DEPARTMENT OF GEOLOGY AND MINES
MINISTRY OF ECONOMIC AFFAIRS

Integrated Geo-Hazard Risk Assessment of Critical Landslide at Box-Cutting, Gelephu-Zhemgang Highway, under Sarpang Dzongkhag

Department of Geology and Mines

Field Season: 2015-2016

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ABOUT DEPARTMENT OF GEOLOGY & MINES (DGM)

Established in 1981 as Division initially and upgraded later to department, Department of Geology and Mines under Ministry of Economic Affairs is the only geo-scientific institution in the Kingdom of Bhutan mandated to carry out and manage geo-scientific and mining activities. Currently, the mandates of the department are fulfilled through four divisions namely: (1) Geological Survey Division; (2) Earthquake and Geophysics Division; (3) Mineral Development Division; and (4) Mining Division.

Contact Address: Department of Geology and Mines
Ministry of Economic Affairs
Royal Government of Bhutan
Thimphu: BHUTAN
P.O. Box: 173
Telephone: +975-2-323096
Web: www.moea.gov.bt

ABOUT THIS REPORT

This report is in accordance with the work plan of the Department of Geology and Mines, MoEA under the National Adaptation Programme of Action II (NAPA II) Project titled *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by GEF-LDCF through UNDP and implemented by RGOB.

Report prepared by:

Jamyang Chophel, Senior Engineering Geologist
Jampel Gyeltshen, Senior Survey Engineer

Reviewed by:
Ugyen Wangda, Chief Geologist
Tashi Tenzin, Project Manager, NAPA II Project, DGM

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Comments and inquiries on this report can be emailed at: jchophel@moea.gov.bt or tashit@moea.gov.bt

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Department of Geology and Mines
Ministry of Economic Affairs
Royal Government of Bhutan
Thimphu

Forward

Located in the eastern part of the Himalayas, the Kingdom of Bhutan is a small landlocked country between India and China. Being a part of young (ca. 55 million years) fold-thrust Himalayan mountain belt, more than 90 percent of the country's area is topographically rugged and geologically very fragile. In the foothills where rainfall is heavy during monsoon, the occurrence of landslides is significant. In recent years, landslide related risk to lives, livelihoods, infrastructures, properties and environment in the country is on rise because of intense and erratic rainfall pattern most likely induced by climate change and interactions of human activities with the nature.

Thus as an intervention to reduce risks associated with climate change induced landslide geohazard, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs (MoEA), Royal Government of Bhutan (RGoB) has carried out the following two key activities under Outcome 1 and Output 1.3 of Second National Adaptation Programme of Action (NAPA-2) Project themed *'Addressing the Risks of Climate-Induced Disasters through Enhanced National and Local Capacity for Effective Actions*, funded by Least Developed Countries Fund (LDCF)-Global Environment Facility (GEF) through United Nations Development Programme (UNDP) and RGoB implementing partner National Environment Commission (NEC) between 2014 and 2017:

1. Integrated geohazard risk assessment and mapping of four critical landslide or landslide affected areas viz.: (1) Moshi landslides and (2) Arong/Lamsorong landslide on Samdrupjongkhar-Trashigang highway; (3) Box-cutting landslide on Gelephu-Zhemgang highway; and (4) Barsa watershed under Phuntsholing Dungkhag, Chukha Dzongkhag; and

2. Landslide monitoring and threshold development of six landslides namely: (1) Moshi landslide, (2) Arong/Lamsorong landslide, (3) Box-cutting landslide, (4) Tshimatsham

Tel: +975-02-322879,323096,323349,323409,324118, Fax: +975-02-323013,326134,324193,339845
P.O.Box No.173, Email:dgm@moea.gov.bt, URL:http://www.moea.gov.bt

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Thimphu

on Phuentsholing-Thimphu highway under Chukha Dzongkhag, (5) Reldri landslide under Phuentsholing Thromdey, and (6) Lem landslide, Phongme Geog under Trashigang Dzongkhag.

The goal and objectives of these studies were to: (1) map and assess the four critical landslide affected areas using geo-scientific methods to provide findings and recommendations on suitable mitigation measures (both long term and short term); (2) monitor landslides using geoscientific methods to understand the movement behaviours and record landslide events; (3) develop rainfall thresholds for landslide initiation in the selected monitoring sites; (4) forecast or issue landslide warnings in regions with similar geological and topographical conditions through National Weather and Flood Forecasting and Warning Center (NWFFWC); and (5) share findings and recommendations of these studies with relevant users (national, district, local government, and others) for awareness and importantly for incorporation of the mitigation measures in their plans and implementations for reduction of risks associated with landslide geohazards.

In this regard, DGM on behalf of the Ministry and RGoB is pleased to publish the reports and maps for the four-critical landslide affected areas and six landslide monitoring sites in the country, whose findings and recommendations were shared to the relevant stakeholders during the two-day workshop held at Phuentsholing from 13-14, November 2017.

On behalf of the department, I acknowledge the effort put into publishing these reports and maps and I am hopeful that these documents will be useful to the relevant stakeholders who are responsible in dealing with risks associated with landslide in the study areas.

(Phuntsho Tobgay)
Director General

Tel: +975-02-322879,323096,323349,323409,324118, Fax: +975-02-323013,326134,324193,339845
P.O.Box No.173, Email:dgm@moea.gov.bt, URL:http://www.moea.gov.bt

EXECUTIVE SUMMARY

Box-Cutting landslide in south-central Bhutan, located about 8 km towards Zhemgang from Gelephu, is one of the landslides that poses high-risk to Gelephu-Zhemgang national highway and its commuters. This highway is a strategic highway for transportation of foods and goods, and business and economic activities for thousands of people living in central Bhutan. As as an intervention to climate-induced geologic hazards, the Department of Geology and Mines (DGM) under the Ministry of Economic Affairs (MoEA) has carried out integrated geohazard risk assessment and mapping of this landslide in the fiscal year 2015-2016, as a part of second National Adaptation Programme of Action (NAPA II) Project for climate-change, funded by Least Developed Countries Fund (LDCF)-Global Environment Facility (GEF), coordinated by Bhutan National Environment Commission (NEC) with support from United Nations Development Program (UNDP) under Outcome 1, Output 1.3 of the Project Document. The aim and objectives of this study were: (1) to understand the landslide characteristics; (2) determine the causes of the landslides; (3) to assess landslide hazards and risks in and around Box-cutting landslide, and (4) propose sustainable mitigation measures or solutions to reduce the risks.

Detailed engineering geological or geotechnical investigation show that the landslide falls within Manas Formation of Baxa Group comprising of mostly thin-bedded to laminated phyllite and intercalated with minor coarse-gained quartzite. The landslide lies within the active tectonic zone, near to MCT and the rocks are highly sheared and fractured, which has led to the weakening of rock mass. The rock mass classification also indicates that the rock mass is poor and weak. The study area lies within sub-tropical climate zone with relatively high precipitation, where maximum rainfall amount of around 7000 mm was recorded in 2004 and the minimum rainfall amount of around 4000 mm was recorded in 2002 and 2006, between 2002 and 2013.

The landslide area has the presence of water seepages both below and above the

highway, indicating that the area holds a significant volume of water or the area is highly water saturated. Electrical resistivity survey indicates a highly weathered and weak rock mass with significant water saturation at a depth of around 14 m from the surface. This landslide may, therefore, be classified as moderately deep-seated landslide as the rupture surface is located at around 14 m below the surface.

Landslide hazard analysis of around 6 km^2 area in and around the landslide using MCA model in GIS using both field data and spatial data obtained from stakeholders as input or causative factors for landslide delineated three hazard zones: (1) Moderately high hazard zone, (2) High hazard zone, and (3) Very high hazard zone. This analysis result show ~ 0.0023 Km^2 of the area as a moderately high hazard zone, ~ 1.2 Km^2 area as a high hazard zone, and ~ 1.6 Km^2 area as a very high hazard zone. Construction or development of the infrastructure is not recommended in high hazard zone to very high hazard zone. Around 0.35 km stretch of highway falls within the very high hazard zone. This model is validated using the conventional method of hazard analysis. Both methods show that the hazard level, in general, is relatively high within the slide and decreases away from the slide.

These methods identified two major risks in the area. The Gelephu-Zhemgang high way is directly exposed to the risk of the slide as the highway passes through the Box-Cutting rockslide. Considering the importance of this highway, the identified risk needs to be reduced with the implementation of mitigation measures. Another risk identified is artificial damming of Galechu in the downslope area by the materials of the slide, which in turn can cause an outburst of huge flood and thereby posing risk to lives and properties in the downstream areas. Therefore, failure time estimation is deemed important to mitigate the risk of damming of the stream flowing across the toe of the slide.

This study concludes that the Box-cutting landslide is most likely caused by: (1) weak geology, (2) erratic and heavy precipitation, and (3) steep topography, but aggravated by human activities such as the highway and poor drainage. Slope

Stability Analyses show that the factor of safety of is ~ 0.91 and/or ~ 0.87, indicating that the slope is not stable. The estimated unstable material in the slide area is around 350,000m^3. The unstable materials comprise mainly of residual soils, boulders and pebbles. The rupture surface of this landslide often run at the transition from weathered weak bedrock to competent bedrock, with a dip angle of about 40° to 50° in the landslide depletion area. This landslide transforms into debris flows, where debris slides into strongly convergent hill slopes or directly into headwater channels. In general, weathering of the fully exposed weak phyllite seems very fast, leading to high-frequency landsliding in the area. As not all landslides transform into fast and long runout debris flows, colluvium from older landslides forms a second important material that becomes mobilized by heavy rainstorms. The depleted volume remaining today in the source areas of the Box-Cutting landslide is a challenge to estimate as the volume of the current slide is observed to be a recurrent slide. The existing boulders and soil masses potentially be mobilized in the future by rainstorms, resulting in landslides.

This study also concludes that the effectiveness of the existing structural mitigation or countermeasures in the landslide to reduce risks are found to be low as their foundation is within the moving mass and therefore simply adding load to the moving mass. This study report, therefore, provides recommendations on proposed remedial measures or solutions in and around this landslide aimed towards better planning and implementation of remedial measures to reduce risks.

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1. INTRODUCTION

The risk of landslide and slope hazards are increasing with global climate change and increasing interactions of human activities with geological environment. The landslide risk is higher in mountainous countries like Bhutan and thus adaption to either climate change or reducing risk associated with landslide hazard is a serious challenge to developing country Bhutan.

Box-Cutting landslide in south-central Bhutan is one of the landslides that poses a high-risk to Gelephu- Zhemgang national highway and its commuters. This highway is a strategic highway for transportation of foods and goods, business and economic activities for thousands of people living in central Bhutan. Therefore, as an intervention to climate-induced geologic hazards, the Department of Geology and Mines (DGM) under Ministry of Economic Affairs has carried out integrated geohazard risk assessment and mapping of this landslide in fiscal year 2015-2016 as a part of National Adaptation Programme of Action 2 (NAPA 2) Project for climate-change, funded by Least Developed Countries Fund (LDCF) – Global Environment Facility (GEF), coordinated by Bhutan National Environment Commission (NEC) with support from United Nations Development Program (UNDP) under Outcome 1, Output 1.3 of the Project Document. The fieldwork was carried out for a duration of 75 days between 26th March 2016 and 10th June 2016.

1.1 AIM AND OBJECTIVES, OUTPUTS AND OUTCOME OF STUDY

1.1.1. Aim and Objectives

The general aim and objectives of this study were:

- to understand the landslide characteristics;
- determine the causes of the landslides;
- to assess landslide hazards and risks in and around Box-cutting landslide, and
- propose sustainable mitigation measures or solutions to reduce the risks.

This report particularly focusses on the addressing the following key questions:

- What type of landslide exists at (the northern part of) in Box-cutting? Explain type based on the observed displacements and structures of the rock mass.
- What are the causes of the movements and the potential triggers of future rock slope failures?
- How big are the potentially released rock/moving mass volumes from release area and what would happen in case of a large rock mass failure? Estimate runout distances and velocities.
- What are the temporal evolution and failure potential and when could a catastrophic failure happen?
- Recommendation of the countermeasures or actions required to reduce risk

1.1.2. Outputs

The study will generate maps and report that will: (1) help visualize and understand hazard and risks from the landslide, and (2) encompass recommendations on mitigation measures or solutions to reduce risks.

1.1.3. Outcome

The end goal is to share findings and recommendations of this study both at a national and local level for: (1) awareness, and (2) mitigation and disaster response planning and implementation to reduce risks of landslide hazards.

1.2 LOCATION AND ACCESSIBILITY OF THE STUDY SITE

Box-Cutting landslide is located on the Gelephu-Zhemgang highway under Sarpang District in south-central Bhutan (Figure 1). The study area lies on the right slope of the N-S trending Galechu valley that stretches down to the Gelephu hot spring. The very important Gelephu-Zhemgang highway runs through the unstable rock slope (locally known as Box-Cutting). In and around this area, rockslide and landslides are common, but the magnitude differs from each other depending on several factors. The study site is located at around 8 km from Gelephu towards Zhemgang with geocoordinates of an around N26.952°and E90.525° and can be easily reached. However, accessibility to the crown of the slide is difficult and observed as high-risk because of the high tendency for sliding of loose materials. For Box-Cutting rockslide, the crown of the slide lies at much higher elevation (around 713 m above msl), whereas, the toe of the slide lies at around 320 m above msl. Journey to the head scar is possible by foot walk for a few hours.

Figure 1. Location of the study area (Google Earth).

2. METHODOLOGY

To fulfil the aim and objectives of this study, the following methods were used to investigate the landslide area:

2.1. AVAILABLE DATA AND DESKTOP STUDY

Generally, documentation of landslides is very poor in Bhutan. However, Box-Cutting rockslide has gained media coverage as it poses risk to the travellers on the Gelephu-Zhemgang highway.

Desktop studies provide a preliminary, yet comprehensive, analysis of the operating environment to focus resources more accurately and efficiently. Desktop studies improve project efficiency and reduce costs by providing a clearer understanding of future challenges by identifying potential problem areas during pre-FEED and FEED that may have otherwise been overlooked. The desktop study includes investigation of the site through Google map, developing the sitemap and reviewing literature related to the landslide. During this study, marking of boundaries of the landslide on Google earth map including mapping of all other materials observed on the map were carried out. The team also planned a day to day work with the help of Google map. Reviewing of past reports like Phuentsholing Municipal Corporation study (Indra et. al., 2008) was also done.

2.2. ENGINEERING GEOLOGICAL MAPPING

Since the objective of the investigation is to understand the hazard and risk associated with the Box-Cutting landslide, detailed engineering geological mapping on 1:2000 scale was carried out. This mapping included: detail mapping of (1) different types of the soils and rocks, (2) sliding mass of the rockslide, (3) fractures and cracks of the sliding mass at the head scarp along the crown of the rockslide; (4) collecting detailed data set of the joints and fractures from both stable and unstable rock; (5) marking of the approximate boundary for the sliding mass on the map; (5) deducing the geological and tectonic setting; (6) carrying out Schmidt hammer test; (7) collecting random sampling of rock and soil from crucial locations for geotechnical laboratory to understand the geotechnical properties of the materials; and (8) two pitting within the slide to understand near surface soil and rock composition.

2.3. DETAIL TOPOGRAPHIC SURVEY

Topographical survey of the study area was carried out using total station TC307 and GPS. The topographical map was prepared in 1:2000 scale with 20 m contour interval using LISCAD and ArcMap software. The topography map was used as a base map to prepare engineering geological map, remedial or mitigation measures map, hazard zonation map using ArcMap.

2.4. GEO-PHYSICAL RESISTIVITY SURVEY

In the conventional array-oriented resistivity equipment, a known amount of current (I) is injected into the ground using the current electrodes and the corresponding voltage (V) is measured at the ground surface through the potential electrodes (Figure 2). Using the measured voltage (V) and a known amount of current (I), resistance (R) is calculated. Resistivity is computed using the formula P = K x (V/I), where K denotes the geometric configuration of the measurement array. The FlashRes Universal equipment used for the survey is a comprehensive array-oriented resistivity equipment whereby it can use all the electrodes simultaneously (expect two current electrodes used for current injection) to collect all surface potential data as shown in Figure 2.

The comprehensive array-oriented equipment collects much more data than conventional array-oriented ones and produces superior data collection speed and versatility. The default ZZ array of the FlashRes Universal resistivity equipment and the standard Wenner and Schlumberger array were used in the current investigation.

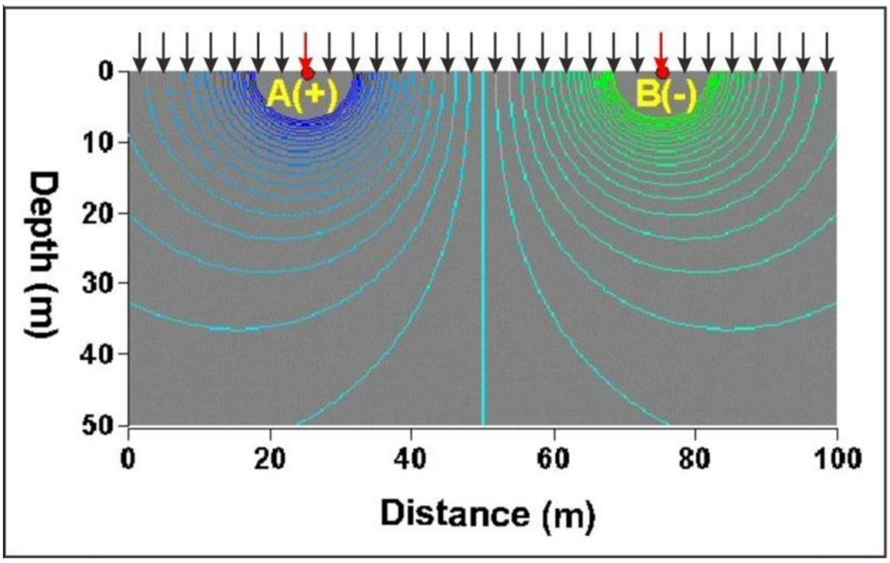


Figure 2. Schematic diagram showing the principle of the resistivity method.

2.5. Hazard and Risk Assessment using Conventional and Multiple Criteria Techniques in GIS

- Image interpreted and analysed the magnitude of landslide area from available data using a GIS technique. Land use Classification used feature class of land use data and updated the feature class of land use to the present.

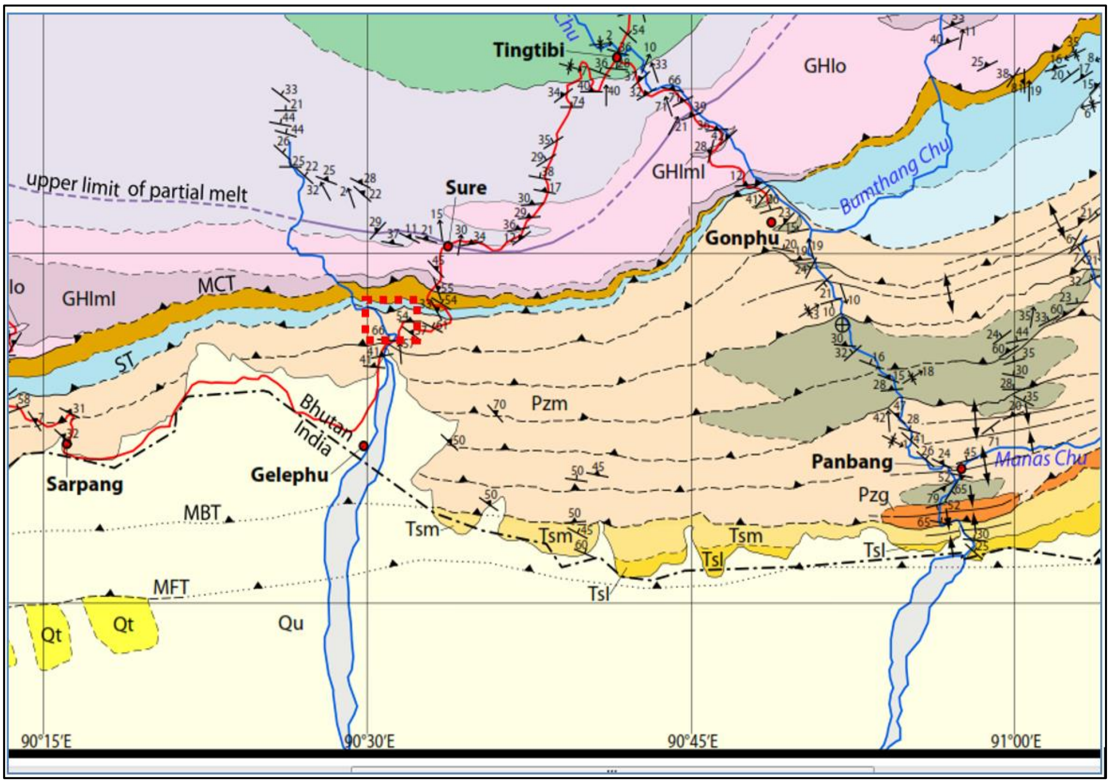
- re-weighing value of parameters. Compared magnitude of landslide area with hazard map. Analysed correlation between magnitude and 5 parameters (i.e. elevation, slope, land use, drainage and geology) used regression analysis of Pearson's correlation coefficient for the re-weighing value of parameters.

- The susceptibility zone around intermountain plateau was classed base on Multiple Criteria Analysis technique (MCA). There were 8 considering factors used in MCA; i.e. elevation, slope, soil, land use, drainage, geology, magnitude of landslide and rainfall, then used GIS technique for classification susceptibility.
- The conventional method for landslide hazard analysis is also done by field mapping, however, the input parameters used are similar to the Multiple Criteria Analysis Technique.

3. REGIONAL GEOLOGICAL SETTING

3.1. Regional Geology

The study area lies within the Manas Formation (Neoproterozoic-Cambrian) under the Baxa Group of Formation (Figure 3). It is composed of NW dipping, grey to white, medium to thick bedded, medium to coarse-grained, locally conglomeratic quartzite exhibiting common through cross-bedding, intercalated with dark grey to dark green, thin-bedded to thinly laminated phyllite (Bhargava, 1995).



Baxa Group

Pzph — **Phuentsholing Formation (age range uncertain; Neoproterozoic[?] or younger)** - Dark-gray to black, finely-laminated slate and phyllite, interbedded with thin- to medium-bedded, gray to tan limestone, thin-bedded, tan to dark-brown, fine- to medium-grained quartzite, and creamy gray dolostone (Bhargava, 1995; Tangri, 1995a). Maximum exposed thickness is ca. 2,250 m near Phuentsholing.

Pzm / dolo — **Manas Formation*** (Neoproterozoic-Cambrian[?])** - Gray to white, medium- to thick-bedded, medium- to coarse-grained, locally-conglomeratic quartzite exhibiting common trough cross-bedding, interbedded with dark-gray to dark-green, thin-bedded to thinly-laminated phyllite, and medium-gray dolostone (locally divided out) (Bhargava, 1995; Tangri, 1995a; Long et al., 2011A). Intraformational thrust faults indicate structural repetition of multiple, 1.5 to 2.8 km-thick thrust sheets (Long et al., 2011B). Lower greenschist facies (Gansser, 1983).

pCp — **Pangsari Formation (age range uncertain; Mesoproterozoic[?]-Cambrian[?])** - Dark-green to dark-gray, thin-bedded to laminated, locally talcose phyllite interbedded with white, pink, and green, medium- to thick-bedded dolostone and marble, and green, fine- to medium-grained, thin-bedded quartzite (Bhargava, 1995; Tangri, 1995a). Maximum exposed thickness is 2,400 m (Tangri, 1995a).

Figure 3. The regional geological setting of the study area (Modified after Long et al., 2011). Study area is shown by the red dotted box.

Intra-formation thrust faults indicate structure repetition of multiple 1.5 to 2.8 km thick thrust sheet (Long et al., 2011b). Highly fractured quartzite and phyllite lithologic contacts and foliation dip approximately 50-60° crossing the slope, kinematically favouring rock slope instability. The grey phyllite which forms the cliff above highway is rather highly fractured. In contrast, the inter-bedded layered of quartzite is observed to be relatively competent than host rock. The local discontinuity network is dominated by three steeply dipping fracture sets.

3.2. TECTONIC SITUATION OF STUDY AREA

The study site lies within the active tectonic zone, near to Main Central Thrust (MCT) and presents a slice of continental crust metamorphosed in the phyllite facies during the Hercynian. The tectonic situation of the area has been shown in Figure 4.

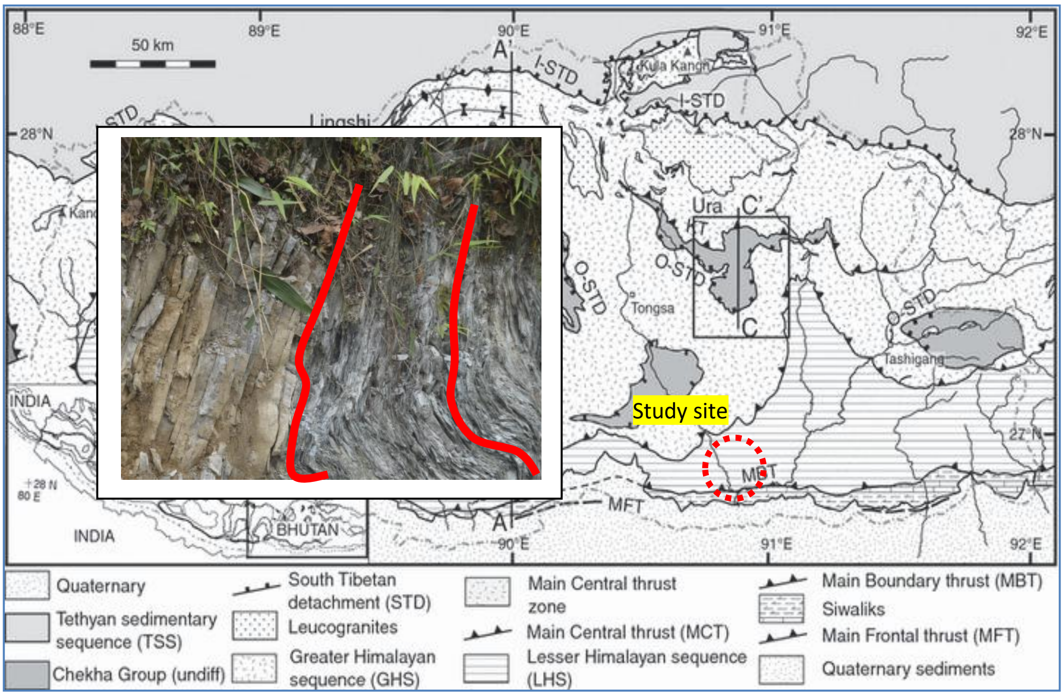


Figure 4. A general overview of the tectonic situation of Box-cutting slide (Modified after Kellett et al., 2009)

The tectonic situation can greatly influence the sliding of the rock and other natural disasters. Therefore, the knowledge of the tectonic situation of an area or region is important for the study of the landslide geohazard. In the study area, the tectonics has played the main role in being part of the factors for rock sliding events. The evidence for folding in the study area is observed and shown in the Figure 4. The rocks in the study area are highly sheared and fractured, which has led to a weakening of rock mass. These tectonic effects in rocks in long run has triggered huge rockslide in the area.

4. RESULTS AND DISCUSSIONS

4.1. FIELD OBSERVATIONS

4.1.1. Engineering geological mapping

During the site investigation in the rockslide area, the detailed mapping of tension cracks and the boundary of the sliding mass were carried out and shown on the Google map (Figure 5). The approximate boundary of the whole unstable and moving mass was also mapped. The largest opening is around 2 to 3 m wide and the smallest is around 1-2mm. The unstable and stable grounds are easily differentiated at the site as the cracks mark the boundary between these two areas (Figure 5).

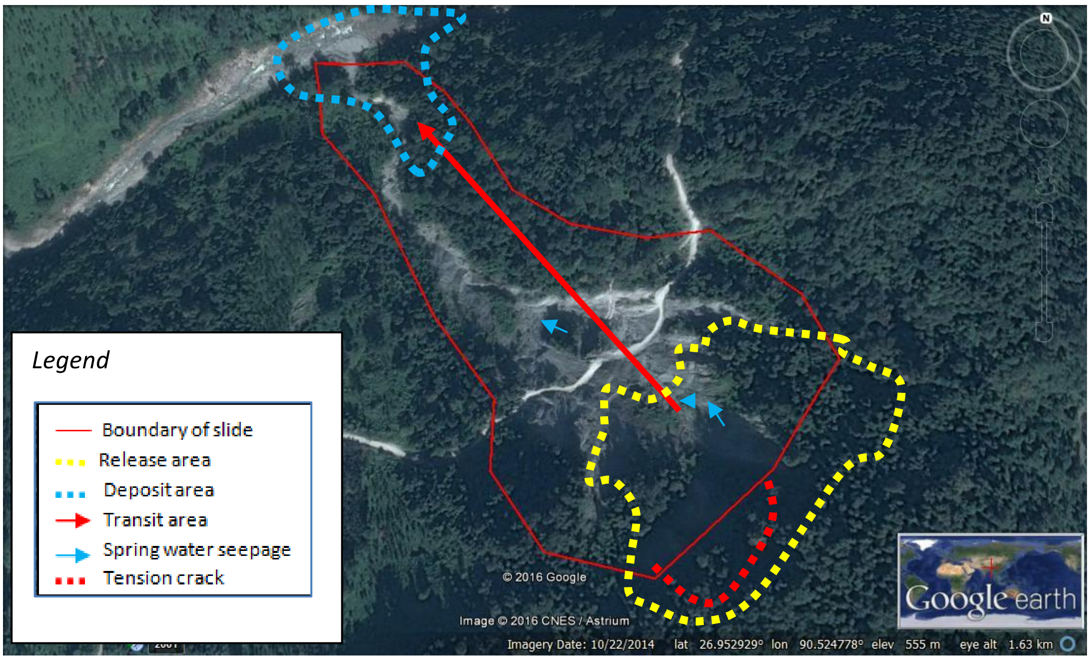


Figure 5. Engineering geological mapping of release area, transit area, deposit area, water seepages, tension cracks and boundaries of the slide (Google Earth).

In general, the sliding rock mass has been channelled as the material reached towards the toe of the area, but as the mass reaches to the toe the material has widely spread forming fan-like structure (Figure 6). The boulders are seen at the deposit area. The bedrocks are visible along the material flow. It is not easy to identify the types of the sliding when investigating from the toe of the rockslide. The toe of the rockslide joins with Galechu, where, the materials deposited are mostly eroded away.

Figure 6. Field photos showing the channel flow and deposit area.

At the head scrap of the rockslide, tension cracks with few mm to few cm openings are aligned in ENE to WSW orientation and unstable materials were observed (Figure 7). The tension cracks are mostly deep indicating greater depth location of sliding or rupture plane and thus estimating the depth to rupture plane and classification of slide type is a challenge in the area. This rockslide may, therefore, be classified as moderately deep-seated slide because of the rupture surface located a few meters below the surface.

Figure 7. Head scarp of the slide showing unstable materials and cracks.

The openings of the tension cracks measured at the different locations on the rockslide are shown in Table 1.

Table 1. Characteristic of the tension cracks in the study area.

Sl. No.	Spot/numbered spot on the map	Crack opening(m)
1	2	0.5-1.0
2	3	0.2-0.5

4.1.2. Hydrogeological observation

A small spring above the highway at the release area of the slide, at the head scarp and transit area of rockslide body, were observed (Figures 5 and 8). Generally, spring water flows out of the formation through contact of rupture surface, and therefore the outlets of several springs were mapped within the sliding area. The information on groundwater observation in the study is not available. In general, the study area receives a high amount of the rainfall for long period during monsoon and therefore it is expected that the groundwater table will increase drastically during monsoon season favouring the instability of the slope. The water seepages in the slide area are managed poorly facilitating the slope failure in the area (Figure 8). Thus, it is most likely that one of the main factors facilitating landsliding in Box-Cutting is high water saturation.

Figure 8. Small spring waters were observed within the release and transit area.

4.1.3. Rock mass Characterization

The rock mass characterization is one of the very important geotechnical means of understanding the properties of the rock mass and strength. The rock mass properties play a huge role in the failure of the slopes. In Box-Cutting area, the dominant rock types observed are talcose phyllite with inter-bedded with highly fractured quartzite. Detailed description of rock mass characterization of these rock types is discussed in this report in later sections.

4.1.4. Discontinuities

Failure of the rock mass is most often associated with discontinuities which act as pre-existing planes of weakness. The discontinuity denotes any separation in the rock continuum having effectively zero tensile strength and is used without any generic connotation. The discontinuity comprises of the joint, fractures, foliation plane, cleavage, bedding plane and faults. Therefore, the discontinuity can be one of the causative factors for the failure of the rock mass. In Box-Cutting area, stable mass is associated with dominate the other rock types, whereas, unstable mass characterized by loose and weak area is associated with phyllite.

Discontinuity in Quartzite

The four prominent joint sets were observed on the quartzite outcrop located above the unstable area (Figure 9). The attitude of the bedding plane of quartzite is 49/265.

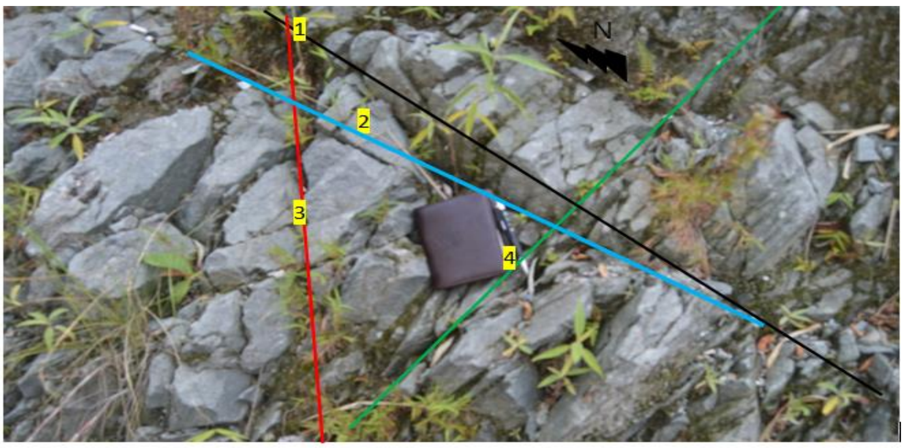


Figure 9. Outcrop of relatively competent quartzite bedrock showing four sets of joints.

The joint sets within quartzite have persistency of 2-3 m and high ranges of the spacing (10 mm to 1 m). The openings are filled with silt and small bushes at places. The quartzite bedrock, in general, is highly fractured and moderately weathered.

Discontinuity in Phylite

Phyllite rock mass is highly fractured and prominent fractures are present at the outcrop of the rock. These fractures influence releasing of blocks of varies sizes and expose the rock mass and intact rock to natural geological weathering agents like water, rain and climate, thereby causing a high degree of weathering of the phyllite.

The stereo plot of the field data of joint sets

Plotting of hundreds of attitudes of joints from quartzite and phyllite on the stereo also show four sets of the joints (Figure 10). The maximum density shown is 14%.

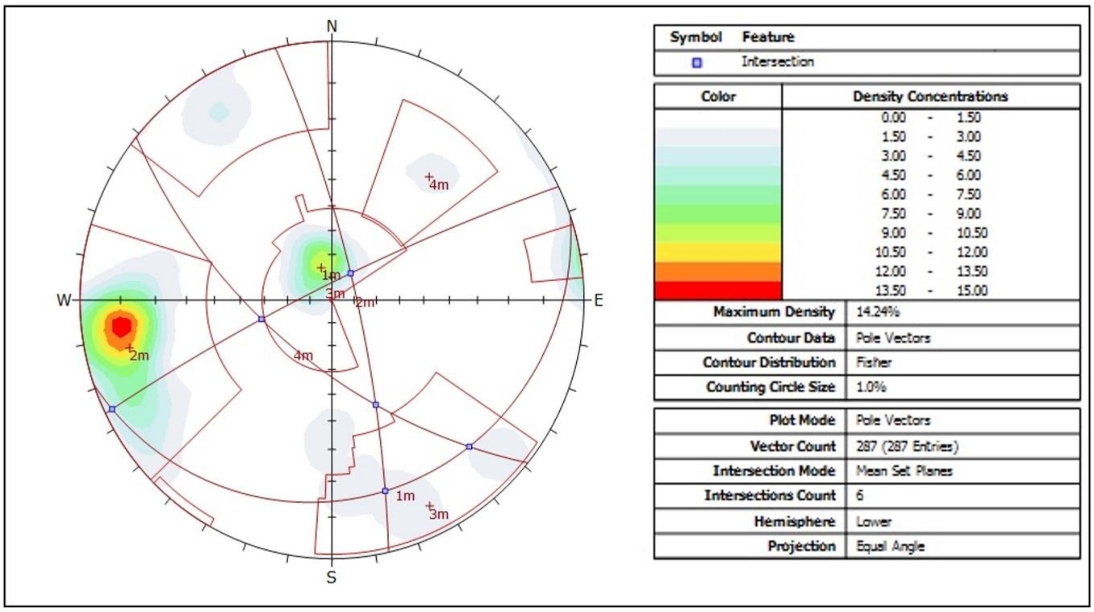


Figure 10. Stereo representation of information from the site.

4.1.5. Slope Stability Analysis

Since the slope consists of both rock and soil, the rock and soil slope stability analyses were done. Both field and stereo net plotting show four sets of joints in the bedrock. There is no sign of wedge failure at the site. Rock toppling and rock slide is likely event at the site.

From the empirical relation F = A tan A + B tan B (where F is a factor of safety; A is plane where dip amount difference is about 35° and B is plane B where dip amount difference is about 30°), the factor of safety is calculated to be 0.91. This indicates that the slope is not stable. However, areas with exposure of hard in-situ rocks are at the verge of gaining stability.

The Box-cutting slide has been classified under moderately deep-seated landslide which means the depth of the rupture plane is at the slide shallow depth. The depth of the rupture plane is about 14 m; hence limit equilibrium method has been applied to analyse the slope stability. In the limit equilibrium analysis, we evaluate the slope as if it were about to fail by sliding with the well-defined body of the slide at limiting equilibrium and determine the resulting shear stress along the well-defined failure surface. Then these shear stresses are compared to that of the corresponding shear strengths to determine the factor of safety.

F = S/S'

Where, F is a factor of safety

S is a shear strength

S' is a shear stress

In Box-Cutting landslide, we assumed the landslide is translational slide and the rupture surface is located at shallow depth about 14 m. The slope angle is about 55^0. The frictional angle is calculated to be about 26^0. The bulk unit density is found to be 21.37 kN/m^3 with cohesion 4 kN/m^3. After analyzing the slope stability in the area, the factor of safety is calculated about 0.87. This indicates that slope is not stable.

4.1.6. Intact rock strength

Intact rock is defined in engineering terms as a rock containing no significant fractures. However, on the small scale, it is composed of grains, pores space and microfractures with the form of a microstructure being governed by the basic rock-forming processes. All types of failure that can occur in different rock mass are highly influenced by the strength of the intact rock. Therefore, it is important to determine the strength of the intact rock (Rock Mechanic and Rock Engineering manual 2011).

In Box-Cutting area, the intact rock strength of the phyllite and quartzite are to be determined. Uniaxial Compressive Strength (UCS) values of quartzite from point load tests carried out in Geotechnical Laboratory of DGM are provided in Table 2. The UCS values indicates that the areas with the occurrence of the inter-bedded quartzite are likely to be relatively stable.

Table 2. Point load rest results from Geotechnical Laboratory of DGM.

Sample No.	**Width(W) (mm)**	**Depth(D) (mm)**	**Load(P) (mm)**	**De2 (mm2)**	**Is (MPa)**	**Is50 (MPa)**	**UCS (MPa)**
BC-R/1A	38.5	41	7	2009.81	3.48	3.31	79.44
BC-R/1B	45.5	21	3	1216.58	2.46	2.09	50.16

Further, the numbers of the readings of the Schmidt hammer on the phyllite were taken and analysed for the compressive strength of the rock. The mean of the strength tested at the site with Schmitt hammer is provided in Table 3. The Joint Compressive Strength can be estimated from Schmidt hammer readings by using empirically determined curves constructed for various hammer types and orientations (Figure 11). For phyllite, the Uniaxial Compressive Strength is estimated to be in the range of 15 MPa since it requires a blow of the geological hammer to a fracture the rock. Although quartzite is highly weathered at the surface and fractured, it requires more than one blow of the geological hammer to create fracture in it, so the UCS is estimated in the range of 30-100 MPa based on Uniaxial Compressive Strength classification of ISRM 1978. This indicate that the areas with quartzite as underlying bedrocks are relatively more stable as compared to areas lying on phyllite.

Table 3. Schmidt hammer test results (On site test).

Rock type	Density	Hammer orientation	Rebound value	UCS (MPa)
Phyllite	20	Horizontal	0	10
Quartzite	23	Horizontal	15	25

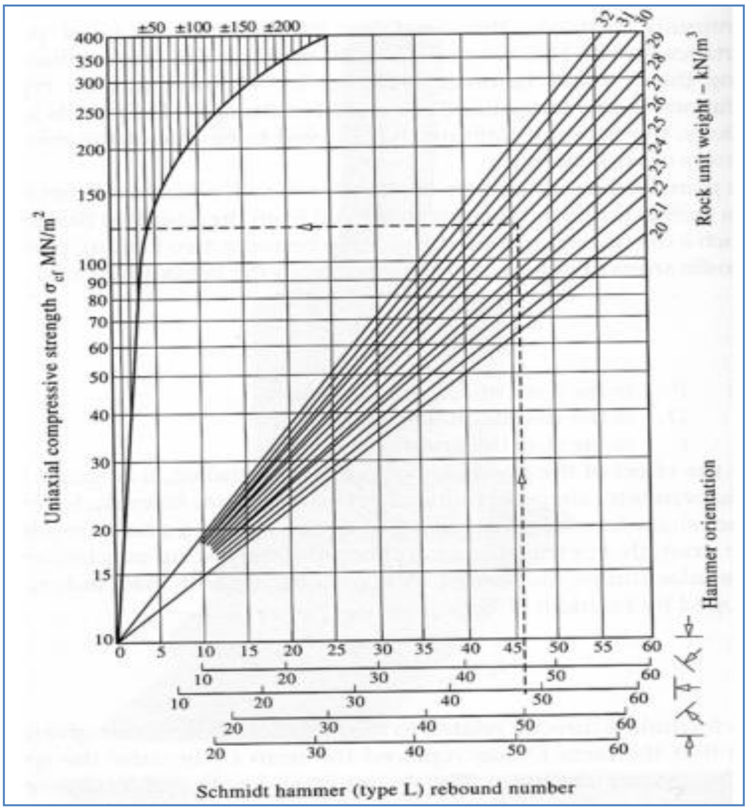


Figure 11. Calculation of UCS values from Schmidt hammer rebound and empirical curve.

4.1.7. Shear strength of the rupture plane

Steep slopes, loose material and rockslide nature pose a great challenge in the identification of the rupture plane in Box-Cutting study area. Therefore, electrical resistivity geophysical method was used for this purpose.

The rupture surface is most likely located at the contact of the highly fractured quartzite and competent phyllite rock as indicated by the presence of water and wet spots. The competent phyllite can be impermeable and therefore water will flow out.

The rupture surface could have been weak as it crosses through the contact of the phyllite rock.

Collection of field data to determine the shear strength of the rupture surface was not carried out since the exact locating of the rupture surface was not possible. However, tracing the moment of the rock mass, the rupture surface is likely to follow the huge tension cracks and end at the boundary between fractured and weakened phyllite and competent phyllite located at a deeper level. The shear strength of the rupture surface is expected to be low as rainwater can easily percolate through tension cracks and rupture surface, which can weaken the rupture surface to the maximum level. This is one of the factors for landslding or rocksliding in Box-Cutting area.

The strength of the rupture plane will be influenced by the rock bridge and the persistency of the joint sets. The set of the joints comprises of the fractures, which is often not continuous. The persistency of joints can be obtained from the ratio of the sum of the area of the persistency along the given line individual joint to the area of the total plane. In 2D, the persistency along the given line can be dependent on rock bridges and joint segments. Based upon the observation made at the site, it is estimated around 10 % rock bridge, which could influence the rupture plane at large. Joint persistency is used for the estimation of the strength of the sliding plane.

4.1.8. Variability and uncertainties

The major challenges in analysing the rockslide arise from uncertainties and variability associated within the analysing of the rockslide itself.

Variability

Variability of ground conditions, as well as spatial and temporal, is important in both regional and site-specific analysis. For this, probability concepts are very useful in both cases although they may be applied in quite different ways. Spatial and temporal variability of triggering factors such as rainfall has a marked influence on the occurrence and distribution of rockslides in a region. The geotechnical properties of the rock mass can be variable with weather, temperature and all other natural factors.

This includes the rock mass strength to the strength of the intact rock. The marked boundary for the instabilities can change with the time and the degree of the sliding.

Uncertainties

The uncertainties are one of the major problems for the prediction of the 100 % accuracy of any description regarding the rockslide in the area. The geotechnical performance of a specific site, facility, system or regional study like Box-Cutting rockslide may be affected by different types of uncertainties such as: (1) geological uncertainty (geological detail), (2) geotechnical parameter uncertainty (variability of shear strength parameters and of pore water pressure), (3) hydrological uncertainty (aspects of groundwater flow), (4) uncertainty related to natural or external events (magnitude, location and timing of rainstorm, flood, earthquake), and (5) uncertainty due to unknown factors (effects of climate change).

The identification of the rupture surface itself is an uncertainty, which can lead to larger uncertainties for estimating the shear strength of the rupture plane.

One of the major uncertainties will be while estimating the rock mass strength. The weathering of the rock mass has always to do with the rock mass strength. The data collected from the field for hammer could be interpreted in different manners, which can even lead to the different properties. If the Schmidt hammer is not handled properly while conducting tests, it can lead to significant errors resulting in uncertainties.

4.2. CAUSE OF LANDSLIDE

The rockslides are driven by natural or human activity induced triggering factors. Often, rockslides are caused by the structure of the slope. Rainfall data from 2002 to 2013 show that the area receives heavy precipitation during the monsoon season (Figure 12). Therefore, besides steep slope (>45°) and weak fractured nature of the rock mass, rainfall is most likely one of the main driving forces of the rockslide in Box-Cutting area.

To understand the failure mechanisms of the rock, it is vital to understand the rockslide structure and kinematics. The acceleration of displacement is correlated with the volume of the rainwater received by the site (Figure 13). As the site receives heavy rainfall, the opening of the cracks widens. The displacements grow steady with the steady increase in the volumes of the rainwater received by the place. This displacement in relation to the few weeks of rain correlates with the long-term acceleration. The daily basis of the rainfall received by the area can be correlated with the short-term acceleration of the displacement. Therefore, the rainwater acts as one of the triggering factors of a rockslide.

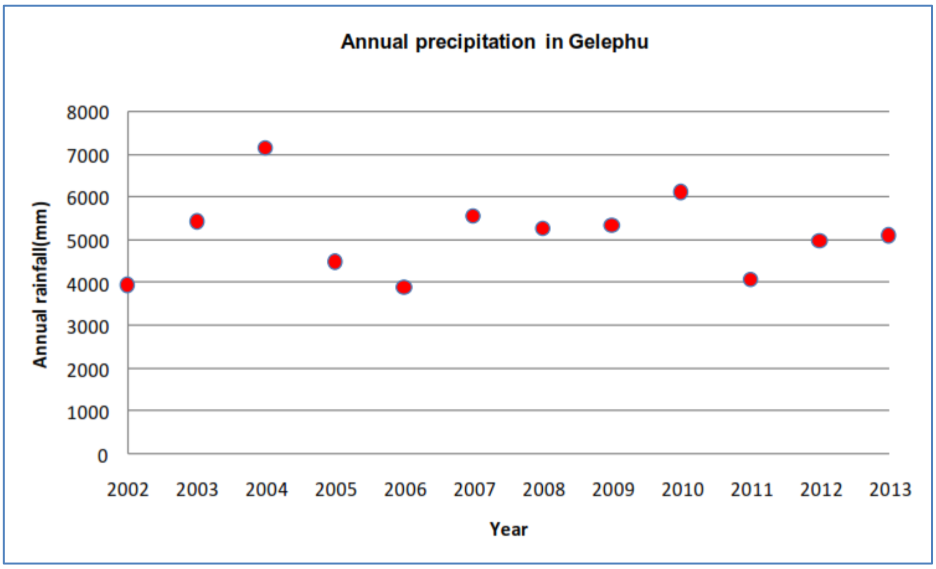


Figure 12. Annual precipitation of Gelephu area for past 12 years (source National Center for Hydrology and Meteorology).

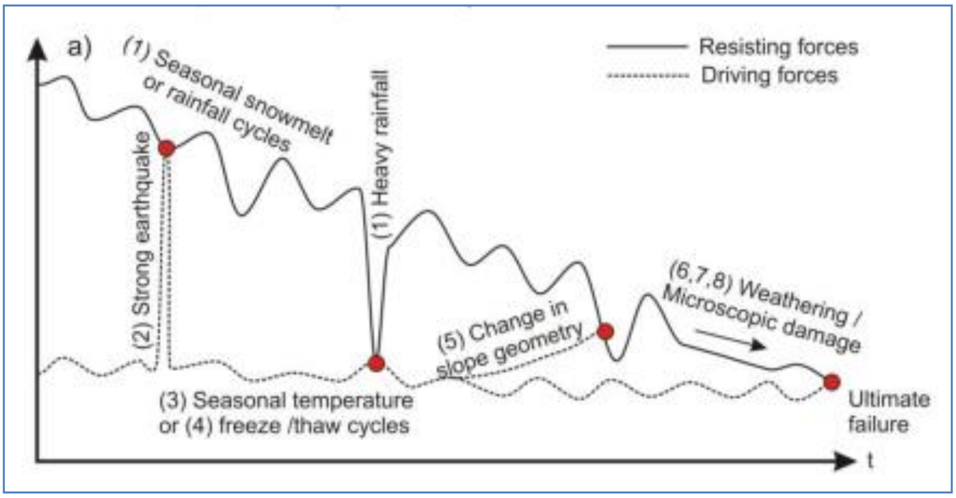


Figure 13. A conceptual model of driving and resisting forces in the slide area.

During rainfall, water percolates through the tension cracks of the rock mass at the main scarp of the rock slide. This will increase the groundwater table within the area and increase pore pressure against the fractured weak rock mass. Further, gravity will play a huge role as the nature of the slope is very steep. All these conditions in the area will highly reduce the resistance of the rock against wedge slide and toppling. It prepares well for the rockslide as it increases the ground pore pressure and weakens the rock mass, tension cracks and allows the blocks of the rock to slide under the influence of gravity. Thus, these conditions in Box-Cutting suggests that the hydro-mechanical forces are one of the main preparatory factors for the rockslide in the area.

4.3. UNSTABLE VOLUME ESTIMATION

Usually, DAN-W tool is used for estimating the runout behaviour of landslides based on specific data on geometry and material properties. However, this method was not used as the runout distance is visible at the site. The runout distance for the current slide is about 900 to 1000 m. Since the highway is directly exposed to slide, the risk is of interest. It is important to determine the volumes of the materials that has slided in the past and more so important is to estimate and analyse the volume of the materials that are likely to fail in the future with high degree of accuracy for better planning, designs and implementation of mitigation measures since the volume of the material can mean the probable energy of the sliding mass. This entails estimation of the volume of the unstable material at the head scarp of the rockslide.

In Box-Cutting, longitudinal cross-section constructed on google earth and width of the path were used to estimate the volume of the unstable materials (Figure 14). The large volume of unstable materials was even observed during the field observation at the site. The unstable volume of the material is estimated to be around 300,000 to 400,000 m^3 (L=1000 m, B=100 m and an average depth of 3 to 4 m) and used in the analysis.

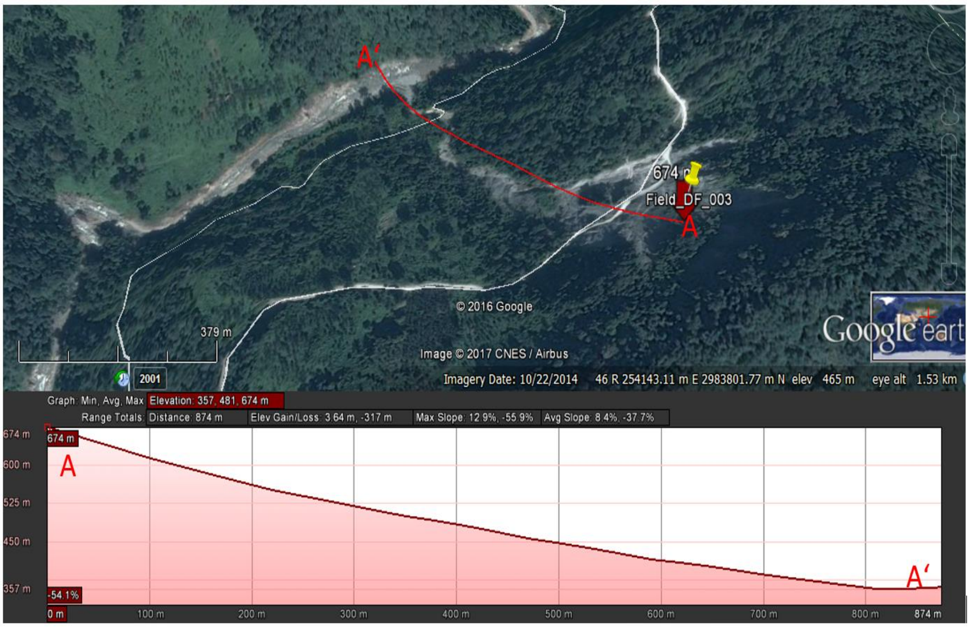


Figure 14. The longitudinal cross section along A-A' constructed on google earth.

4.4. GEOPHYSICAL RESISTIVITY IMAGING

A geophysical resistivity survey was aimed to map sub-surface, understand the water saturation and to understand the depth of the rupture surface in the slide area. This method is applied to complement the engineering geological field observations. Therefore, this section shall provide detail of geophysical survey methods or procedures, results and result interpretations. The typical values of resistivity for different materials are provided in Figure 15.

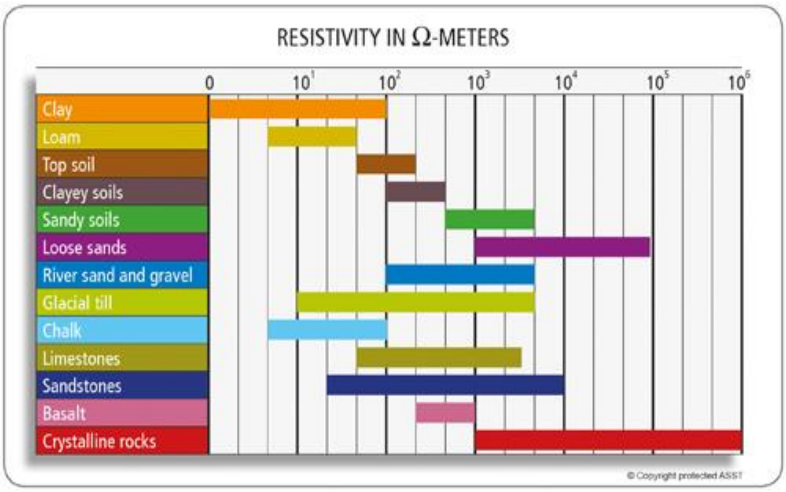


Figure 15. Typical values of resistivity of materials (Applied Scientific Service and Technology).

4.4.1. Equipment type

The type and details of the equipment used for this survey is shown in Table 4.

Table 4. Details of resistivity equipment used for field survey.

Items	Specification
FlashRes-64 Universal ZZ Resistivity Meter	Power: 250W; Current: up to 3A; Channel: 61; Voltage: Option 1: -50/120/350V, Option 2: - 100/250/600V
Electrodes	64 electrodes
Power supply	External battery 12V (>=90AH)

4.4.2. Field data collection

Data were collected using FlashRes 64 Universal ZZ resistivity equipment. Once the electrodes are fixed on the ground and cable layouts are completed, the contact resistance of each electrode was performed. Knowing the contact resistance of each electrode is important mainly to ensure that there is enough current injection at each electrode point along the profile line. This is because the strength of the current is proportional to the applied voltage and inversely proportional to the resistance between two electrodes. Increasing the voltage has a limit and therefore it is important to lower the ground resistance of each electrode. Ground or contact resistance, especially in the dry surface, can be lowered by sprinkling salt water in the circumference of the electrode or connecting two or more pole bolts in parallel.

Two electrical resistivity profile lines were conducted (Figure 16). ZZ array developed by the FlashRes Universal equipment manufacturer and other standard configuration such as Wenner, dipole-dipole and Schlumberger were used to collect data. Electrode spacing of 3 m was selected for all profile line 1. In the case of profile 1, 32 electrodes were used, whereas for other profile only 32 electrodes were used with a spacing of 5m.

Figure 16. Electrical Resistivity Tomography profile layout in the study area shown on Google Earth by the red line.

4.4.3. Data analysis

Res2dinv by Geomoto Software is used for data analysis. The following procedures were followed for data analysis:

- Using the ZZ Resistivity data acquisition software, data were converted into Res2dinv readable format.
- Data imported into Res2dinv program.
- Inversion of the data was carried out whereby the apparent resistivity collected from the field is correlated with the computer-generated model resistivity. In the inversion process, the model resistivity is obtained by using the residual error between the apparent resistivity and the theoretical resistivity model as an indication. If the apparent resistivity model and theoretical resistivity become closer to each other in an iterative process, it can be judged that analysis is proceeding properly.
- The final model resistivity section thus generated is co-related and interpreted with the sub-surface geological strata.

4.4.4. Result and Interpretation

- **Water Saturation**

  The profile No. 1 with a total spread length of 93 m using 32 electrodes spaced at 3 m was surveyed. The profile is oriented to collect data from the interested spots within the study area. Hence electrode number 1 is stationed at 0 m in the northern end. Both ZZ and Wenner configurations were used to collect data along this profile. The ERT model using the ZZ array configuration is shown in Figure 17. Resistivity values along this profile range from 80-8000 ohm.m. The area with resistivity value equal to and less than 100 ohm.m may be representative of groundwater or saturated zones, while higher resistivity values could be attributable to boulders and coarse materials inter-soil particle spaces filled by air at the depth of 2-3 m. The scree deposit has been observed at the end of the profile and it is represented by higher resistivity value. Small spring observed in the field is well indicated in the model at the profile distance 39 m.

- **Depth to Rupture Surface**

  A prominent competent layer of higher resistivity is observed at around 10-14 m depth from the surface (Figure 17). This layer can be correlated to saturated clayey soil or talcose phyllite. This kind of material has good water holding capacity and is usually impermeable. This character provides it to be the best surface where a maximum rupture can take place. Therefore, resistivity results indicate rupture surface at depth of about 10-15 m from the surface, which is in conformity to engineering geological field observations.

4.5. LANDSLIDE HAZARD AND RISK ANALYSIS

Hazard assessment in Box-Cutting is one of the key objectives to understand the hazard of rockslide and estimate risk associated with rockslide hazard. This will help to plan and implementation migration measures to reduce risk to lives and properties.

Therefore, this section shall provide details on hazard zonation and estimation of failure time.

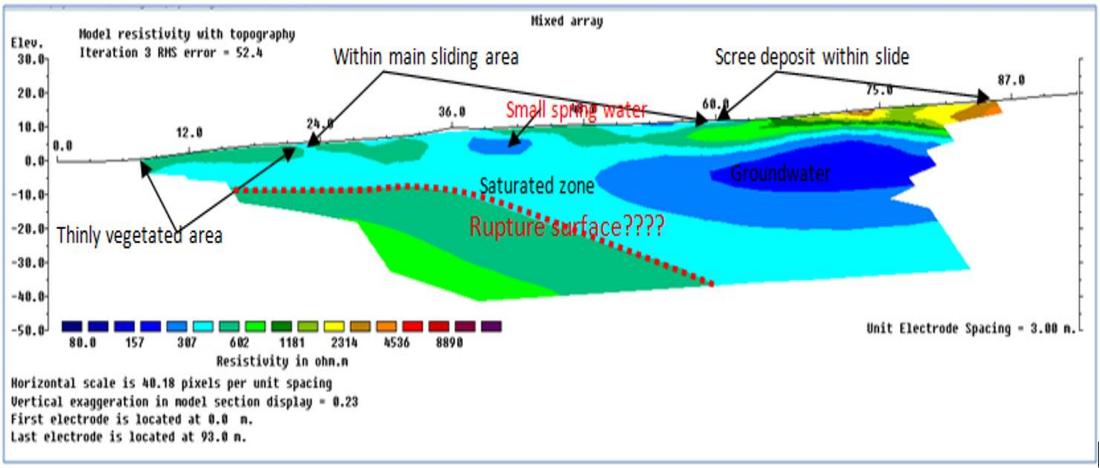


Figure 17. ZZ array configuration ERT model along profile 1.

4.5.1. Hazard Analysis and Zonation

In this study, hazard analysis and zonation are carried out using (1) Multi-Criteria Analysis (MCA) using GIS and (2) Conventional method.

(1) Multiple Criteria Analysis technique (MCA)

Field data and observations are used as input parameters for analysing the hazard scenario in Box-Cutting slide area using GIS-based MCA. The input parameters with assigned weights used for this analysis are provided in Table 5. The three hazard zones are delineated based on slope angle, drainage, material type, geomorphology including active and old landslides, land cover type and susceptibility to erosion and climatic factor and shown as: (1) Moderately high hazard zone in green colour, (2) High zone in yellow colour, and (3) Very high hazard zone in red colour (Figure 18).

About 0.0023 Km^2 of the mapped area falls in the moderately high hazard zone. About 1.2 Km^2 mapped area falls in the high hazard zone. About 1.6 Km^2 the mapped area falls in the very high hazard zone. Construction or the development of the infrastructure is not recommended in high hazard zone to very high hazard zone. Around 0.35 km stretch of highway is within the very high hazard zone.

Table 5. The input parameters with assigned weights.

Variables	Definition of Variables	Ranges and Categories	Weighted Value	Influences %
Drainage	Streams and rivers that may induce instability of slope. The effect decreases with increase in the distance on either side from the drainage.	Regions within 20 m of the drainage segments	4	30
		Regions outside 20 m of the drainage segments 2	2	
Land use/land cover	Different types of land use/land cover in the area play an important causative factor.	Cultivated Land	2	5
		Barren Land	5	
		Scrubs	3	
		Forest	4	
		Build-up Area	2	
		Water Body	1	
Lithology/ soil	Various type of materials, lithology and soil cover	Grey Phyllite	3	20
		Pebbly Phyllite	4	
		Colluvium	2	
Slope	The gradient between the Centre and the neighbourhood cell with maximum or minimum elevation. Slopes are classified from flat (level) to very steep slopes. The greater the slope, the greater is the probability of landslide occurrence.	Less than or equal to 15°	2	20
		From 16‡ to 25 °	3	
		From 26‡ to 35 °	4	
		From 36‡ to 45 °	5	
		Greater than 45 °	6	

Thrust	Two major thrusts, Main Central Thrust and frontal thrust both marked by large shear zones. The areas near to thrust are more prone to landslide occurrence	Zones within 500 m of thrusts Zones between 500 to 1000 m of thrust Zones outside 1000 m of thrust	3 2 1	10
Highways	Highways construction is one of the crucial factors, this can cause landslide due to land cutting, and filling, no proper drainage system. The effective area will at both side of the depending on the increase and decreased distance from highway.	Regions within 20 m of the highway segments Regions outside 20 m of the highway segments	2 1	10
Geomorphology	Geomorphology, landform type is an important factor for the cause of the landslide.	Eroded Landform Floods Plain Pediments Undulating landform	6 2 3 4	5
				100%

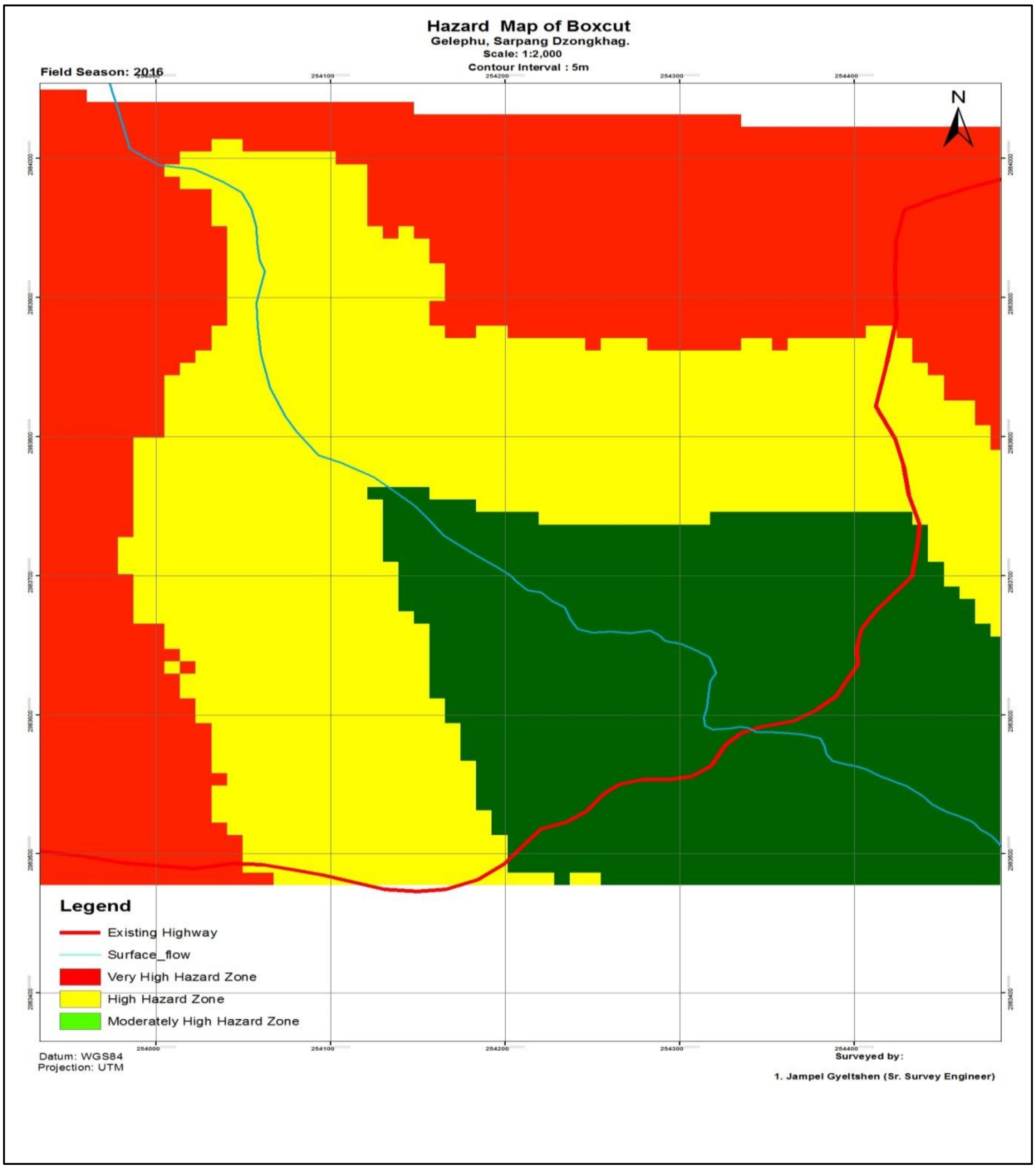


Figure 18. Hazard Zonation map of Box-Cutting slide generated using MCA in GIS.

(2) Conventional Method

The results and outputs from detail geotechnical and geophysical investigation serve as input parameters for slide hazard analysis in the Box-Cutting area. The key inputs to landslide hazard analysis are:

i. The estimated volume of the unstable material (is around 350,000m^3),
ii. Slope angle greater than 45°,

iii. Very less or no vegetation cover,
iv. Very weak geology, geological structures,
v. Heavy rainfall,
vi. Drainage systems
vii. The density of soil and general condition of the area.

Hazard zonation in and around Box-Cutting rockslide covering an area of around 6 km^2 with the help of the GIS software and Google earth image is carried out and shown in Figure 19. The flow path for same friction angle of 28° and volume of 400,000m^3 of unstable material is considered. It is the width of the flow path that controls the probability of the material to reach different area and failure of the slope within the area.

Three hazard zones are delineated (Figure 19). The area shaded with red colour is analyzed as high hazard zone. This is also the main sliding area where are is mostly barren with little or no vegetation. The zone is comprised of very weak and highly fractured rock. The shear zone occurring in the area contributes to identifying the zone as high hazard zone. The high hazard zone is the zone where the landslide and rockslide are still active. The medium hazard zone represents relatively low hazard as compared to high hazard zone. The vegetation cover is better, the slope angle has reduced, the bedrock has gained strength and the zone is exposed to a lesser hazard. This zone is shown in yellow colour and identified and mapped as medium hazard zone. The low hazard zone is marked with blue colour on the map. This zone is exposed to much lesser slide hazard than other two zones. This zone consists of very thick vegetation and much competent bedrock. This zone is less disturbed by the human activity and remained stable. These are major factors contributing to identifying the zone as a relatively low hazard.

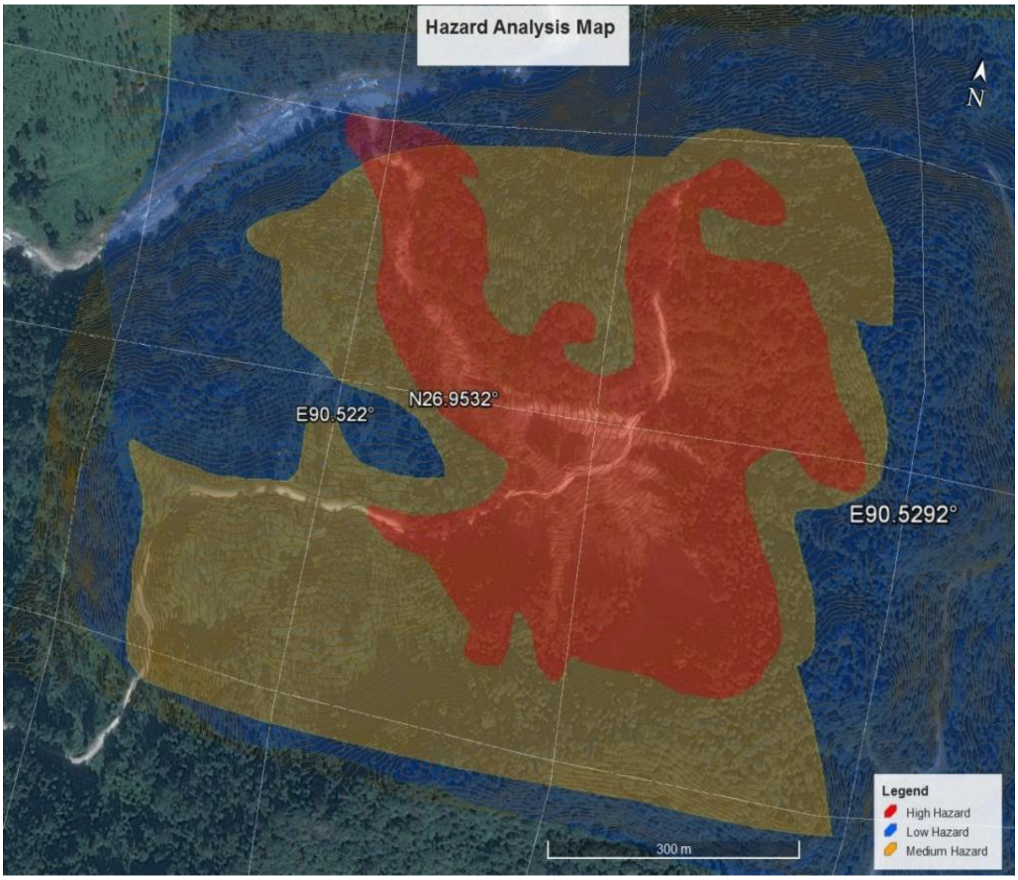


Figure 19. Hazard zonation map of Box-Cutting rockslide generated using the the conventional method.

4.5.2. Landslide Risk Analysis

The risk is the product of vulnerability and hazard. The risk map is shown in Figure 20. The two major risks are identified in the area. The Gelephu-Zhemgang high way is directly exposed to the risk of the slide as the highway passes through the Box-Cutting rockslide. Considering the importance of this highway, the identified risk needs to be reduced with the implementation of mitigation measures. Another risk identified is artificial damming of Galechu in the downslope area by the materials of the slide, which in turn can cause an outburst of huge flood and thereby posing risk to lives and properties in the downstream areas. Therefore, failure time estimation is deemed important to mitigate the risk of damming of the stream flowing across the toe of the slide.

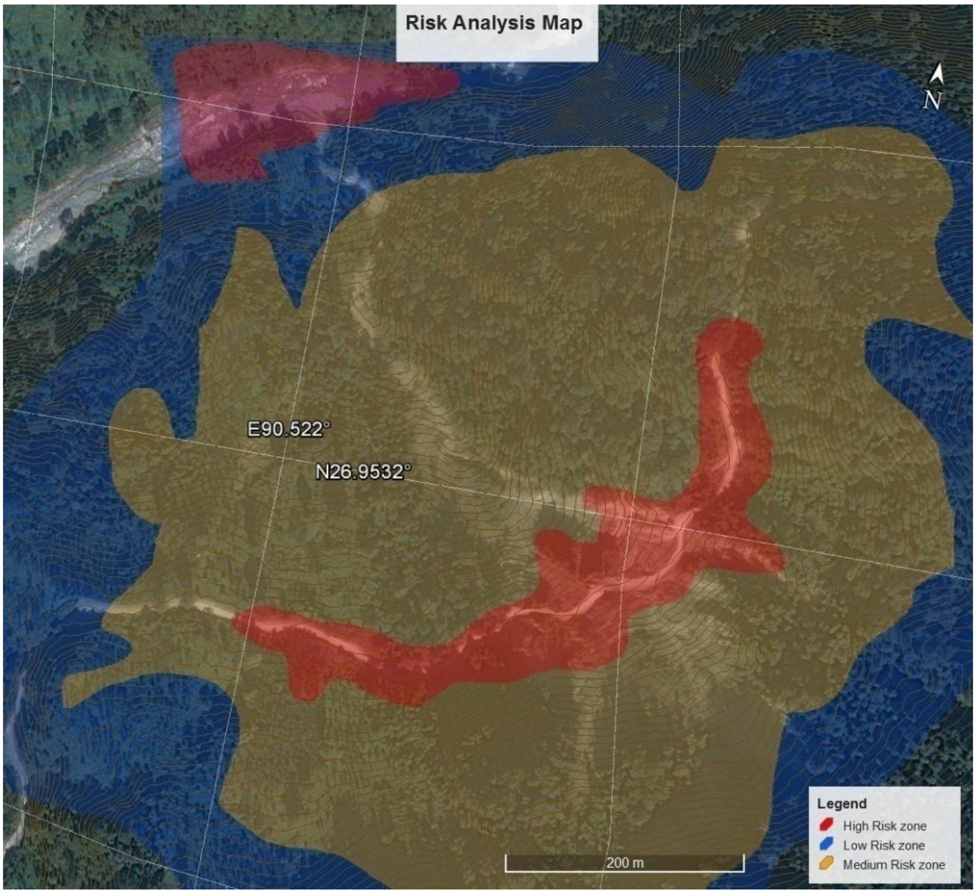


Figure 20. Risk map of the Box-Cutting Rockslide.

4.5.3. Estimation of failure time

The estimation of the failure time of rockslide or landslide is one of the biggest challenges faced by geoscientists and engineering geologists mainly because landslide phenomenon is controlled by several factors like geology, soil, water content, slope, vegetation, aspect, human activity. Although advanced modern methods are used to predict or estimate the failure time, such information is only good to be used for advocacy and preparation to counter hazard, and therefore should not be misused to mislead the public. One of the popular methods used to predict or estimate the failure time is the Inverse-Velocity method of Fukuzono (1985), which is shown in the Figure 21.

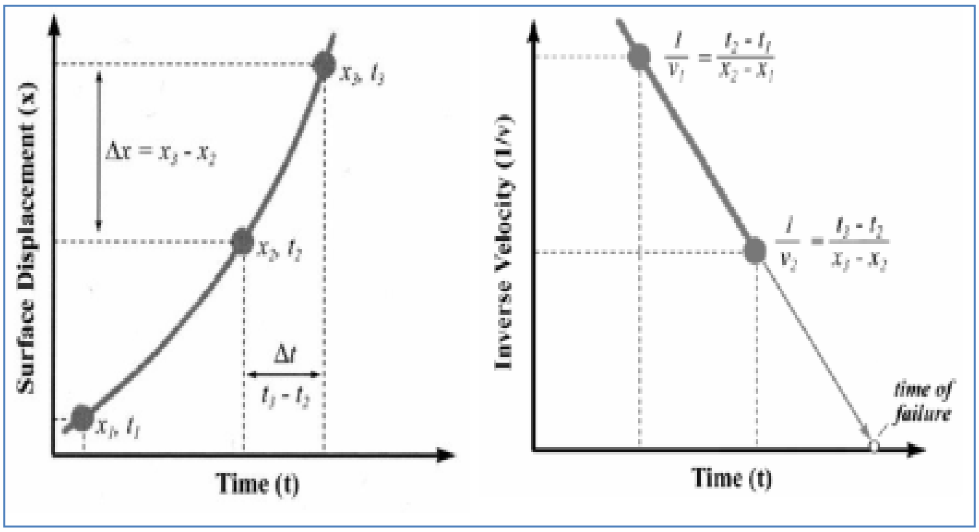


Figure 21. Inverse velocity method to predict the time of failure (Fukuzono,1985).

This method is considered as effective to estimate the failure time, but it is fully dependent upon velocity against time. The failure time can be estimated as shown in Figure 21. The inverse velocity versus time has been plotted in linearly and the line when intercept the time 't' axis, this time could be critical for failure. Because failure time can be influenced by other factors like degree of weathering and the amount of rainfall received by the area, therefore this method has a limitation in estimation.

The other popular method of estimating the failure time is using creep method (Figure 22) of Saito (1965). This method comprises of the three general phases as indicated in the Figure 22. It is basically based on time-dependent deformation. In the Box-Cutting, the displacement of the unstable mass is directly proportional to the opening of the tension cracks and progressive failure. Therefore, creep method seems better method to estimate the failure time in Box-Cutting. Since failure probability is high during monsoon, it will require the collection of displacement and rainfall data to use creep method to estimate the failure time and a threshold of rainfall for sliding in the area can be estimated.

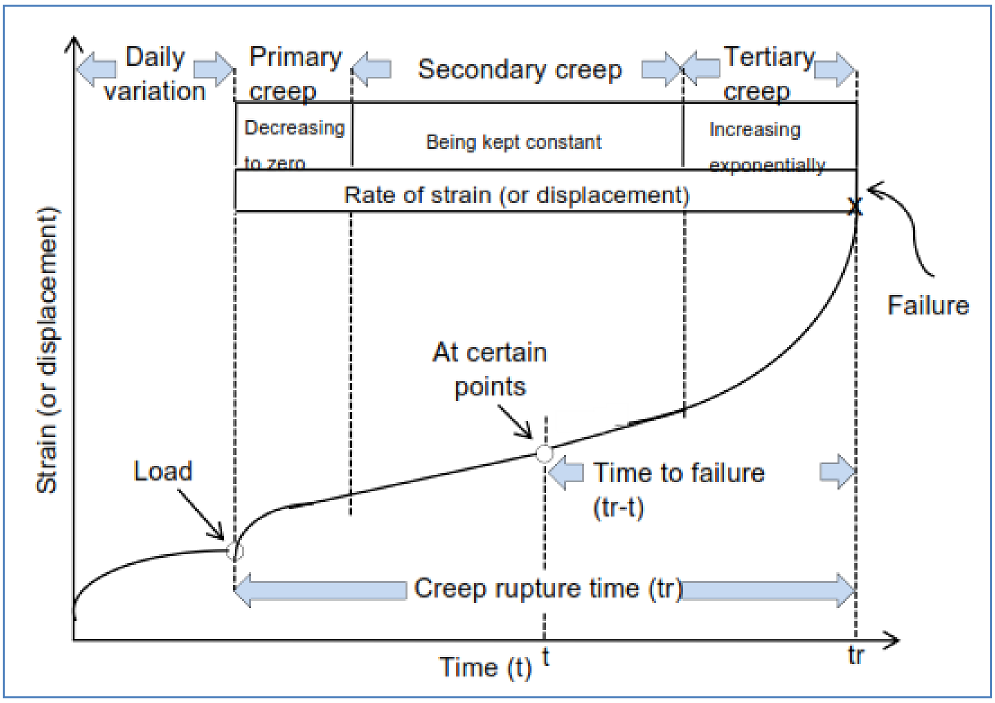


Figure 22. Relationship of strain and time series of creep deformation (Saito 1965).

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this study, the following conclusions are made in Box-Cutting Landslide:

5.1. Conclusions

(1) Box-Cutting landslide falls within Manas Formation of Baxa Group comprising of mostly thin-bedded to laminated phyllite and intercalated with minor coarse-gained quartzite.

(2) The landslide lies within the active tectonic zone, near to MCT and the rocks are highly sheared and fractured, which has led to a weakening of rock mass. The rock mass classification also indicates that the rock mass is poor and weak.

(3) The study area lies within sub-tropical climate zone with relatively high precipitation, where maximum rainfall amount of around 7000 mm was recorded in 2004 and the minimum rainfall amount of around 4000 mm was recorded in 2002 and 2006, between 2002 and 2013.

(4) The landslide area has the presence of water seepages both below and above the highway, indicating that the area holds a significant volume of water or the area is highly water saturated.

(5) Electrical resistivity survey indicates a highly weathered and weak rock mass with significant water saturation at a depth of around 14 m from the surface. This landslide may, therefore, be classified as moderately deep-seated landslide as the rupture surface is located at around 14 m below the surface.

(6) Landslide hazard analysis of around 6 km^2 area in and around the landslide using MCA model in GIS using both field data and spatial data obtained from stakeholders as input or causative factors for landslide delineated three hazard zones: (1) Moderately high hazard zone, (2) High hazard zone, and (3) Very high hazard zone. This analysis result show ~ 0.0023 Km^2 of the area as a moderately high hazard zone, ~ 1.2 Km^2 area as a high hazard zone, and ~ 1.6 Km^2 area as a very high hazard zone. Construction or development of the infrastructure is not recommended in high hazard zone to very high hazard zone. Around 0.35

km stretch of highway falls within the very high hazard zone. This model is validated using the conventional method of hazard analysis. Both methods show that the hazard level, in general, is relatively high within the slide and decreases away from the slide.

(7) These methods identified two major risks in the area. The Gelephu-Zhemgang high way is directly exposed to the risk of the slide as the highway passes through the Box-Cutting rockslide. Considering the importance of this highway, the identified risk needs to be reduced with the implementation of mitigation measures. Another risk identified is artificial damming of Galechu in the downslope area by the materials of the slide, which in turn can cause an outburst of huge flood and thereby posing risk to lives and properties in the downstream areas.

(8) The Box-cutting landslide is most likely caused by: (1) weak geology, (2) erratic and heavy precipitation, and (3) steep topography, but aggravated by human activities such as the highway and poor drainage.

(9) Slope Stability Analyses show that the factor of safety of is ~ 0.91 and/or ~ 0.87, indicating that the slope is not stable.

(10) The estimated unstable material in the slide area is around 350,000m^3. The unstable materials comprise mainly of residual soils, boulders and pebbles.

(11) The rupture surface of this landslide often run at the transition from weathered weak bedrock to competent bedrock, with a dip angle of about 40° to 50° in the landslide depletion area. This landslide transforms into debris flows, where debris slides into strongly convergent hill slopes or directly into headwater channels.

(12) In general, weathering of the fully exposed weak phyllite seems very fast, leading to high-frequency landsliding in the area. As not all landslides transform into fast and long runout debris flows, colluvium from older landslides forms a second important material that becomes mobilized by heavy rainstorms. The depleted volume remaining today in the source areas of the Box-Cutting landslide is a challenge to estimate as the volume of the current slide is observed to be a recurrent slide. The existing boulders and soil

masses potentially be mobilized in the future by rainstorms, resulting in landslides.

(13) The effectiveness of the existing structural mitigation or countermeasures in the landslide to reduce risks is found to be low as their foundation is within the moving mass and therefore simply adding load to the moving mass (Figure 23).

Figure 23. Mitigation or countermeasures that are in place.

5.2. Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed for Box-Cutting Rockslide:

The short-term mitigation measures

(1) The well-designed retaining wall with anchoring with a reasonable length of rods, incorporating the proper drainage system is deemed necessary.

(2) Since the probability of the sliding mass in the future is estimated to be high, the current retaining wall seems to be ineffective to counter the huge rockslide. Therefore, it is recommended to increase the retaining capacity of

the wall and with improving the foundation beyond the depth of rupture surface.

(3) The outlet of the drainage should be properly managed. This requires clearing of the drainage from the larger boulders to avoid blockage of the water and mud so that the water can freely flow without any risk of eroding in the area.

(4) The proper drainage system may be required within the slide area. Drains must be well designed both in release and transit area as shown in the detail map. Water seepages in the slide must be properly managed by channelling through the area where the bedrock is present.

(5) Benches (Step like structure) are also recommended to be constructed within the release area of the slide area to reduce the slope angle.

(6) Detailed drilling method may be recommended to assess the thickness of overburden and validation of depth of the rupture plane in selected locations.

The long-term mitigation measures:

(1) The other alternative mitigation measures are to bypass the slide. This can be done in three different ways as shown in the Figure 24. One possible way is ~~to~~ either realigning the highway from other side of the ridge or through Hot spring - Rongri rough highway to avoid the slide.

(2) Another possible bypass could be constructing a highway tunnel as shown in the Figure 24. These alternative mitigations are proposed as the slide is observed to be a recurring slide. The probable alignments are also shown in the Figure 24.

(3) Further to reduce the risk to human lives and properties, an early warning system is also proposed to be put in place in the area. It could be placed at the site to warn the people and motorists from the danger of the rockslide.

These countermeasures should be enhanced and day to day monitoring systems are required.

Figure 24. Proposed possible re-alignment of highway and highway tunnel.

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APPENDICES

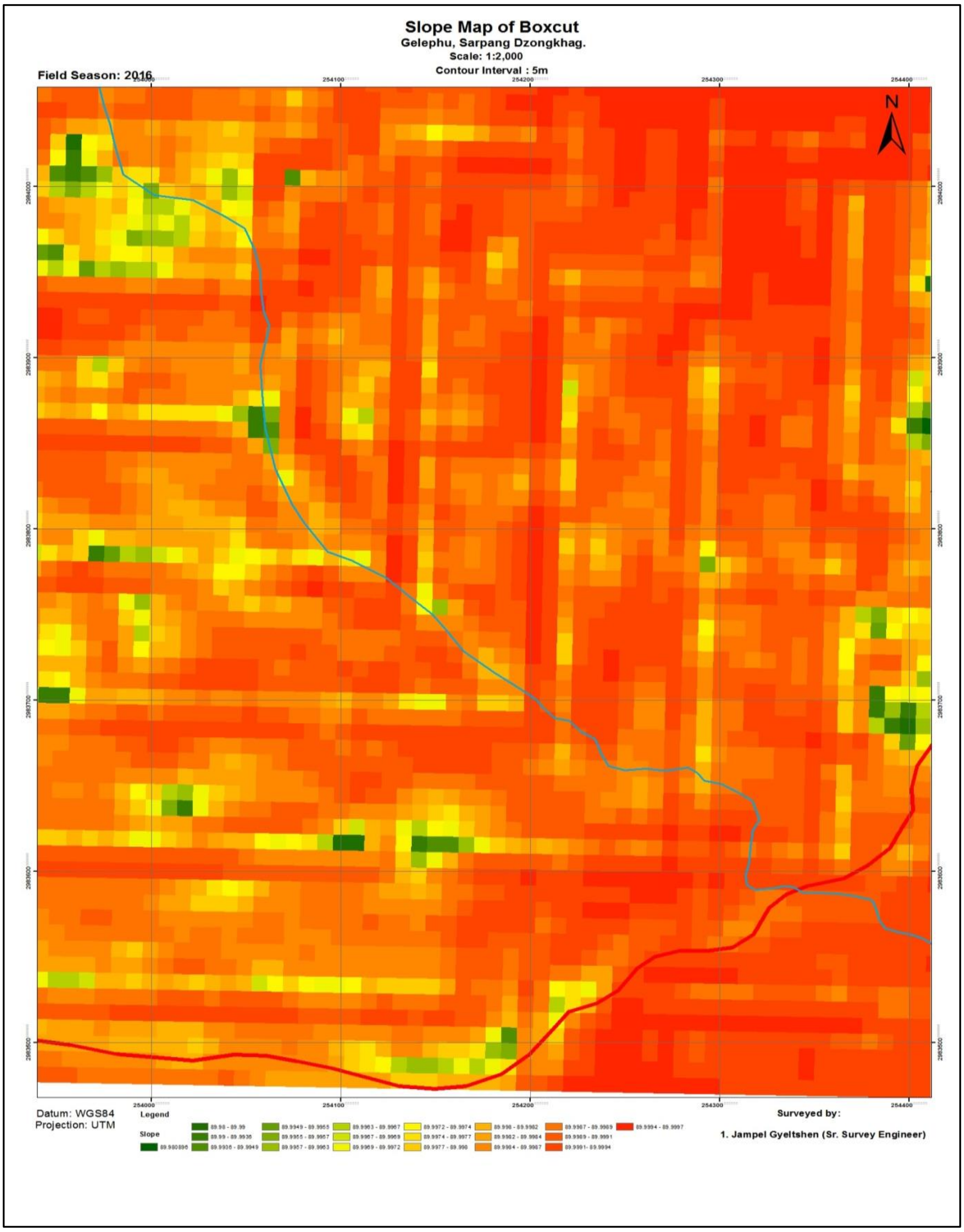
A. Photos from the field work

Field Photo 1 - Left photo shows the outcrop of the Quartzite and right one represents the phyllite

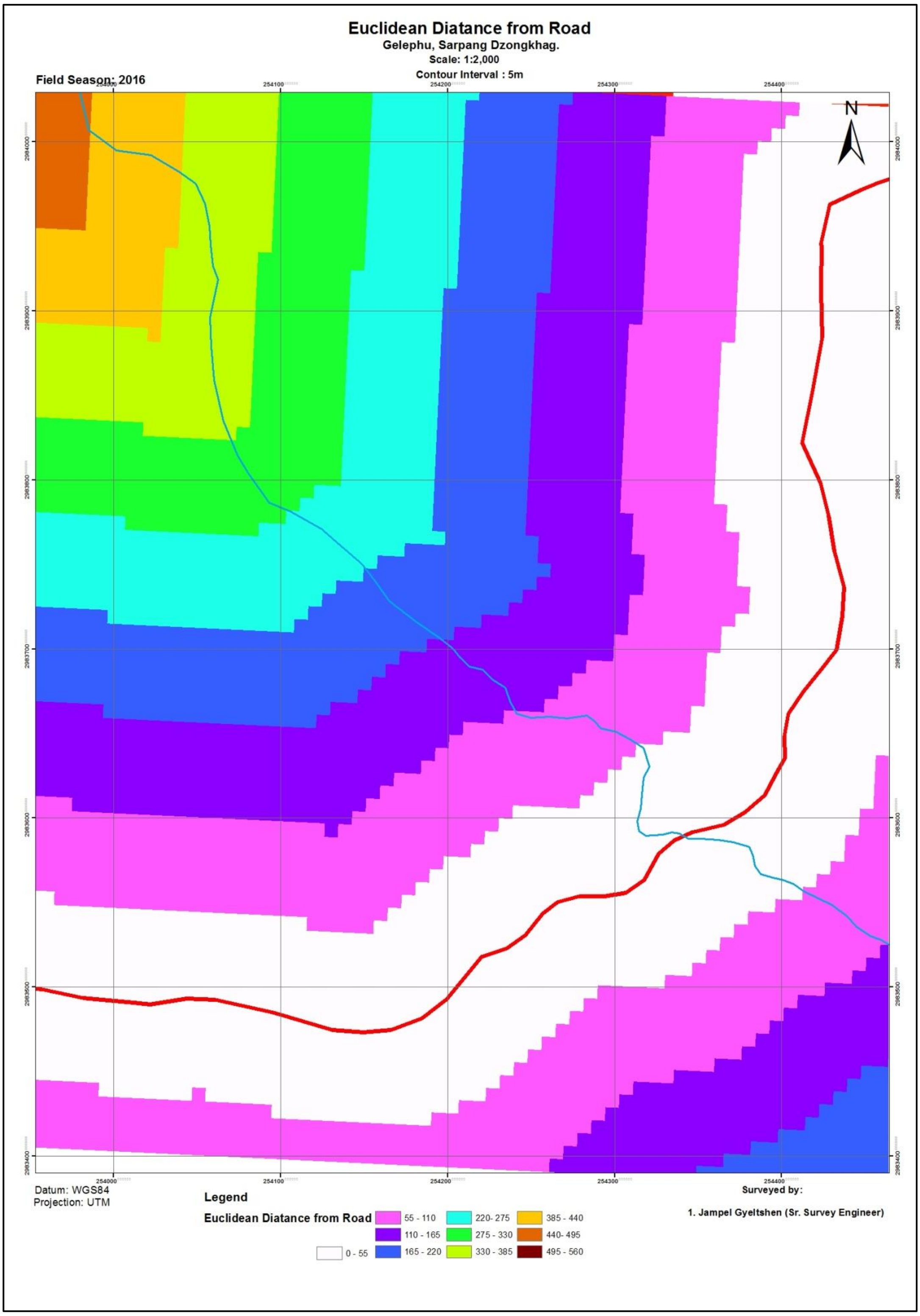
Field Photo 2 - Sampling of the soil and rock from the slide area

Field Photo 3 - Resistivity survey at site

B. Slope Map


Slope Map of Boxcut
Gelephu, Sarpang Dzongkhag.
Scale: 1:2,000
Contour Interval : 5m
Field Season: 2016
N
254000
254100
254200
254300
254400
Datum: WGS84
Projection: UTM
Legend
Slope
89.98 - 89.99
89.99 - 89.9936
89.9936 - 89.9949
89.9949 - 89.9955
89.9955 - 89.9957
89.9957 - 89.9963
89.9963 - 89.9967
89.9967 - 89.9969
89.9969 - 89.9972
89.9972 - 89.9974
89.9974 - 89.9977
89.9977 - 89.998
89.998 - 89.9982
89.9982 - 89.9984
89.9984 - 89.9987
89.9987 - 89.9989
89.9989 - 89.9991
89.9991- 89.9994
89.9994 - 89.9997
Surveyed by:
1. Jampel Gyeltshen (Sr. Survey Engineer)

C. Euclidean Distance from Highway



D. Euclidean Distance from Stream

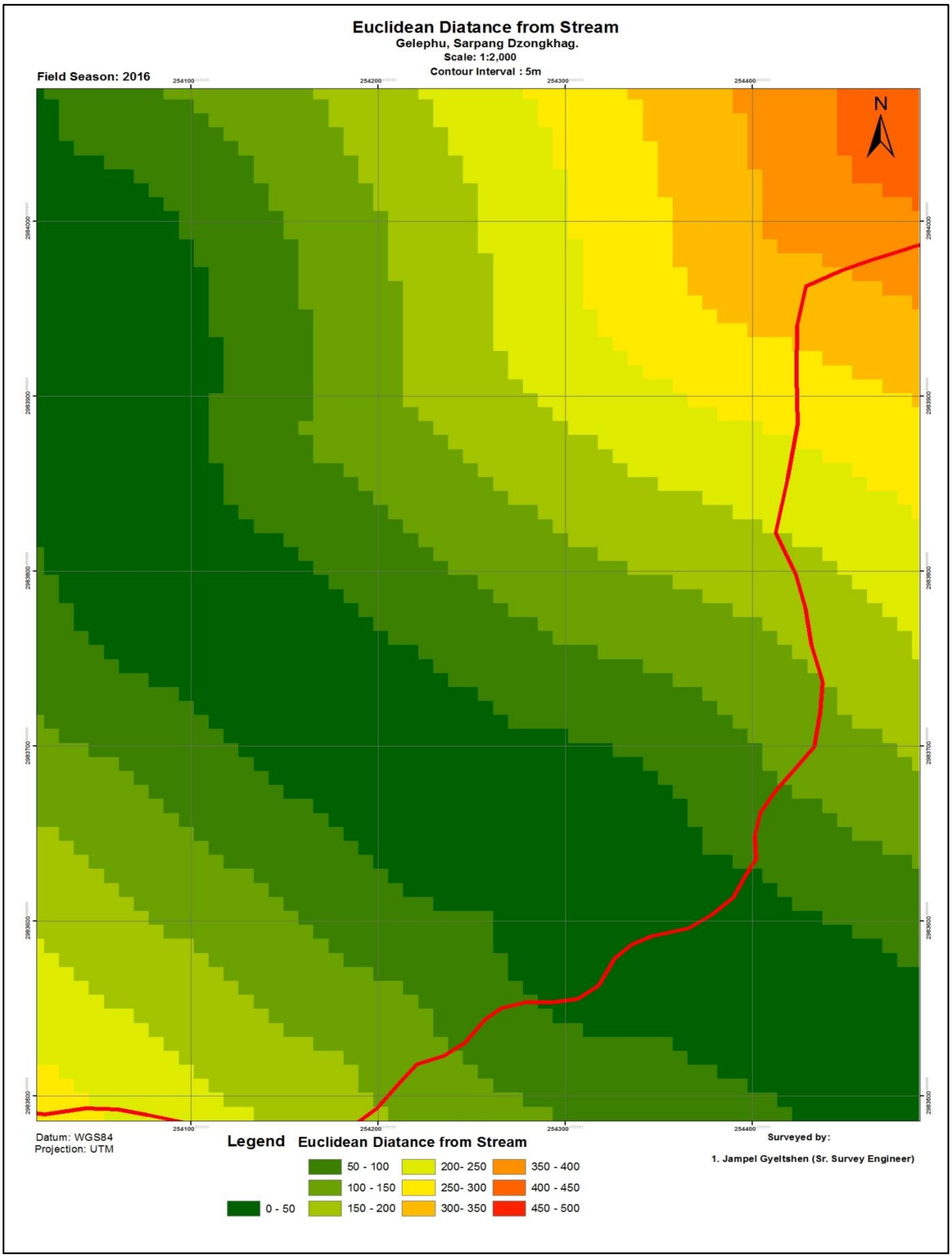


Table 6. Joint set data

Dip angle (°)	**Dip direction (°)**	**Dip angle (°)**	**Dip direction (°)**
80-90	70	89	50
85	56	75	89
85	56	76	83
80	86	72	97
80	78	72	103
75	356	41	229
90	42	20	234
85	82	31	191
85	86	17	210
85	98	19	203
85	340	72	353
10	172	66	327
15	160	70	349
85	80	75	354
85	78	55	214
75	98	55	203
19	170	65	210
76	84	67	211
70	55	66	215
47	10	88	81
75	20	67	2
8	155	88	262
19	172	17	191
81	80	12	183
60	97	16	172
59	7	13	168
89	83	16	169
61	7	55	330
76	65	52	356
21	160	65	341
85	85	53	352
11	130	87	307
15	10	86	133
86	85	82	314
89	83	85	312

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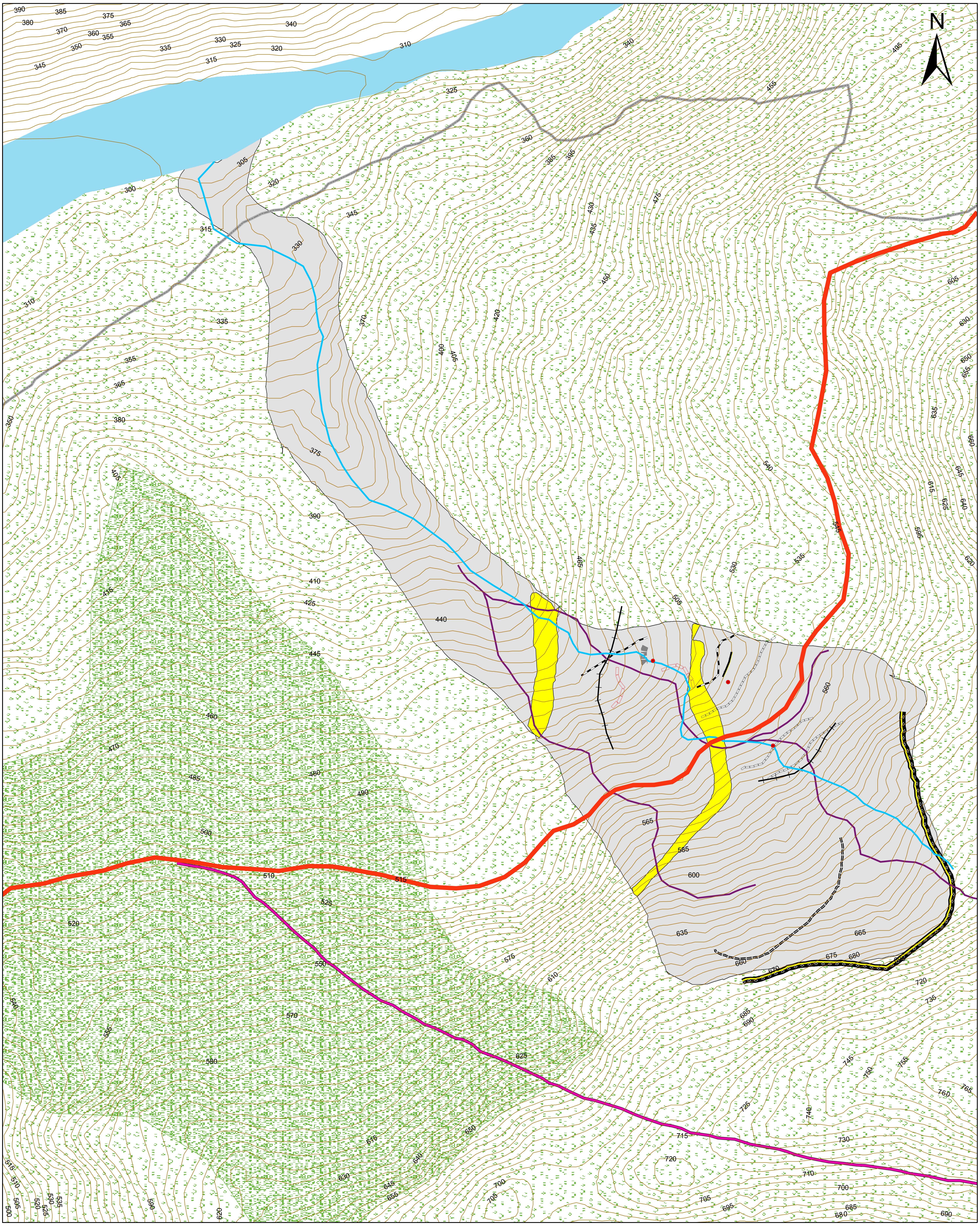
Engineering Geological & Proposed Remedial Measure Map of Boxcut

Gelephu, Sarpang Dzongkhag.

Scale: 1:2,000

Field Season: 2016

Contour Interval : 5m



Datum: WGS84
Projection: UTM

Legend

- Seepage
- Existing Highway
- Stream
- Resistivity Profile Line
- Gabin Wall
- Contour
- Washed out Wall
- Tension Crack
- Roads Re-alignmnet
- Proposed Road Tunnel
- Proposed Retaining wall
- Proposed Drainage System
- Proposed Bench
- Newly Erected Wall
- Crown
- Orchard
- River
- Phyllite
- Quartzite
- Vegetation

Geology by:

1. Jamyang Chophel (Sr. Geologist)
2. Nidup Wangmo (Geologist)

Surveyed by:

1. Jampel Gyeltshen (Sr. Survey Engineer)
2. Pem Tshewang (Field Survey Assistent)