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Research Paper

Spatial distribution of coseismic mass movements by 2015 Gorkha Earthquake in six districts of Central Nepal

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ABSTRACT

The Mw 7.8 Gorkha earthquake of 25 April 2015 and its many severe aftershocks generated about 4000 landslips. We have carried out field investigation of mass movements in the most severely-affected six districts of Central Nepal. The study revealed that the size and distribution of slides is strongly controlled by their position on landscape. An overwhelming majority of them was less than 5 m deep. Many slides were found to originate near a long and high crest or a peak. The slopes that had the highest internal relief suffered the most from the seismically-triggered failures. On the other hand, the old and large failures that were confined mainly to the river valleys were rather insensitive to earthquake shaking.

1. Introduction

The Mw 7.8 Gorkha Earthquake struck Central Nepal at 11.56 a.m. (local time) on 25 April 2015. The quake and its major aftershocks brought about massive destruction, including 8,686 deaths and 16,808 injuries (reported on 25 May 2015 by the Ministry of Home Affairs, the Government of Nepal). The National Planning Commission (NPC) Post Disaster Needs Assessment (PDNA) Report (NPC, 2015a) identified 31 of the country's 75 districts as affected, of which seven were declared 'severely hit' (the worst category) and seven 'crisis-hit' (NPC, 2015). Six of the crisis-hit districts including Gorkha, Dhading, Rasuwa, Sindhupalchok, Dolakha, and Ramechhap are investigated in this study. Its epicentre was located at 28°15'07'' N latitude and 84°07' 02'' E longitude, near the village of Barpak (**Fig. 1**), about 80 km NW of Kathmandu (DRR Portal Nepal, 2015).

Himalayan seismicity is attributed to the movement of the Indian plate relative to the Eurasian plate at a rate of about 5 cm per year. When the convergence is locked in some sector, the energy is ultimately released in the form of tremors along the mountain range and in its surroundings (Seeber and Armbruster, 1981; Pandey et al., 1995; Bilham et al., 1997). Most of the convergence is accommodated within the Himalaya by movement on various thrusts. Microseismicity in Nepal is characterised by a narrow belt that follows approximately the front of the Great Himalayan Range. This kind of confined distribution reflects deformation between the upper and lower crusts along the Main Himalayan Thrust under the Lesser and Higher Himalaya (Pandey et al., 1999; Avouac, 2003). Though the entire country is seismically active, there is a significant lateral variation. Microseismic

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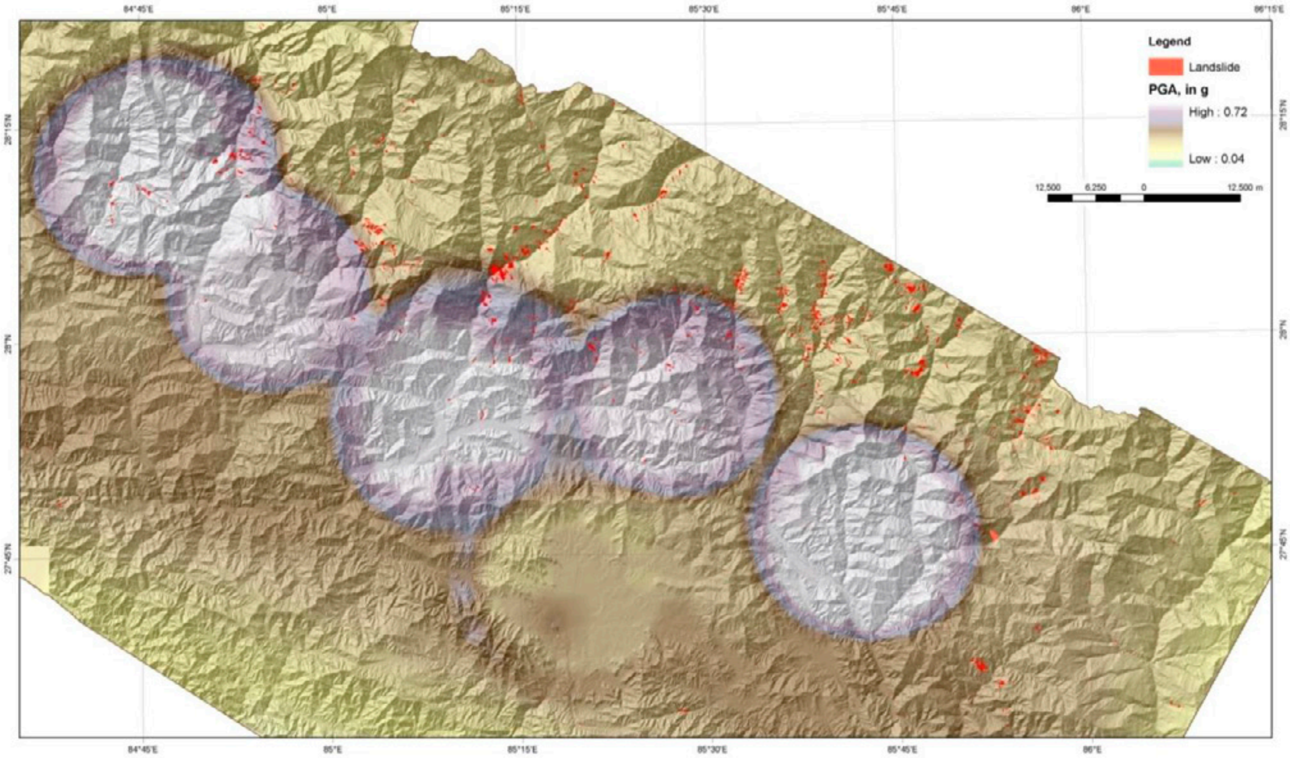

Fig. 1. Landslides triggered by 25 April 2015 earthquake and its aftershocks in Central Nepal. The peak ground acceleration (PGA) by the mainshock (USGS 2015) is also shown.

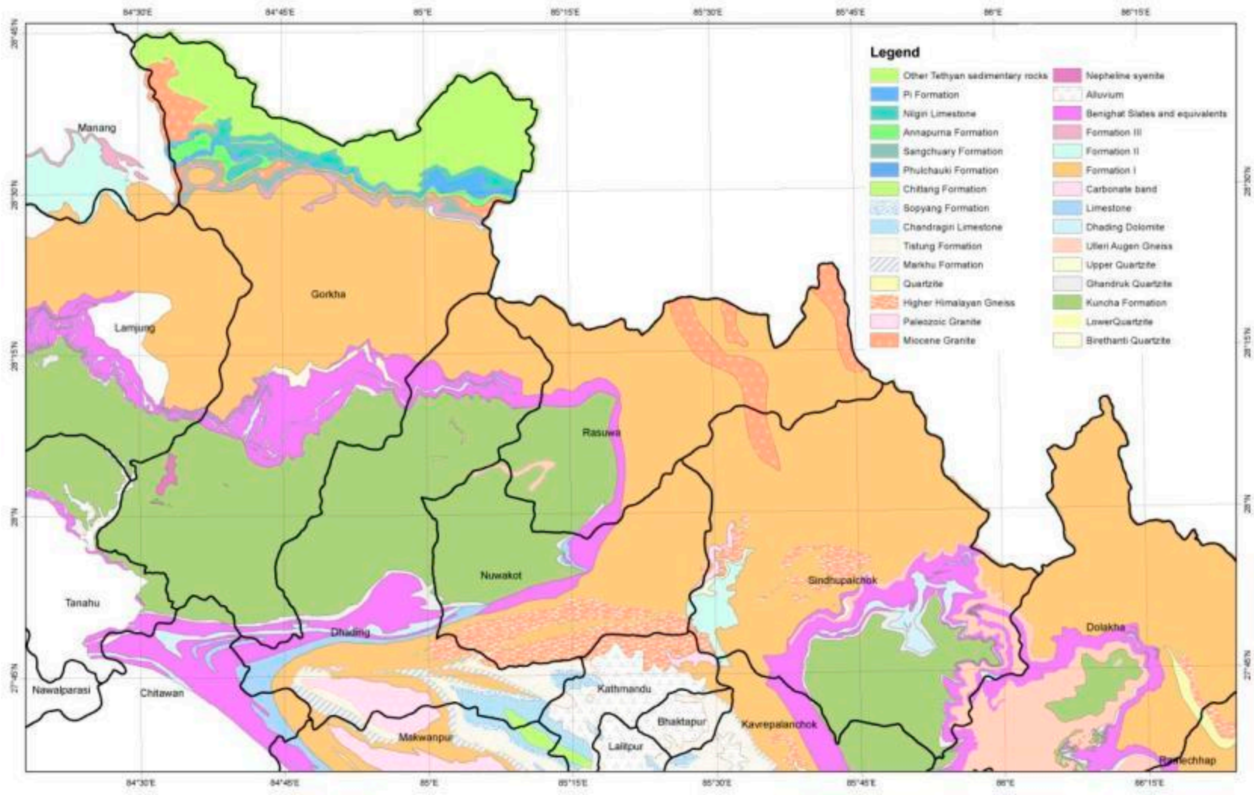

Fig. 2. Geological map of the earthquake-affected region of west and Central Nepal. Source: Modified from Dhital (2015).

activity is quite intense in east and far-west Nepal, whereas the level of seismic activity is low in west Nepal. The earthquakes are generally shallower than 30 km and they are clustered around a depth of about 20 km. This quake occurred as a result of faulting near the foothills of the Great Himalayan Range. In this case, the fracture propagated from Barpak to the east, up to Dolakha, and to the south respectively for about 150 and 60 km (**Fig. 1**).

2. Regional Geology

The 25 April 2015 earthquake-affected area can be divided into the Lesser Himalayan Sequence, Higher Himalayan Crystallines, and the Tethyan Himalayan Sequence (Dhital, 2015). These rocks have been classified into various formations (**Fig. 2**) based on their lithological characteristics and structural differences.

The Lesser Himalayan Sequence begins with the Kuncha Formation, consisting of phyllites, metasandstones, and schists with a few bands of quartzite and gneiss, including some nepheline syenites. This formation is succeeded by the Fagfog Quartzite, Ghandruk Quartzite, or Birethanti Quartzite. These quartzite bands are resistant, have light yellow to white colour, and attain a thickness of several hundred metres. The quartzite unit is then followed up-section by variegated schists, slates, and carbonates named as the Dandagaon Phyllites, Nourpul Formation, or Lower and Upper Schists. Further stratigraphically upwards are found grey dolomites with columnar stromatolites, belonging to the Dhading Dolomite. This formation is followed upwards by the black Benighat Slates and grey limestones belonging to the Jhiku carbonates and Malekhu Limestone. The topmost unit of the Lesser Himalayan Sequence is represented by slates, schists, amphibolites, and quartzites (Stöcklin, 1980; Colchen et al., 1986).

The Higher Himalayan Crystallines override the Lesser Himalayan Sequence along the Main Central Thrust. They are made up of schists, gneisses, and quartzites (Formation I), some marbles and gneisses (Formation II) intruded by Palaeozoic and Miocene granites. Formation III is represented by calcareous schists, marbles, and augen gneisses (Le Fort, 1971).

In the Kathmandu area, the Tibetan–Tethyan Sediments are classified into the Tistung Formation (biotite schist and quartzite) overlain successively by the Sopyang Formation (limestone and slates), Ordovician Chandragiri Limestone, Chitlang Formation (grey-green slates and quartzites), and the Silurian Phulchauki beds of dolomite Stöcklin, 1980).

3. Mass movements

Landslides are one of the most destructive events associated with an earthquake. In fact, damage from them sometimes exacerbates the destruction from strong shaking and fault rupture (Keefer, 1984).The Gorkha earthquake and its aftershocks triggered off more than 4000 landslips (**Fig. 1**) (Kargel et al., 2016). Most of them were shallow (less than 5 m), ranging from plane rockslides and wedge slides to rock falls, debris falls, and topples. The mass movements were investigated in the following six severely affected districts.

3.1 Gorkha district

Though the village of Barpak was very close to the epicentre of mainshock, its vicinity did not suffer much from large and deep failures. Nonetheless, the region was impregnated with many shallow slides, cracks, and fissures (Shrestha et al., 2016). These vulnerable slopes were further damaged by the monsoon of 2015. At the south end of the village, about 100 m northeast of the Nepal Telecom’s tower, many tension cracks are crisscrossing a foot trail (**Fig. 3**). The cracks are up to 27 m long, about 40 cm deep, and have a of lateral displacement of about 25 cm and a vertical displacement of about 20 cm. They are filled up with soil and extend across the slope. An active debris slide is observed on the Barpak-Laprak road passing through the middle portion of the slide. The slide is about 100 m long, 52 m wide, and from 5 to 8 m deep. It is actively expanding towards its crown and flanks.

On the northern slopes of the Laprak village, the earthquake reactivated an old soil slide, which is about 300 m wide, 100 m long, and 20 to 25 m deep. The original ground surface on which the slide developed was even, but presently it is undulating. The reactivated slide has affected the cultivated land and forest. About 50 m wide, 5 to 10 m deep, and 70 m long debris slide is present at Kusku Pakha. It is also a reactivated landslide. It has damaged the cultivated land and the ground surrounding the slide is wet. Towards its left flank a spring lies about 25 m west of the slide and a stream flows through its toe. An extensive crack zone is found in the western hill slope of Laprak, where numerous cracks are randomly oriented and a cultivated terrace has subsided by about 60 cm. At the mid southern portion of the Laprak VDC, on the way to Gumda, a number of active landslides occur on the southern hill slope. They are represented by rock falls, debris falls, debris slides, and soil erosion. The slope consists of highly weathered schists and quartzites, with a thin colluvial cover.

Fig. 3. Tension cracks at about 100 m NE of NTC mobile tower, Barpak. View to W.

Fig. 4. Landslip on left bank of Budhi Gandaki River at Galane.

Fig. 5. Rock fall zone at Soti Bajar. View to N.

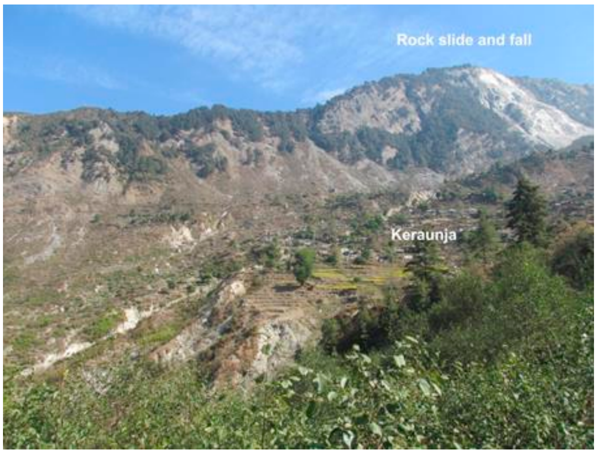

Fig. 6. View of Keraunja village affected by many landslides and gullies.

The Budhi Gandaki valley is one of the most severely landslide-affected regions in the Gorkha District. In the past, there have also been many incidents of rocksliding with some cases of landslide damming (Shrestha et al., 2016). At the eastern end of the Arkhet Bajar, close to the village of Galane of the Budhathum VDC, an alluvial soil slide occurs on the left bank of the Budhi Gandaki River. The landslip was reactivated by the earthquake and it is about 30 m long, more than 100 m wide, and 2-4 m deep. The alluvial deposits consist of sand, gravel, and boulders of up to 2.5 m in diameter (**Fig. 4**).The slide is facing west with a dip of 35 degrees in its deposition zone and its main scarp is almost vertical.

A debris slide lies on a convex slope, about 500 m downstream from the Soti Bajar of the Thumi VDC, and about 300 m above the Budhi Gandaki River. The landslide is about 300 m long, 200 m wide, and 5-8 m deep. The failure has taken place on schist and the failed slope is inclined by about 40 degrees.

Rock falls affect the road between Soti and Arughat at several places. There is a significant risk of rock fall at Soti Bajar of the Thumi VDC, where multiple extension joints are present in the rock cliff (**Fig. 5**) and about 10 houses are situated within its runout zone. The cliff is about 50 m high and steeply (70-80 degrees) facing due east. At Soti Bajar, the Budhi Gandaki River is also undercutting its right bank by scouring about 10 m high alluvial terrace for a length of about 300 m. Some of the buildings are just a meter away from the cliff. Hence, they are under a high risk of failure, especially in the rainy season.

A large landslide and several smaller ones are distributed between Shyamchet to the west and Ghamling Gaun to the east for a distance of about 2 km. Many tension cracks are also distinct in the southwestern slope of Shyamchet. Most of the paddy field is left barren due to ground deformation and subsidence. Some of the houses from Shyamchet are relocated near Ghamling Gaun.

At the village of Khani Gaun in the Lapu VDC, large rock falls and debris flows are widespread. About 6 m deep and 3-5 m wide erosive gully has many cracks in its both banks and adjacent paddy field throughout a length of about 1.5 km. Past debris flows from the gully have accumulated a huge mass on the bank of Budhi Gandaki River. A reactivated landslide is also present at the bottom of the slope. An actively eroding gully of an average depth of 6 m and width of 8 m runs through the lower part of Keraunja, where most of the houses are damaged by debris flows and floods. A prominent spring is also present on the slope. Keraunja also suffered from massive destruction of houses due to rockslides and falls, especially towards the upper reaches of the gully (**Fig. 6**).

An old landslide lies about 20 m below the school of Rumchet in the Keraunja VDC. The crown of slide has a deformed ground that has subsided by about 3 m. The failed slope dips about 60 degrees due north. About 1 km upstream from the suspension bridge at the Dobhan village in the Keraunja VDC, a huge landslide has accumulated an enormous amount of debris on the left bank of the Budhi Gandaki River. The failure propagated on an alternating succession of quartzite and gneiss. The original slope before landsliding was concave and it was dipping at an angle of about 70 degrees. At present, the landslide is about 500 m long and 400 m wide, and it was partly reactivated by the earthquake. There is a high risk of a large failure that may dam the Budhi Gandaki River. Currently, the slide is obstructing the trekking route to the Manaslu conservation area.

The upper slope of Sirdibas village is composed of highly jointed and fractured rock mass. The main rock type is gneiss with some schist and quartzite bands. The village lies on a southeast-dipping slope of 60–68degrees, on an old landslide debris. A spring appears on the left flank of the slope, most of which is covered by grass. There is a risk of rock fall, the runout from which may affect the village lying about 125 m below a cliff.

An actively eroding gully passes through the mid portion of the Padi village in the Sirdibas VDC, whereas a large landslide occurs at its lower reach. The ground around the landslide is wet and sliding towards the gully.

At the village of Khorlabesi in the Uiya VDC, a debris flow has reached the banks of Budhi Gandaki River and damaged a few houses. The upper slope of Khorlabesi has highly jointed rock masses and the rock falls originating from that slope have destroyed several houses (**Fig. 7**).

3.2 Dhading district

The Ri VDC is one of the largest in the Dhading District that was severely affected by the quake. Especially, its north part witnessed many failures. North of the school of Tawal, a large rockslide-rock fall (**Fig. 8**) occurred periodically. This slope failed at first during the earthquake and then in the rainy season for several times. Its runout zone is about 150 m high, 200 m long, 200 m wide, and the accumulated debris is forming a cone near the toe is 5-15 m deep. The boulders from the failure can reach the school compound. Some large boulders (1-3 m) are scattered to the north of school, whereas some of them are resting just at the brink of school compound. Presently several wedge slides are active at the crown. A wedge slide – fall is also seen on another cliff, about 75 m east of the main debris cone. Some part of the openly fractured rock is overhanging and can come down in the next monsoon.

At the south end of Latap, a small (about 100 m long and 50 m wide) strip of paddy field is seen to the west of a developing soil slide along with gully erosion. The slide is 5-7 m deep, about 20 m wide at the crown, and contains boulders (10-3 m) of quartzite and its wet matrix is a silty sandy clay. About 25-30 m below is an alder forest, which is rather intact. Tension cracks are found around the crown within a width of about 50 m and length of about 300 m.

On the way to Tajumrang, a rock cliff is suffering from a wedge failure at the junction of two trails, where massive, cliff-forming, grey, pelitic quartzite and biotite schist are exposed. The rock is strongly lineated. Many shallow rockslides, debris slides, and rock falls are seen on the slope, where the village of Kichet is located (**Fig. 9**).

The foothill of Kichet is hazardous for rock or boulder fall during the monsoon season. The west part of village lying on old talus cone-debris fan with large (8-10 m) boulders at base is unsafe. According to the villagers, there are many tension cracks or wide joint openings in the slope or cliff above the village.

A very big rockslide devastated the village of Gangmrang, where all the houses have collapsed. Many tension cracks are seen in the trail below the abandoned village. The crown of landslide has reached the village in the form of a wedge slide (**Fig. 10**). The rock is represented by grey schist.

On the uphill side of the Linjo village, many tension cracks are present in a dry paddy field. They record a vertical displacement of up to 10 cm and lateral shift of about 50 cm.

At the village of Puru, a larger landslide occurs just below the road on 2-4 m thick colluvial soil and bedrock. The slide is about 50-70 m long, 50 m wide, and has a straight failed slope. Its runout path is about 600 m long. The slide is actively expanding upwards due to the presence of a stream and steep topography. The landslide area is surrounded mainly by cultivated land with some forest cover and grassland near the stream.

The tension cracks in the crown are 5-7 m away from the main scarp.

At a small village of Pyang Gaun, the runout debris from a rockslide reaches a stream. The debris comes from a scarp located at the top of a hill, about 1 km away from the stream. The debris consists of quartzite and schist boulders of up to 1 m in diameter. It is accumulated in the channel of the stream, whose both banks are cultivated. Highly jointed rock and steep slope are the main causes of sliding.

A numbers of reactivated landslides are located just below the village of Lawadung, to the north of a high school. They are mainly wedge failures, the main portion of which lies in the forest, but their crown reaches the cultivated land. The runout from them continues for about 500 m and damages the cultivated land. This landslide-affected zone is about 300 m wide in the east–west direction.

About 100 m east of Tipling Thulo Gaun, a fresh, shallow rock fall is about 5 m long and 10 m wide and its runout path is about 200 m long. The rock fall begins from the upper part of slope and it consist of highly jointed (at least 3 sets) garnetiferous schist. The foliation strikes 220 degrees and dips 50 degrees due north. The slide is surrounded by paddy field and the area is dry. The clasts in the landslide debris range from a few centimetres to 1 m. A trail, connecting the northern villages to Tipling Thulo Gaun, passes through the depositional part of the rock fall.

About 50 to 60 m eastwards from Tipling Thulo Gaun, a rock fall-rockslide (**Fig. 11**) occurs on the cultivated land of stepped topography. The shallow slide was formed on a straight slope with an angle of 70-80 degrees. The landslide begins from the upper part of slope and there are 2 or 3 tension cracks in the crown. The active slide is 15 m long and up to 60 m wide with more than 200 m of runout distance. The bedrock is represented by garnetiferous schist with colluvial soil cover, having a thickness of up to 1 m. The landslide is surrounded by cultivated land with temporary cowsheds. Most of the failed zone is dry but a spring is present in its depositional part.

In the vicinity of Hindung, a few rockslides occur on the upper part of a west-facing hill slope. The runout from these failures can reach the village. Another rockslide is situated near the primary school of Hindung. There is one more rockslide just below the main village. An erosive gully (or runout), originating from the upper slide, passes through a stream and affects the village (**Fig. 12**).

At the village of Newor in the Latap VDC, a rockslide occurs on the mid hill slope and passes through the settlement. Its runout length is approximately 500 m and width is 40-50 m. After the earthquake, the houses are relocated to the paddy field, lying to the south, at a distance of about 200 m from the main Newor village and about 200 m above it.

Two rockslides are located about 200 m southwards from the Sertung village, on the north-facing hill slope. Out of them, one is a reactivated slide and the other is a fresh failure with 1-2 m deep topsoil. Though the landslides lie mainly in the forest, both the crown as well as runout from them is in the paddy field. The failures affect the main settlement of Sertung, consisting of more than 200 houses. In the upper part of the slide, there are a number of tension cracks in the paddy field up to 10 m away from main scarp. The tension cracks record a lateral displacement of 60 cm and a vertical drop of 50 cm (**Fig. 13**). Presently, the flat area above the crown is dry, but it will be wet during the paddy cultivation in the rainy season. The natural slope below the slide is about 25 degrees; the slope on which the slide has developed is about 70 degrees.

A rock fall is observed on a barren land composing the west-facing uphill slope of the Gobregaun village in the Sertung VDC. The Borang–Sertung trail crosses the fall, which is about 30 m long and 20 m wide, and its failed slope angle is about 80 degrees (**Fig. 14**). The runout from the fall has travelled for more than 300 m and it may even reach a distance of 1000 m. Here, the bedrock consists of garnetiferous schist, the foliation of which strikes 285 degrees and dips at an angle of 45 degrees due north. The rock has three perfect joint sets.

The steep western slope of the Kapurgaun village in the Latap VDC suffers from rock falls, located at a distance of 60-70 m. Many wide tension cracks are also observed near the crown of the fall. In the past, there were some rock falls, which were reactivated significantly by the Gorkha earthquake. Due to the fall, the houses were relocated at a nearby safer place. In this rock fall zone, especially in its upper section, there is a high probability of failure in the upcoming monsoon season.

A rock fall-rockslide occurs about 500 m south of the Rannen village in the Jharlang VDC, along the Dundure–Borang trail. The length of landslide is 30 m and width is about 25 m. Open-jointed and medium-banded schist is present in this area. The size of boulders reaches 2 m and they have travelled down to the Ankhu Khola, lying at a distance of about 300 m.

A number of slides and falls are present on both banks of the Lisne Khola in the Jharlang VDC, where the clast size is up to 5 m. The debris has moved up to the Ankhu Khola (**Fig. 15**). A large fan is formed at the influence of the Lisne and Ankhu Khola. The fan has damaged the powerhouse of a micro hydroelectric project. These landslides affect the road as well as a suspended bridge.

Fig. 7. Rock fall damaging a building at Khorlabesi. View to W.

Fig. 8. The dip slope with a large failure reaching the school of Tawal. View to NW.

Fig. 9. A general view of Kichet from the southeast. Note many shallow sides and falls on steep rocky slopes. View to NW.

Fig. 10. A large wedge slide at Gangmrang. View to NW.

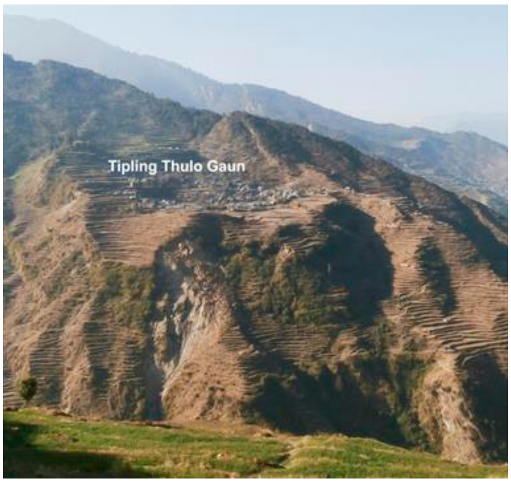

Fig. 11. Rock fall and rockslide below Tipling Thulo Gaun. View to NW.

Fig. 12. Rockslide with gully erosion on Hindung village. Source: Soil Conservation Office, Dhading.

About 50 m long, 30 m wide, and 3 m deep, colluvial soil slide is located approximately 40 m above the Ankhu Khola, at the lower end of the Chyamthali village in the Jharlang VDC. The slope is west-facing and its dip is about 50 degrees. The slope is cultivated and partly saturated with water. A house lies very close to the right flank of the slide. Above the crown, there are a number of tension cracks with a vertical displacement of 5-7 cm and lateral shift of 10-50 cm. The runout from the slide has reached the Ankhu Khola.

Near the Kalmrang village in the Jharlang VDC, along the road section, rock fall and rockslide are present. Their runout has reached the Ankhu Khola. The length of the landslide is about 200 m and width is 30-35 m, and in the displaced mass, the clast size is up to 1.5 m. Highly jointed schist is exposed on the southwest-facing steep slope. About 15 m above the main scrap, another scrap is developing. A house lies on the right flank of the landslide, and the road between the two scarps is damaged. Most of the area is dry.

From the Kalmrang village lying on the left bank of the Ankhu Khola, a rockslide is observed on the opposite bank of the river, about 300 m above the village of Richet in the Ri VDC. The village is essentially north-facing and the constituent slope dips at an angle of about 40 degrees, whereas the failed slope is steeper (about 60 degrees). The village of Tajumrang is located on the eastern slope and is about 100 m away from the main landslide scarp. Between the main landslide scarp and settlement, there is a forest as well as a cultivated land. The landslide is 50-60 m long and 30-40 m wide. To the uphill side from the Ankhu Khola, towards Tajumrang, there is a large rock fall zone (**Fig. 16**).

About 60 m long and 30 m wide soil slide occurs at the village of Singan in the Dharkha VDC. The size of clasts in the landslide reaches 1 m. The slide occupies the right bank of the stream (Rangsel Khola) and it has damaged the cultivated land and a trail.

At the Dharna village in the Dharkha VDC, an old reactivated rock fall – rockslide is observed. The slide is about 150 m long and 50 m wide. In it, the clasts are up to 1.5 m in size. The debris from the slide has travelled for about 500 m and reached the river. A road passes through the middle portion of the slide. The slope around the slide is covered by grass and forest. The landslide is saturated with water, as a stream is flowing through its central part (**Fig. 17**).

From approximately 300 m uphill side of the Dharna village in the Dharkha VDC, a number of rock falls are bringing down boulders of up to 6 m in diameter. Another landslide is positioned roughly 200 m west of the road to Dharna. It is about 100 m long and 30-40 m wide. Since headward expansion of the slides continues, the settlement of Dharna is at a high risk of failure, as it is located just at a distance of 60-70 m from the landslide head scarp. A large portion of the village is already situated on an old landslide containing a colluvial soil with large (up to 5-7 m in diameter) boulders. The slide is surrounded by forest and barren land.

Many soil slides occur at the village of Lapang in the Tripureshwar VDC. The slides are distributed along the Lapang Khola, nearly 50 m upstream from its confluence with the Ankhu Khola. In this area, the colluvial soil is 3 to 5 m thick and the landslide zone is 30 to 50 m long, 180 m wide, and its failed angle is about 70 degrees. The slides affect the Lapang–Dundure road and adjoining forestland. A suspended bridge is situated just below a plane soil slide. There are also many other smaller landslips on the river terraces and they also damage the road. The slope face dips at an angle of about 52 degrees and the bedrock, consisting of thin- to medium-banded phyllite, gently dips due south.

In the vicinity of Lapang, the Lapang Khola makes a gorge, where rockslides and falls occupy its both banks. Due to them, 3 houses were relocated. On the left bank, about 5 m long and 2 m wide plane rockslide is present, and the debris from it has reached the riverbed (30 m from top). Close to the riverbed, the lower river terrace is converted into a paddy field. Steep slope and highly jointed rocks are the main triggering factors of this landslide.

3.3 Rasuwa district

On the left bank of the Bhote Koshi River (**Fig. 18**), near the Friendship Bridge, more than 300 m high and about 50 to 100 m wide rock fall destroyed many office as well as private buildings, killed about 30 people, and blocked the road to Rasuwa Gadhi for several months.

The office building construction site of the Rasuwa Gadhi Hydropower Project is located on the left bank of the Ghatte Khola and the Bhote Koshi River. It is stretched along the foothill of a large rock cliff with talus cones (**Fig. 19**). This area suffered from severe rockslides and rock falls, which significantly damaged the five buildings under construction. Many large boulders and debris came down periodically during the main shock as well as aftershocks from about 400 m high cliff lying immediately southeast of the building site. Much of the material also came down when a series of rainfall events hit the area. The boulders destroyed roofs, columns, and ground floors of the buildings.

The earthen road leading to the two portals of valve chamber and access tunnel was severely affected by the earthquake and rainfall. The road was constructed on a wide colluvial and alluvial fan with large quartzite boulders. Presently, the road is severely damaged owing to its cut slope failure. Two portals are located within the rock fall zone from about 150 to 200 m above a rock cliff and gully (**Fig. 20**). Though most of the debris has already reached the base of the slope, about 25 % of it is still remaining there.

The beautiful Langtang Valley, lying at an altitude of about 3400 m, is the third most popular trekking destination in Nepal. At Ghodatabela, at an altitude of

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Fig. 13. Rockslide above Sertung village.

Fig. 14. Rock fall affecting the trail above Gobregaun village.

Fig. 15. The village of Richet. The large rockslide of Jharl-ang is seen in the background. View to E.

Fig. 16. Some large rock falls and rockslides at Richet and Tajumrang villages. View to W.

Fig. 17. Dharna colluvial slide affecting Dundure-Dhading Besi road.

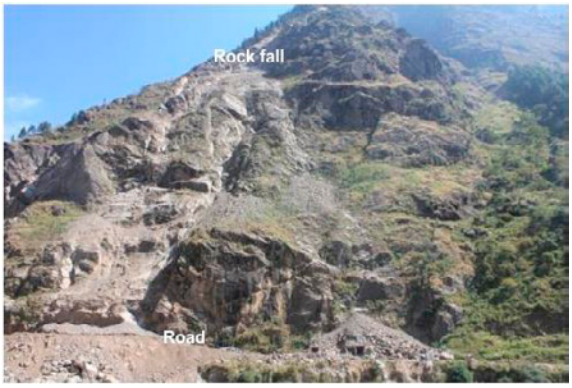

Fig. 18. Massive rock fall near the Friendship Bridge of Rasuwa Gadhi. View to NE.

about 3011 m, rock falls and slides are very common and the area lies in a high hazard zone (**Fig. 21**).

In the Lama Hotel area, the rock falls have also affected the main building, causing a huge loss of property. There are large boulders that hit the hotel during the avalanches.

The Langtang village was located below a very steep ridge, and above it is a glacier towards the northwest and a large snow field right above the village. A mixture of snow, ice, and debris, which originated at the snowfields on the slopes above Langtang, suddenly fell into the Langtang River as an avalanche and buried the village (Shrestha et al., 2016; Lacroix, 2016). The buried area occupies about 0.5 sq km. The extent of damage incurred in this area can be surmised by examining the buried Langtang valley and the river channel (**Fig. 22**). The wind blast during avalanching ripped and uprooted trees and aligned them in the direction of blow.

Fig. 19. Buildings of Rasuwa Gadhi Hydropower Project damaged by rock fall. View to E.

Fig. 20. Rock fall entering the area surrounding the valve chamber and severely damaged road on the talus cone below the portals. View to SW.

Fig. 21. Rock fall at Ghodatabela**.**

Fig. 22. Buried Langtang village. View to NE.

A large landslide occurs at Thulo Haku, near a school. The slide moves on the residual soil that is about 3 m in thick. Besides landsliding, gully erosion is another severe geological problem in the Haku village. The gully is approximately 2 km long and it comes from the upper part of the village and confluences with the Trishuli River. Most of the cultivated land has been affected by gully erosion. Many cracks are present in the cultivated land in the vicinity of gully, where erosion is intense. In the gully, pelitic schist is exposed at a number of places and it is covered by 1 to 10 m thick residual or colluvial soil.

The large and actively moving deep-seated slides at Grang, Mulkharka, and Ramche were not much affected by the earthquake (**Fig. 23**).

The Trishuli River valley below the Mailung Khola confluence was devastated by many coseismic failures (**Fig. 24**), such as rockslides, debris slides, and rock falls. At the weir of the Trishuli 3A Hydroelectric Project, on the left bank, two debris cones, about 30 m wide and about 10 m high (upper) and about 15 m wide and 7 m high are positioned. The debris contains boulders of gneiss, fine-grained augen gneiss with well-developed lineation. The boulder size ranges from 10 cm to 4 m in diameter. The material has come down from about 100 to 150 m above the riverbed (**Fig. 25**). The upper part of the failed slope is steep (40 to 45 degrees) and its middle part is gentle (25 to 30 degrees). Then, there is a cliff of about 40 to 50 m height. The rock fall came mainly in the monsoon period.

The uphill slope of the desander area contains large (1 to 5 m) angular gneiss boulders, some are old and others are newly brought down by the earthquake. Mainly wedge failures (with vertical joints) are prominent.

Fig. 23. Actively moving deep-seated landslide at Ramche. View to N.

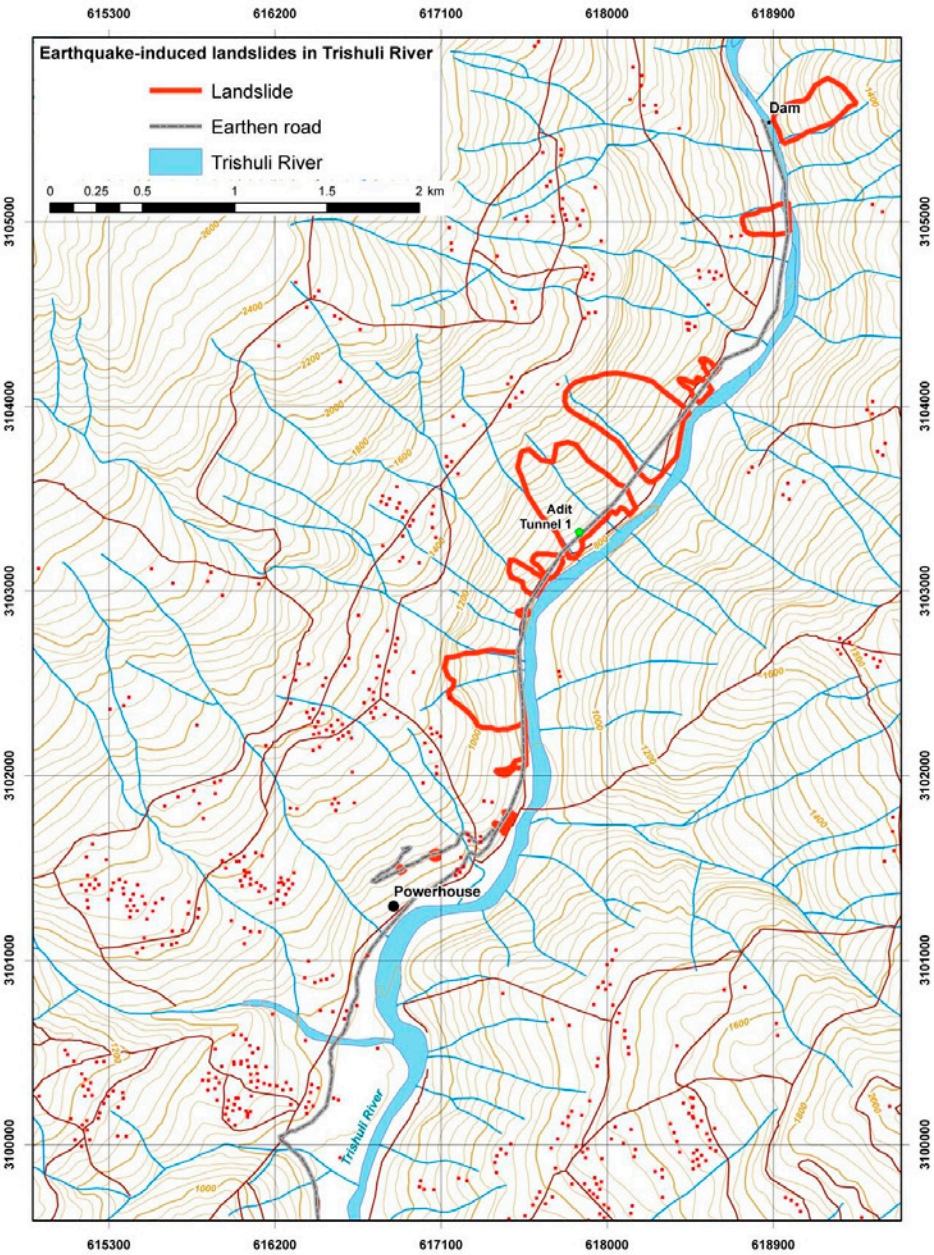

Fig. 24. Earthquake-induced landslides on the earthen road through the right bank of the Trishuli River.

At the village of Bhorle, soil slides, gully erosion, and rock falls are prominent. Most of the landslides occur on the banks of the Phalakhu Khola. Almost all landslides have affected the cultivated land. At their crown, the cultivated land has subsided by a few centimetres, indicating continued movement. A landslide is located on the right bank of the Phalakhu River. The main lithology of the area is an alternation of pelitic schist and psammitic schist.

At the Gairigaun village, soil slides and gully erosion have destroyed the cultivated land. Besides, rock falls are prominent on the banks of the Phalakhu Khola. They lie far away from the settlements, but destroy the cultivated land situated in the vicinity of the crown. At the Kaphali village, a rockslide is damaging the cultivated land (**Fig. 26**). However, the settlement is not affected by the failure.

3.4 Sindhupalchok district

In the Bhote Koshi watershed of the Sindhupalchok District, many shallow and long slides (**Fig. 27**) were formed by the earthquake. The right bank of the Bhote Koshi River west of Chaku is made up of grey, massive, calcareous quartzite. The vertical joints in the unstable

Fig. 25. About 150 m high rockslide-rock fall with a large talus cone on left bank of Trishuli River. View to E.

Fig. 26. Rockslide near Kaphali village. View to NE.

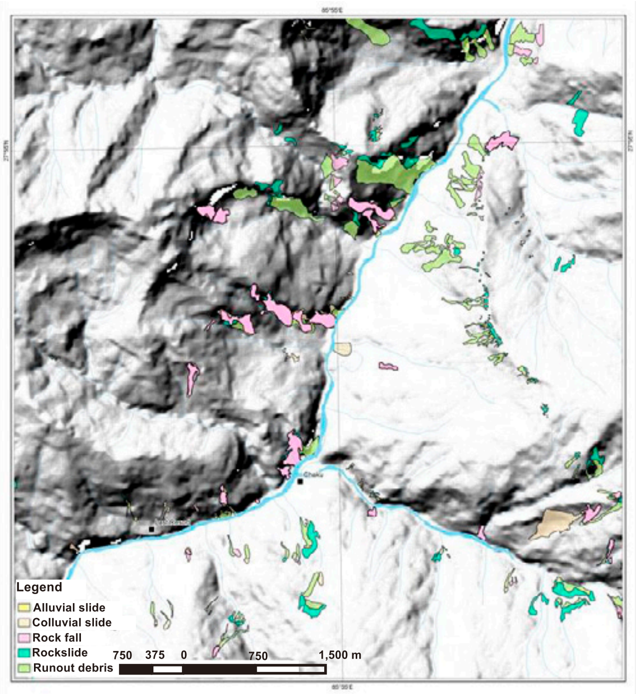

Fig. 27. Details of earthquake-induced slides developed in the vicinity of Chaku in the Bhote Koshi watershed.

Fig. 28. Cliff south of Chaku, where Arniko Highway is suffering from rock falls. View to N.

Fig. 29. Rock falls and shallow slides developed above the Upper Bhote Koshi Powerhouse. View to SE.

rock cliff trigger rock falls or topples and frequently obstruct the Arniko Highway (**Fig. 28**) passing through the left bank.

There is a few hundred meter-high rock cliff (monocline) between the village of Khokundol and the Upper Bhote Koshi powerhouse (**Fig. 29**). The Khokundol Khola is flowing along the strike of bedroIts left bank has suffered from many dip-slope failures and wedge slides that have transferred to rock falls at the road level. These earthquake-triggered slides have originated from the upper edge of the slope.

On the left bank of the Khokundol Khola, a large plane failure is positioned on white fine calcareous quartzite with a subordinate amount of grey dolomite, crystalline limestone, black graphitic schist, and garnet schist. Boulder size in the rockslide ranges from 10 cm to 5 m. On the right (west) bank of the Bhote Koshi, the dip slopes of Duguna Gadhi have many superficial slides.

The crown of the rock fall zone (**Fig. 30**) above the Upper Bhote Koshi Hydropower project is represented by fine- to very-fine grained white to yellow quartzite and calcareous quartzite with blue-grey to black schist bands. The upper, about 20 m thick, band is predominantly of quartzite. About 25 m north, the quartzite has open (2 mm to 20 cm wide) and irregular joints. The right bank of the Bhote Koshi River, just above the dam of the Upper Bhote Koshi Hydropower Project, has a large alluvial fan resulting from a distant rockslide on the dip slope. It is an old fan (formed before 1987), which is now reactivated owing to rock sliding on the upper slopes of the mountain, from where the boulders of schist and quartzite are moving into a gully.

The large deep-seated landslides of Daklan (**Fig. 31**) and Kothe did not show any signs of reactivation by the earthquake.

3.5 Dolakha district

The earthquake triggered shallow mass movements in the Tama Koshi watershed, especially between Charikot and Lamabagar. Most of them were similar to those observed near Sundrawati (**Fig. 32**). Like in other districts, the old soil slides and debris slides were not affected much by the earthquake. For example, a large debris slide at Km 10+500 m of the Upper Tama Koshi Road (**Fig. 33**) was insensitive to the quake. A weathered garnet schist is exposed on both ends of the soil slide. At this place movement was severe in the monsoon of 2012, and about 50 m length of road was damaged, as it was subsided for more than 5 m and shifted laterally for more than 12 m.

The village of Singati was impregnated by rock and debris falls (**Fig. 34**). A shallow but relatively wide wedge slide lies on the left bank of the Tama Koshi River, south of the Tinkhu Khola confluence (**Fig. 35**). It is an old failure reactivated by the earthquake and subsequent monsoon rain. On the left bank of the Tam Koshi River, just upstream from the Gongar Khola, a long rockslide-rock fall forms a large talus deposit. It is an old slide reactivated by the earthquake.

3.6 Ramechhap district

The effect of earthquake on hill slopes diminished significantly in the Ramechhap District, and only some minor failures and tension cracks resulted. The rockslide scarp below the Lower Hanba village is about 25 to 30 m high and its crown contains open joints and cracks. The landslide debris includes many large (2-3 m in size) boulders. The cracks are from 1 to 5 m long and 10 to 50 cm wide. About 75 m north of the above failure, another wedge slide contains boulders reaching 50 cm to 1 m in diameter. Further up the spur, there is a tension crack about 50 m long, 20 to 40 cm wide, and 1 to 2 m deep. This crack may trigger failure (rock fall, rockslide) during the monsoon period. Some large (1-2 m) cubic boulders are overhanging. The boulder fall during the earthquake has hit several pine trees lying about 75 m below the cliff.

About 150 m long, 10-15 cm wide, 0.5-2 m deep, and 10 cm vertically displaced tension crack was generated by the earthquake of 12 May 2015 in the gentle slope northeast of Pipaldanda. An old rockslide (**Fig. 36**) lies south of Pipaldanda and west of Gogane. Another tension crack is seen in the crown of the old slide consisting of residual soil and weathered gneiss. The crack is 5 mm to 30 cm wide. Most of it is an old crack, which was partly widened by the quake. In the nearby spur with gentle slope covered by pine forest, about 150 m long tension crack is developed in the residual soil and colluvium. The crack discontinues towards the east, i.e., near the old landslide scarp, but becomes extensive to the west. The main crack is 5 to 10 cm wide and has slipped by about 10 cm towards the downhill.

4. Causative factors

The coseismic mass movements are distributed neither symmetrically nor densely around the highest peak ground acceleration value (**Fig. 1**). An overwhelming majority of them is concentrated mainly towards the adjacent northern steep and high upper mountain slopes. During an earthquake, the transient strong ground motion produces a force imbalance within the variety of materials composing the hill slope, and the occurrence of coseismic landslips is directly influenced by

Fig. 30. Open joints in pale yellow to white calcareous quartzite exposed at the crown of the rockslide and rock fall zone lying about 300 m above the riverbed. View to NW.

Fig. 31. Deep-seated landslide of Daklan affecting Arniko Highway. View to S.

Fig. 32. Many shallow slides reactivated by the earthquake at Sundrawati, close to the Upper Tama Koshi Road. View to N.

Fig. 33. A large soil slide at Km 10+500 of the Upper Tama Koshi Road. The slide was not much affected by the earthquake. View to W.

Fig. 34. Rock and debris falls from the south-facing slope of Singati. View to N.

Fig. 35. Wedge slides and rock falls on the left bank of the Tama Koshi River, south of the Tinkhu Khola confluence. View to S.

such seismic loading. Though the intensity of earthquake decreases as the distance from epicentre increases, the landslides are distributed rather uniformly throughout a stretch of about 150 km in the northwest-southeast direction. Therefore, together with ground shaking, other causative factors, such as geology, geomorphology, and hydrology of the region also contributed significantly to the development of coseismic slips.

Geology strongly affects the occurrence of instabilities in a region. Lithology controls the distribution of landslides, as different compositional units have varying physical and chemical properties, including weathering intensity as well as bedrock fracturing and jointing. The earthquake-affected area consists mainly of resistant metamorphic rocks, such as gneisses, quartzites, schists, and marbles belonging to the Higher Himalayan Crystallines or the Kathmandu Complex. They constitute the hanging wall of the Main Central Thrust and are resting over the slates, dolomites, limestones, and phyllites of the Lesser Himalayan Sequence or the Nawakot Complex. The Gorkha Earthquake occurred very close to the Main Central Thrust, and most of the aftershocks were also distributed in its vicinity. The Great Midland Antiform (Hagen, 1969; Dhital, 2015) is a regional-scale fold passing through the earthquake-affected area. Since the Gorkha earthquake and its major aftershocks were distributed close to this fold, it can be considered to be an important structure controlling the

Fig. 36. Reactivated landslide at Pipaldanda. View to NNE.

propagation of rupture and the occurrence of coseismic mass movements.

In the six districts, most landslides occurred on steep upper valley slopes of the hilly terrain, while the gentler lower slopes suffered from very less or no failures. Landslide occurrence in an area is strongly dependent on the slope gradient, as the increase in gradient causes the increase in the level of gravity-induced shear stress in the hill slope materials, thus making them prone to failure. The high internal relief facilitated seismic wave amplification and generation of falls and slides on long spurs and ridges.

Since most of the landslides are confined to river valleys, the major drainage system was also one of the influencing factors. The river constantly erodes and steepen its banks, and saturates the ground lying within its vicinity.

Some anthropogenic factors also seem to be played a role. The haphazard construction of earthen roads on mountain slopes modifies the natural hill slope and exposes the cut slope to weathering and degradation. Also, such construction deviates the natural course of streams or gullies and also modifies the direction as well as amount of runoff and groundwater flow.

5. Conclusions

The 25 April 2015 Gorkha earthquake and its many strong aftershocks triggered off more than 4000 landslides. The investigated districts of Gorkha, Dhading, Rasuwa, Sindhupalchok, Dolakha, and Ramechhap suffered from rock falls, debris falls, rock slides, and debris flows caused by the Gorkha earthquake and subsequent summer monsoon. The damage was confined mainly to steep mid and upper slopes, high and long rock cliffs, and erosive gullies with fractured rock or colluvium. The slides were, narrow, but long and shallow (less than 5 m). It is remarkable that the deep (more than 50 m), old slides were not affected by the earthquake. For example, the landslide of Mulkharka and Ramche in the Rasuwa District, a few kilometre-wide and more than 50 m deep slides at Kothe and Daklan on the Arniko Highway, and the soil slides on the Tama Koshi Road were not reactivated by the quake. Despite many concerns and inferences, regarding the occurrence of earthquake-triggered landslide dams, there were just a few of them. Except the devastating Langtang rock and snow avalanche, the remaining of the landslide dams were either very short-lived or they only partially dammed the flow.

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