Figure 19 shows an example of computations of slope angle and slope height relations for bedding plane inclination of 135° . Tensile strength of layers was inferred to be about 475 kPa in view of rock mass conditions in the epicentral area and in-situ tests on shale in a hydraulic power plant project in Akaishi region of Shizuoka prefecture, Japan. While the lower angle of rock slope can be very steep (90°) for a slope height of $6-10$ m, the slope angle must be reduced in relation to the slope height when no reinforcement measure is implemented.

The wedge sliding failure at Hattian was quite large in scale. The sliding area was 1.5 km long and 1.0 km wide. Rock mass consisted of shale and sandstone and it constituted a syncline. The estimated wedge angle was about 100° and it was asymmetric. The friction angle of

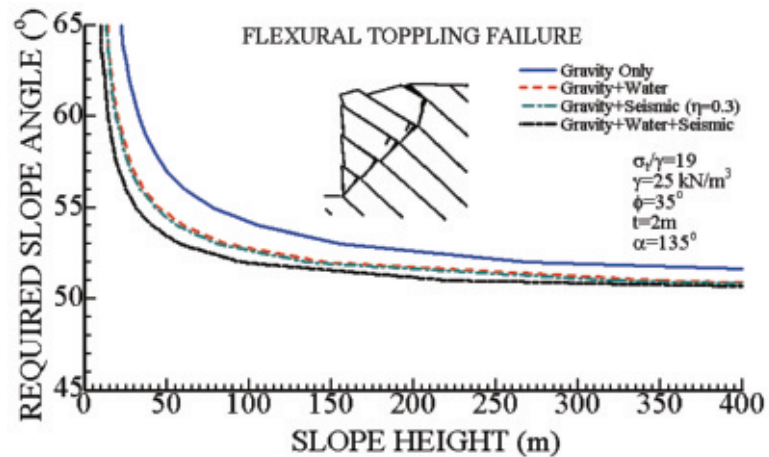
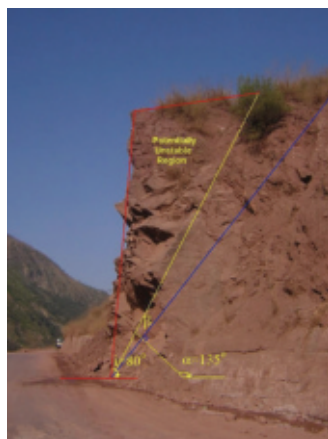


Figure 19. Stability chart for rock slopes against flexural toppling

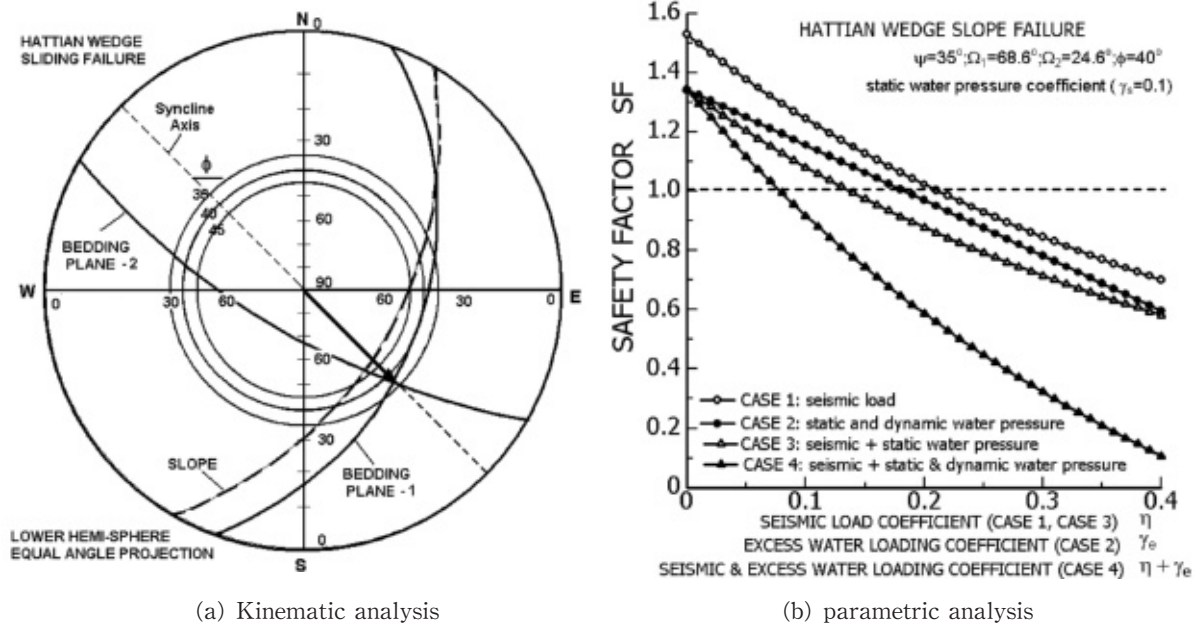


Figure 20. Kinematic and parametric stability analysis for Hattian wedge sliding failure

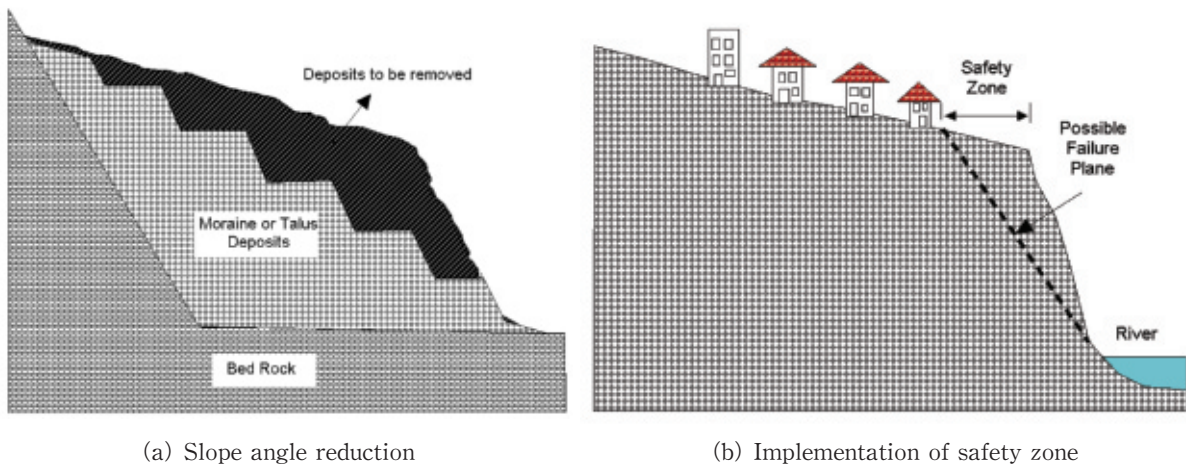


Figure 21. Some measures in reconstruction for earthquake affected area

shale from tilting test was more than 35° with an average of 40° . Figure 20(a) shows a kinematic analysis of the Hattian slope through the projection of structural planes on equal angle stereo-net together with friction cones. The limiting equilibrium analysis indicated that the safety factor of the slope would be 1.55 under dry static conditions. However, the mountain wedge becomes unstable when acceleration is equivalent to the horizontal seismic coefficient of 0.3 and the safety factor becomes 0.9 under such a condition. Some parametric studies for the same wedge sliding at Hattian were carried out and the results are shown in Figure 20(b). The result indicated that the seismic loading was the most critical parameter governing the wedge sliding.

When the slope angle and/or slope height are greater than those required for natural stability, the slope stabilization measures would be necessary. Furthermore, slopes of soil and soft-sedimentary rocks may deteriorate or erode due to exposure to atmosphere, which may require the surface protection of slope surface. Probably slope angle reduction would be the most desirable measure, and the fundamental concept should be such that the overall stability of the slope must be attained by the self-resistance of ground (Figure 21(a)). Therefore, the stabilization measures should be kept to the minimum. When there are some occasions, that is, it is impossible to reduce slope angle due to slope-cut height, tunneling, viaduct construction may be an effective way of dealing with the problem. If the construction next to

slopes is allowed, there should be a safety zone between the slope crest and allowable construction boundary (Figure 21(b)).

4. CONCLUSIONS AND RECOMMENDATIONS

In this article, an overall view of geology, tectonics, seismicity of 2005 Kashmir earthquake was presented, and structural and geotechnical damages concerning civil engineering structures and buildings their possible causes were described. The maximum ground acceleration and velocity at Balakot were inferred to be, at least, 0.9g and 300kine, respectively. The computational results indicated that the failure of soil slopes containing large cobbles was imminent under such ground strong motions. Furthermore, the loose surficial and talus deposits were laterally spreaded, which resulted in further damage in Balakot as well as in Muzaffarabad. In spite of the translation of the girder of Balakot bridge more than 1m, the bridge could stand against high ground motions and forces imposed by ground due to slope failures. Although some damage to several bridges were observed, it may be stated that large bridges with good engineering design and construction did stand against high ground motions.

Slope failures were observed along entire Neelum and Jhelum valleys. Particularly slope failures associated with heavily fractured dolomitic rock unit were spectacular in both scale and its areal distribution. However, these slope failures were aligned on locations, which may be interpreted as the surface expression of the causative fault.

The implications of natural and cut slope failures on civil infra structures and for the site-selection of buildings and urban developments may be summarized as follows:

- 1) The both sides of the steep valleys should be connected to each other at certain intervals in order to facilitate by-pass routes in case of emergencies resulting from bridge collapses and/or slope failures.
- 2) Since the region is a mountainous terrain, it is recommended to built tunnels and/or viaducts when there is a high risk of slope failures.
- 3) Embankment slopes are highly steep and they are prone to fail either by ground shaking or heavy rainfalls. It is recommended to either reduce slope angle of embankments or to introduce support, rein-

forcement or protection measurements. Furthermore, measures should be introduced to eliminate the toe erosion problems.

- 4) The slope angle and slope height of slope cuts should be such that the slope is stable under its natural resistance. If such a condition is difficult to be fulfilled, some measures for supporting and reinforcement should be undertaken. Since the valleys are very steep, there is high possibility of surficial slope failure risks.
- 5) The design of slopes and the assessment of failure risk must be based on the guidelines of modern slope engineering.
- 6) Natural slopes of the mountains are now in their equilibrium state. Unless some artificial disturbances are introduced, it is expected that the problems would be negligible.
- 7) Slopes of dolomitic rock unit along the fault line are susceptible further failures. Therefore, it is recommended that no permission for housing or structure construction should be given in such locations.
- 8) Housing and constructions on soil slopes containing large cobbles as observed in Balakot and Muzaffarabad should not be allowed. Although these slopes can be stable for high slope angles under static conditions, they are prone to failure during earthquakes. If the construction is allowed, there should be a safety zone between the slope crest and allowable construction boundary.

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要 旨

2005年カシミール地震の地質および地震学的特徴と自然および人工斜面の崩壊に対する地盤工学的な評価

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パキスタンに発生する地震の大半はインドプレートとユーラシアプレートの衝突によるものである。インドプレートは約 40mm/year の速度でユーラシアプレートの下に沈み込んでおり、ヒマラヤスラストに沿って逆断層型の地震活動が多い。インドプレートの西側では Chaman (チャーマン) 断層に沿っては左横ずれ、一方インドプレートの東側では右横ずれ型の地震が主な地震機構である。ヒマラヤスラストは四つに分類され、これらは主フロントスラスト (Main Frontal thrust, MFT)、主中央スラスト (Main Central thrust, MCT)、主境界スラスト (Main Boundary thrust, MBT) および主マントルスラスト (Main Mantle thrust, MMT) である。主境界スラストは約2500km であり、ヒマラヤアークに沿ってアッサムからパキスタンの西まで延びている。2005年10月8日の地震は主境界スラストのカシミール・ハーザラシタキスの西側で発生した。地震発生地域の主な断層は Murree 断層と Panjal 断層である。これらの断層は共役であり、Murree 断層は NE、Panjal 断層 SW に傾斜しており、主境界スラストの下盤に位置する。Murree 断層は Muzaffarabad で Tanda 断層と合流し、Balakot まで延びている。

この地域の地震活動についてビルハム (i.e. Bilham 1989; Bilham & Ambraseys, 1988, etc.) 氏が研究している。ヒマラヤスラストに沿って発生した地震とその影響範囲を Figure 4 に示す。2005年10月8日に発生した地震は空白域として考えられる地域で発生した。しかし、この空白域全体が今回の地震で破壊したものではない。未破壊の部分では同規模な地震が起きる可能性がこの地域に存在しているといえよう。1973年から本震が発生するまでの間に、震源域にほとんど地震活動が認められない。

2005年10月8日に発生した地震について様々な機関が地震の発生機構を求めた。USGS の地震発生機構に対する解以外、他の機関の解はほとんど同様である。余震活動と地域のテクtonics 的な特徴から走行が NW-SE で NE に 30-39° で傾斜している右横ずれ成分を有する逆断層運動によって地震が発生したと推定されている。東京大学地震研究所と HARVARD 地震研究所の公表した解を Figure 7 に例として示す。地震断層運動による相対ずれは機関によって異なり、推定値は 6-12m の間に変化している。しかし、過去の同規模な地震に対するデータよりその相対ずれは 4-5m 程度であると推定される。SAR 技術を利用して国土地理院によって地震に伴う地表面変位分布が推定され、その最大値は 4-6m であると報告された。地表面に明瞭な地割れの発生は報告されていないが断層の位置とその長さは解析結果より明瞭である。地形的に推定される断層線にそって帯状に斜面崩壊が Bagh (バグ) より Muzaffarabad (ムザファルアバット) を通って Balakot (バラコット) まで発生した。特に地震断層帯を形成している白い石灰岩層 (パキスタン地質局によれば苦灰石) における斜面崩壊の規模が最も大きい。この現象は逆断層運動による地盤の変形挙動に対する室内で見られた現象と同様であると思われる。推定断層長は 80-90km と推定された。本震後、地震断層の NW 端に活発な余震活動が見られ、その余震の地震機構はほとんど本震のものに類似している。

震源に最も近い Abbotabad (震源から44km) の強震記録であり、Abbotabad は地震断層の下盤であり、最も大きい揺れは EW (0.231G) に発生している。震源に最も近い Muzaffarabad および Balakot において地震記録はない。しかし、Balakot で大きく被害を受けた橋周辺でマイクロ・バスの転倒したことから少なくとも 0.9G 以上の加速度が作用したと推定された (Figure 10)。加速度応答解析結果を見ると、加速度応答スペクトラは大変フラットで、0.4 と 1.5 秒の間にその卓越固有周期があると考えられる。

カシミール地方は急傾斜を有する山地であり、谷底と山の落差は 2000m を超えている。2005年カシミール地震によって Jhelum, Neelum および Kunhar 谷の両側の斜面に大規模な斜面崩壊が多数発生した。震源地域における斜面崩壊は土質斜面の崩壊、風化岩盤の表層すべり破壊と岩盤斜面の崩壊に大別される。土質斜面の場合、深い円形すべりと浅い平面すべり崩壊が発生した。特に Balakot および Muzaffarabad で家屋や建物の崩壊要因となったのは大きくて丸い礫を含む土質斜面の崩壊であった。この地方に過去に存在した氷河によって谷底に堆積したこの地層は急流である Jhelum, Neelum および Kunhar 川によって削り取られ、70° を超える急傾斜で高さ 20m 以上の斜面が形成されている。今回の地震の揺れによってこれらの斜面が崩壊した。一方、風化した頁岩や断層運動によって破碎された苦灰石で形成されている岩盤斜面では地震断層にそって深い表層すべり破壊が発生した。岩盤斜面の場合、平面すべり破壊、くさび破壊、たわみ性やブロックトップリング破壊が発生した。特に平面すべり破壊とブロックトップリングによる崩壊物が道路に被害をもたらした。交通が寸断された。地震断層の SW 端にある Kalrahi 地域では面積が 2×1.5km である大きな斜面崩壊が発生した (Figure 12)。この斜面崩壊は平面すべり破壊に類似したくさびすべり破壊であり、崩壊物が川をせき止め、天然湖が形成された。岩盤は Balakot 赤い頁岩と呼ばれている岩盤で、すべり面の大半は層理面で構成されている。また、崩壊した斜面に存在した家屋が破壊され、十数名の犠牲者がでた。