Annex 4.1: Technical Report of DGM: proposed landslide mitigations in P/Ling Thromde (PPG study)

Abbreviations

ρ	bulk densidty
η	porosity
γd	dry unit weight
ρd	dry density
°	degree
BT	baxa thrust
C_c	Coefficient of concavity
C_u	Coefficient of uniformity
DGM	Department of Geology and Mines
DHMS	Department of Hydro-Met Services
DOR	Department of Roads
e	void ratio
FQ	Family Quarters
GEF	Global Environment Facility
GIS	Geographic Information system
GLOF	Glacial Lake Outburst Flood
GPS	Global Positioning System
GSB	Geological Survey of Bhutan
HD	high density
Ip	Plastic index
IPCC	Intergovernmental Panel on Climate Change
Km	kilometer
kN/m^2	kilonewton per meter squared
kPa	kilo Pascal
LDCF	Least Developed Country Fund
Masl	meter above sea level
MBT	Main Boundary Thrust
MCT	Main Central Thrust
MDD	Maximum Dry Density
m	meter
mm	millimeter
MoEA	Ministry of Economic Affairs
NAPA	National Adaptation Programme of Action
NE	North East
NNW	North North West
NW	North West
OMC	Optimum Moisture content
PM	Phuetsholing Municipality
PPT	Portable Penetration Test
PT	Phuentsholing Thromde
RBA	Royal Bhutan Army
SE	South East
SPT	Standard Penetration Test
S	Saturation
ST	Shumar Thrust
SW	South West
Thromde	Municipality
TS803	Total Station 803
Tsho	Lake
UNDP	United Nation Development Programme

Executive Summary

This study was carried out for NAPA-II follow-up project, as part of the technical feasibility study to assess the geological and geotechnical conditions of the landslide and to propose various remedial measures in the critical landslide prone areas under P/ling Thromde: Old Hospital, Rinchending Goenpa, Kharbandi Check post and Northern Side of Reldri School and its immediate surroundings. Direct Shear Box Test, Proctor Compaction Test, Grain size analysis, Atterberg limit test, Specific Gravity, bulk density test and water content were conducted in order to come to a sound appraisal and based on which the stability assessment and mitigation measures were identified. As part of the fact finding and formulation of possible mitigation measures the capacity of staffs of both the Department of Geology and Mines and the Phuentsholing Thromde were enhanced in the fields of slope stability analysis and geological and geotechnical assessments through on-the-job training.

The above area forms a part of the Himalayan foothill belt with a youthful topography, abruptly rising from the plains like a ram-part up to 400m from Mean Sea Level (MSL). The elevation in the construction site varies between 200m to 400m from MSL. The general drainage pattern of the area is dendritic to sub- dendritic. The area experiences a humid tropical climate. The summer is fairly warm between March and October with temperature rising up to 35^{o}C. The winter months between Novembers to February experiences quite a pleasant climate, whereas the monsoon months experience heavy rainfall between June and September. The area experiences average annual rainfall of about 6699mm (DHMS).

<u>Methodology adopted for the study</u>

Desk review

The study was started with a short review of existing literature related to landslides around Phuentsoliong areas. In Thimphu, the desktop and preparation phases were completed with a short series of presentations on geology, rock mechanics and slope instability to the relevant staff members of the Department of Geology and Mines and Phuentsoling Thromde in preparation for field investigation as well as for capacity building of the staffs from DGM for similar studies.

Field work

The field phase covered the period from December 19, 2012 to February 9, 2013 in Phuentsholing, with multiple site visits to the four areas and its immediate surroundings. During this period, detailed topographic survey on the scale of 1:1000 was carried out and a geomorphologic, geological and geotechnical data were incorporated in an integrated manner.

In order to assess the stability of the slope the following methods were adopted:

- Geological traverse was taken from the crown of the slide to the toe of the slide to actually determine the type of materials, structure of the rocks, slip planes, tension cracks and seepage points.
- A topographic map on 1:1,000 scale was prepared to actually determine the length, width, crown of the slide, tension cracks in the slide and the exact location of seepages and gulley to come up with appropriate structural mitigation measures.
- A longitudinal profile was made to determine the slope angle, the actual length of the slide and also to locate the mitigation measure sites.
- Cross sections were prepared to know the width of the slide and also to plot the geological information.
- Reports by NGI and DGM had been referred to use the material properties for working out the stability of the slope.
- In-situ test such as Portable Penetration Test (PPT), dilatency and shine test were carried out to determine the relative bearing capacity and material type in the slide area.

Observations

Topography and Geology

The geomorphic features of the areas are characterized by the abrupt rise of the topography from the Indian flood plain from the altitude of as low as 100m to 400m within an aerial distance of less than 1km. Numerous parallel type of drainages flowing from north to south marks ruggedness of the topography.

The geology of the area falls into Phuentsholing Formation belonging to Baxa Group of Rocks which comprises of quartzite, greenish grey, variegated and carbonaceous phyllilite. There occurs occasional dissemination of the mineral pyrite in the rock formation in the slide areas. The mineral pyrite with chemical composition of (FeS_2) when coming in contact with water oxidizes very fast forming iron hydroxide which releases sulphur making the terrain little acidic, which ultimately enhances the process of weathering on the rocks. Moreover the formation falls over the Main Boundary Thrust and besides that sign of active faulting within the formation itself has been reported by previous workers in the nearby area towards south east of Goenpa where inversion in the river terrace has been observed. The rocks here have a general trend of N10ºW-S10ºE having a dip amount ranging from 58º to 80º towards NE. The rocks are crushed and highly weathered which could be easily picked by a geological hammer. A lot of minor folds have been observed in the phyllite. A fault trending E-W and dipping towards north with an amount of 26º have been observed below ChereyJe's residence. Displacement in the upper lying quartzite has been observed where the hanging wall had been dragged over the footwall. The quartzite is also highly fractured and is blocky in nature.

Material Type

The type of material in the study area basically comprise of reddish brown soil on the top having a thickness of 2m. This then is underlain by grey quartzite with varying thickness. The quartzite is highly fractured in nature. This is underlain by greenish to grey phyllite which is quite compact, which in turn is underlain by carbonaceous phyllite intermixed with talcose and chloritic phyllite. Then there is a suite of grey phyllite underlying the carb-phyllite. Huge boulders of quartzite ranging in size from 1 m^3 to 80 m^3 were observed in the slide zone.

The structure of the rock is well preserved though the rocks are highly fractured. They are also highly weathered and have low strength and cohesion. On carrying out the in-situ test of the materials such as dilatency and shine test the materials exhibited low strength as it could be crushed with some pressure. On the dilatency test, it exhibited dull to shiny layer indicating presence of silt and also clay. While doing the shine test it did give a shiny look. As such the material is quite sticky in nature thereby indicating the presence of clay. Rajinder et al. (2003) have analyzed the carbonaceous phyllite sample of Kharbandi Check Post and reported the finer fractions to be Silty Sand with a liquid limit of 19.5 %. On analyzing the disturbed sample using the triaxial test the following properties have been reported

Table 1: Result of Triaxial Shear Test and other index test

Moisture Content (%)		3.30
In-situ Density (gm/cc)		2.15
Total shear Parameter	C (kg/cm^2)	0.37
	Φ (º)	17.8º
Effective shear parameter	C (kg/cm^2)	0.23
	Φ (º)	32.1º
Specific Gravity (Sp.gr.)		2.70
Water content (ω)		7.26 – 18.30% (Test conducted by DGM)
Bulk Density (ρ)		1.27 – 2.10 g/cc(Test conducted by DGM)
Coefficient of Curvature (C_C)		0.40 – 2.19(Test conducted by DGM)

Void Ratio (e)		0.5 – 1.14(Test conducted by DGM)
Porosity (η)		39.26% - 53.19 %(Test conducted by DGM)
Degree of saturation (S)		21.25 – 66.60%(Test conducted by DGM)
Direct Shear Box Test	Cohesion	0 Kpa – 16Kpa
	Angle of Internal Friction	24° - 32º
Standard Proctor Test	Maximum Dry Density (gm/cc)	0648 – 0968
	Optimum Moisture Content (%)	10.33 – 16.95
Plasticity Index (%)		13.20 – 22.02 (Test conducted by DGM)

Cause of the Landslide

The slides have taken place due to intermittent rainfall during the month of July and October. The total amount of rainfall during the months of July and September is 1,023 mm and 299 mm respectively. The annual rainfall in the region is 6,900mm. This was aggravated by the absence of proper drainage in the slide zone. The upper layer of the slide is permeable to semi-permeable in nature, allowing the water to percolate into the soil. This saturated the soil with water and thereby decreasing the strength of the soil thus resulting in slope failure. The drains from the Kharbandi Check post and Goenpa area are allowed to flow freely into the unstable slope which too is contributing to sliding of the material. It is also reported by the Lama of the Goenpa that the boulders from the stream channel were being collected by the people from Jaigaon area and sold for construction elsewhere. Excavation for extraction of boulders and clayey material were being carried out illegally near the border, which has also indirectly contributed to the failure of slope as the toe support has been removed.

Seismic activity

South Asia is one of the most earthquake prone regions in the world. Six countries of South Asia, from Afghanistan in the west, through Pakistan, India, Nepal and Bhutan to Bangladesh in the east are located within most seismically active Himalayan-Hindukush mountain belt which has seen some of the worst earthquakes recorded in human history.

The world's youngest mountain belt, the Himalaya is still evolving due to northward push of the Indian Plate towards the Eurasian plate. As a result Himalaya has emerged as the largest active continent-continent collision zone on earth causing numerous major and great earthquakes. About 46 seismic events have been recorded within the territory of Bhutan during 1928 to 1998.

In recent years, Thimphu, Paro and Phuentsholing have witnessed the effects of four significant earthquakes, which had caused some damages to buildings, blocking of highways and also some loss of lives. While it is agreed that Bhutan lies in one of the most seismically active regions of the world, there is no real consensus on how vulnerable Bhutan is, given the lack of adequate research.

Geotechnical Assessment

The field observations show on average very weak intact rock strength having Uniaxial Compressive Strength (UCS) value ranging from 0.60 - 1.50 MPa which can be broken down by hand in most cases. There are occasional interbands of quartzite and dolomite which is moderately to strong rock with (UCS) values ranging from34 to 55 MPa.

Slope stability assessment

Visual observation during the field investigation supported by different analyses from the earlier studies and by the DGM (Table 1) show that the landslides areas are not stable. This is because the geology is very fragile and the area experiences very heavy precipitation during monsoon (June to September).The geotechnically sensitive rock mass of thinly bedded of phyllite and talcose phyllite in the landslides areas means, proper mitigation structures should be built in order to contain the problems.

Ground water table

The water table is the top surface of the saturated zone of water in an aquifer. It fluctuates as water enters or leaves it and is usually measured in two ways: depth to water and height above sea level. Water table levels are monitored worldwide. They indicate the availability of drinking water and the potential to irrigate farmlands. Nearly every major city on earth depends on water derived from the aquifer. The Department of Geology & Mines normally determines the depth of ground water by carrying out geophysical studies of the ground through resistivity survey. Though no resistivity survey was conducted to determine the depth of ground water table, through the study of the nature of terrain and the data available from the nearby areas, the depth of ground water table in this area is expected to be greater than 50m depth.

Regional Geology

The Phuentsholing area exposes the rocks of the Himalayan frontal belt trending in ENE - WSW direction with shallow to moderate dips towards North. The tectonic succession of the area from north to south is presented in the table below:

Table 2: The tectonic succession of the area from North to South

North	
Shumar Formation	Variegated calcareous quartzite with bands of dark grey carb shale talcose bands, phyllites white to greenish grey massive quartzite with occasional pebble beds.
-------------------------------- Thrust------------------------------	
Manas Formation	Grey phyllites, carb phyllites quartzite and limestone bands. Grey to light grey dolomite, with phyllites and thin limestone bands.
Phuentsholing Formation	Variegated purple and green phyllites and quartzite, minor limestone and meta basic sills.
----------------------------MBT------------------------------------	
Alluvium	
South	

Local Geology

Variegated (purple, gray, pink, carbonaceous) phyllite, talcose phyllite with thin bands of grayish white quartzite, limonitic quartzite , dolomite bands and basic rocks are the rock types found in the area of study which belongs to the Phuntsholing Formation of Buxa Group of rocks. The variegated phyllite is highly weathered, fractured and at places decomposed to residual soil. These areas are traversed by major tectonic and neo-tectonic activities resulting in formation of landslides at different structural levels. Geological mapping was carried out to know their structures such as bedding, foliation, lineation, faults and folds, etc.

Proposed remedial measures

- Catch/garland drain should be constructed on top of the crown of the active landslides
- The tension cracks have to be filled by fine materials and stemmed it properly so as to avoid infiltration of the surface run off during precipitation.
- Check dams are recommended to construct as shown in the Plate No. (Remedial measure map).
- Some of the drains have to be re-aligned (or course of the river/stream have to be changed) so as to control active erosion and incision of the stream/river bed.
- Water seepages from the landslide areas should be properly collected and safely channeled to preferably to the natural gully or depressions.
- Bio-engineering with suitable species of plants where possible are recommended to carry out prior to onset of the rainy season.
- Landscaping by benching and gentle sloping should be done particularly in the steep slopes.
- Application of the geo-textile may be done near the crown of the landslides on highly to completely weathered rock and soil.
- Excavation to offload the upper part of landslide may be done to reduce the deadload.
- Lime/cement columns should be negotiated where ever feasible.
- No excavated materials should be thrown downhill.

Acknowledgement

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Table of contents

Table of Contents

List of Figures

List of Tables

List of Plates

I. Landslides in between Old Hospital and RBA family colony under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag

II. Rinchending Goenpa Landslide

III. Kharbandi Check Post Landslide

Plate-9: Geological and engineering geological map of the Kharbandi Check Post Landslides areas under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-10: Slope map of the Kharbandi Check Post Landslide areas under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-11: Remedial measure map of the Kharbandi Check Post Landslide areas under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-12: Geological cross-section along A-A` (N75^{o}W to S75^{o}E),B-B’ (N58^{o}W to S58^{o}E),C-C’ (N36^{o}W to S36^{o}E) and D-D’ (N16^{o}W to S16^{o}E) showing the landslide and other topographical features of the Kharbandi Check Post areas under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

IV. Landslide of the West of Reldri Higher Secondary School

Plate-13: Geological and engineering geological map of the landslide areas of the West of the Reldri Higher Secondary School under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-14: Slope map of the landslide areas of the West of the Reldri Higher Secondary School under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-15: Remedial measure map of the landslide areas of the West of the Reldri Higher Secondary School colony under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

Plate-16: Geological cross-section along A-A` (N78^{o}W to S78^{o}E) and B-B’ (N17^{o}W to S17^{o}E) showing the landslide and other topographical features of the of the West of the Reldri Higher Secondary School under the extended Township of Phuentsholing Thromde,Chukha Dzongkhag. Scale 1:1000

1. GENERAL INTRODUCTION

1.1 Objective of the PPG technical feasibility study

The main objective of the PPG technical feasibility study was to assess the geological and geotechnical conditions of critical landslides and to propose various remedial measures (in terms of civil structures, drainages and bio-engineering) in the landslide prone areas under P/ling Thromde.

1.2 Bhutan Geology

From a geo-tectonic perspective Bhutan has three zones: the Frontal Belt, making up the foothills and parts of the Lesser or Lower Himalaya; the Central Crystalline Belt, occupying portions of the Lesser and Higher Himalaya; and the Tethyan Belt, covering the Higher Himalaya and isolated but large portions of the Lesser Himalaya. The Frontal Belt consists of recent deposits of sand, gravel, and boulders in the foothill terraces. The Siwalik group of rocks consists of sedimentary and meta-sedimentary rocks extending in an east-west direction and dipping north. They are exposed in the south-central part of the country extending from the east of Raidak river (Wang Chhu) to the west of Sarpang town and in the eastern part from the east of Manas river to the eastern boundary with the Indian state of Arunachal Pradesh. The Damuda (Gondwana) and Diuri Formations are exposed in the eastern part of the country. The Damuda rocks of Permian age consist of sandstone, shale, and coal seams; they overlie the Siwalik rocks along the Main Boundary Thrust. The Diuri Formation, at times considered part of the Damuda, comprises grey slate boulders, made up of pebbles of quartzite, phyllite, dolomite, and gneiss in a slaty matrix. The Buxa group of rocks consists of dolomite, variegated phyllite, quartzite, and conglomerate. This group of rocks stretches from the western-most part of the country to the east along the foothills. The Shumar Formation overlies the Buxa group and consists of meta-sedimentary phyllite, quartzite, and thin marble bands.

The two main lithological groups of metamorphic thrust sheets of the Central Crystalline Belt are the Thimphu Gneissic Complex and the Paro Formation. The Thimphu Gneissic Complex is characterized by migmatites and biotite-granite-gneisses with thin beds of quartzite, quartz mica schist, calc-silicate, and marble, and is the major rock type covering the country. The Paro Formation is characterized by quartz mica schist, quartzite, calc-silicate, marble, and a thin bed of graphitic schist, and this is exposed in and around Paro. The Central Crystalline Belt is affected by intrusion of tourmaline bearing granites and pegmatites in the form of dykes, sills, laccoliths, and larger intrusions. The larger intrusive bodies are concentrated in the northern ranges.

The geology and topography of Bhutan are thus shaped by the intense tectonic activity and made up of uplifted sedimentary and metamorphic rocks, which makes the geology among the most fragile in the Sub-Himalayan range. The geology is also highly sensitive to intense rainfall and surface runoff and erosion rates are high, frequently resulting in substantial landslides[1] and other climate-induced disasters such as landslides and flash floods.

[1] A Provisional Physiographic Zonation of Bhutan by Chencho Norbu et al, National Soil Services Center, Semtokha, and Cranfield University, 2004.

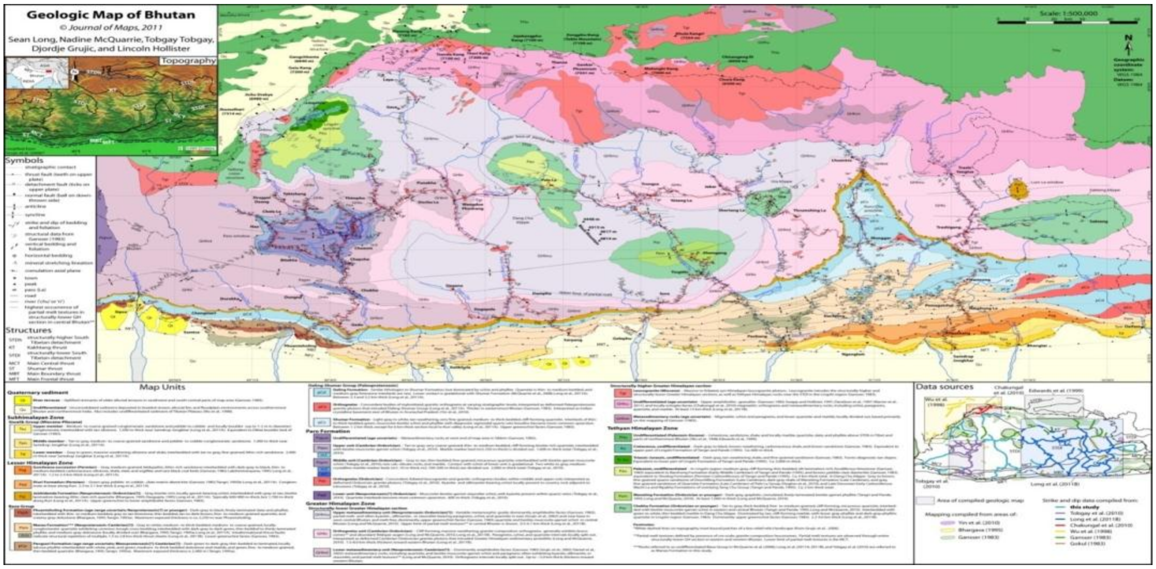


Figure 1: Geological map of Bhutan

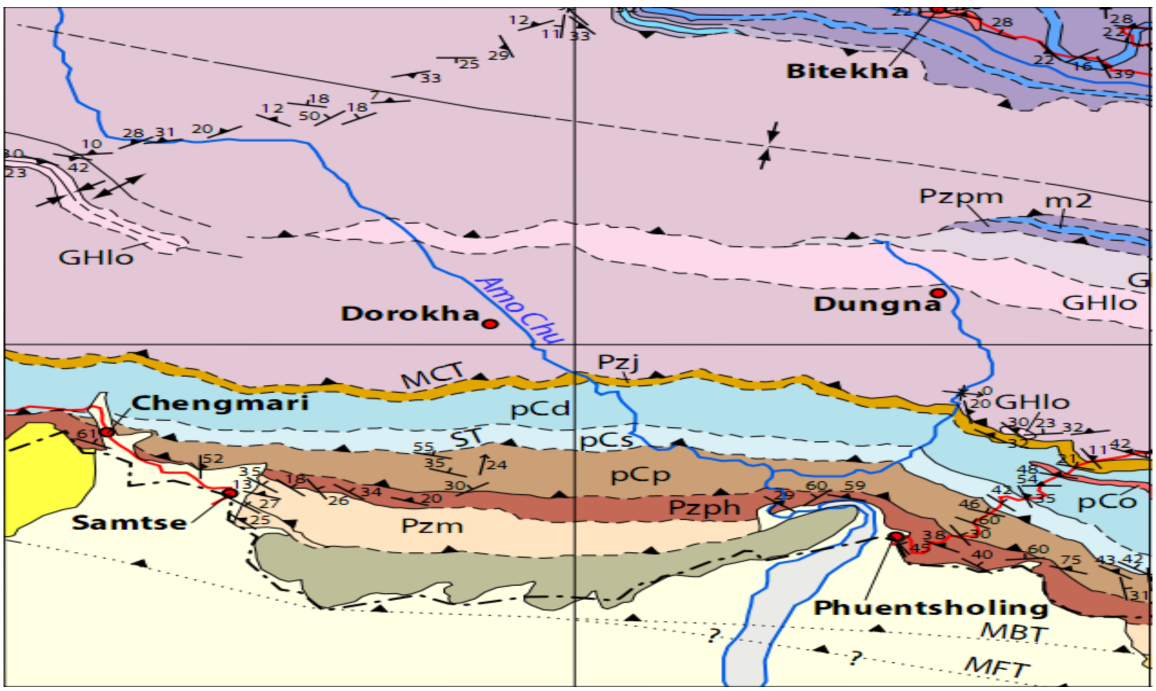


Figure 2: Regional geological map of Bhutan Himalaya

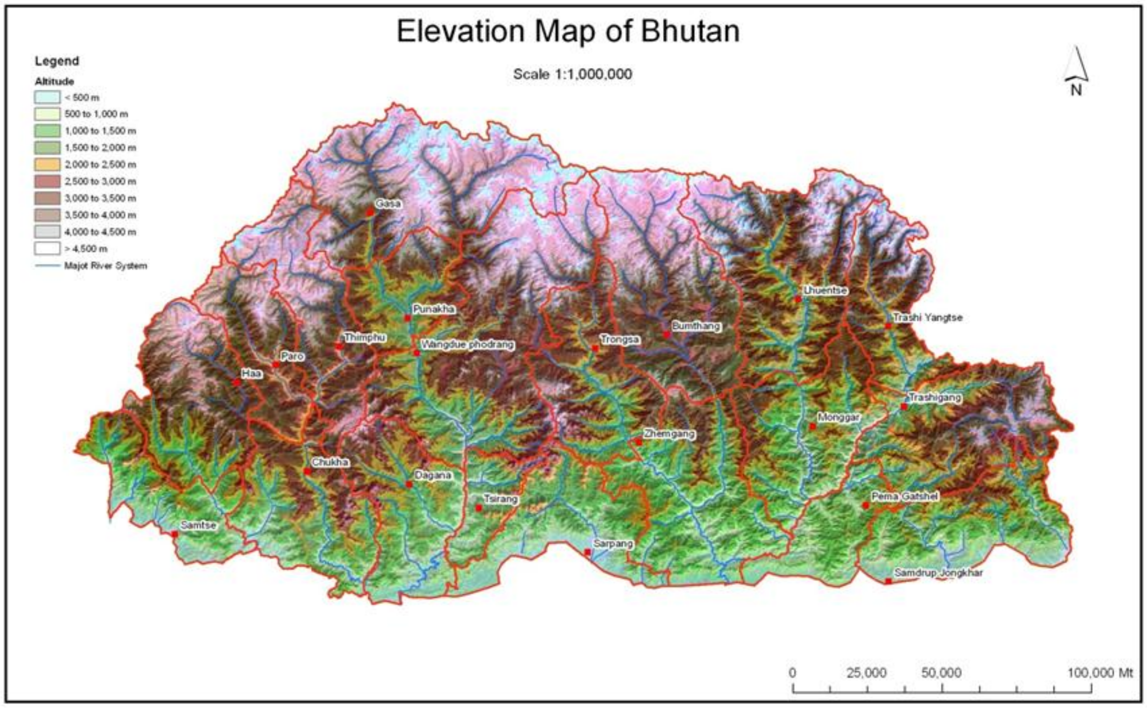


Figure 3: The digital elevation map of Bhutan based on regional geomorphic map

Table 3: Tectonostratigraphy of Bhutan Himalaya from North to south

NORTH			
Group	**Formation**	**Rock types**	**Age**
------------------------------Main Central Thrust---			
Daling-Shumar Group	Daling Formation	Similar lithologies to Shumar Formation, but dominated by schist and phyllite. Quartzite is thin-to medium-bedded, and medium-gray limestone interbeds are rare. Lower contact is gradational with Shumar Formation.	P A L O P R O T E R O Z O I C
	Orthogneiss	Concordant bodies of mylonitized, granitic orthogneiss at varying stratigraphic levels; interpreted as deformed Paleoproterozoic granite plutons that intruded Daling-Shumar Group. Thicker in easternmost Bhutan .Interpreted as Indian crystalline basement east of Bhutan in Arunachal Pradesh	
	Shumar Formation	Light-gray to white, tan-weathering, very fine-grained, medium- to thick-bedded, cliff-forming quartzite. Interbeds of thin to thick-bedded, green, muscovite-biotite schist and phyllite with diagnostic sigmoidal quartz vein boudins become more common up section. Between 1-2 km thick, except for 6 km-thick section local to Kuri valley .	
------------------------------------- Shumar Thrust--			
Baxa Group	Phuentsholing	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. Maximum	age range uncertain; Neoproterozoic[?] or

		exposed thickness is ca. 2,250 m near Phuentsholing.	younger-
	Manas:	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) . Intraformational thrust faults indicate structural repetition of multiple, 1.5 to 2.8 km-thick thrust sheets . Lower greenschist facies	Neoproterozoic-Cambrian[?]
	Pangsari:	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	age range uncertain; Mesoproterozoic[?]-Cambrian[?]
---------------------------------------Baxa Thrust---			
Lesser Himalayan Zone	Gondwana succession	Coal bearing horizon, quartzitic-sandstone, carbonaceous slate and shales.	Permian
	Diuri Formation	Green-gray, pebble- to cobble-, slate-matrix diamictite .	Permian
	Jaishidanda Formation	Gray, biotite-rich, locally garnet-bearing schist, interbedded with gray to tan, biotite lamination -bearing, lithic clast-rich quartzite Typically 600-900 m-thick, but 1,700 m-thick along Kuri .Upper greenschist to lower amphibolite facies.	(Neoproterozoic-Ordovician [?])
------------------------------------- Main Boundary Thrust ---			
Sub himalayan Zone S I W A L I K	Upper	Medium- to coarse-grained conglomeratic sandstone and pebble-to cobble- and locally boulder-conglomerate, interbedded with tan siltstone. 1,500 m-thick near Samdrup Jongkhar.	Miocene-Pliocene
	Middle	Tan to gray, medium- to coarse-grained sandstone and pebble- to cobble-conglomeratic sandstone. 1,300 m-thick near Samdrup Jongkhar.	
	Lower	Gray to green, massive-weathering siltstone and shale, interbedded with tan to gray, fine-grained, lithic-rich sandstone. 2,900m-thick near Samdrup Jongkhar .	
------------------------------------Main Frontal Thrust---			
Quaternary sediment	River terraces	Uplifted remnants of older alluvial terraces in southwest and south-central parts of map area .	
	Undifferentiated	Unconsolidated sediment deposited in braided stream, alluvial fan, and floodplain environments across southernmost Bhutan and northernmost India. Also includes undifferentiated sediment of Tibetan Plateau.	
SOUTH			

1.3 Geology in Phuentsholing

The geomorphic features of the areas are characterized by the abrupt rise of the topography from the Indian flood plain from the altitude of as low as 100m to 400m within an aerial distance of less than 1km. Numerous parallel type of drainages flowing from north to south marks ruggedness of the topography.

The geology of the area falls into Phuentsholing Formation belonging to Buxa Group of Rocks which comprises of quartzite, greenish grey, variegated and carbonaceous phyllilite. There occurs occasional dissemination of the mineral pyrite in the rock formation in the slide areas. The mineral pyrite with chemical composition of FeS_2 when coming in contact with water oxidizes very fast forming iron hydroxide which releases sulphur making the terrain little acidic which ultimately enhances the process of weathering on the rocks. Moreover the formation falls over the Main Boundary Thrust and besides that sign of active faulting within the formation itself has been reported by previous workers in the nearby area towards south east of Goenpa where inversion in the river terrace has been observed. The rocks here have a general trend of N10ºW-S10ºE having a dip amount ranging from 58º to 80º towards NE. The rocks are crushed and highly weathered which could be easily picked by a geological hammer. A lot of minor folds have been observed in the phyllite. A fault trending E-W and dipping towards north with an amount of 26º have been observed below ChereyJe's residence. Displacement in the upper lying quartzite has been observed where the hanging wall had been dragged over the footwall. The quartzite is also highly fractured and is blocky in nature.

All the four critical landslides proposed for mitigation in Phuentsholing (details in subsequent chapter) are located in between150masl to 440masl having their slope angle ranging from 25º to more than 60º and with undulated and rugged topography rising suddenly from the flood plains of West Bengal, India. These flood plains appears to be formed by the Amochu (Toorsa River) and the Bhalujhora,Pazdekha chu and Singye chu in the western and the eastern parts of the areas. Rivers/streams/gullies in the area are mostly dendritic pattern and very susceptible for changing their courses especially during monsoon.

All the landslide crowns are easily approachable by 1.5km to 7km road from the Phuentsholing town and base of the landslides from the Jaigaon/Khokla, West Bengal, India. But the accessibility in the body parts of the landslides is inaccessible owing to their steep and rugged topography.

Predominantly dark gray to black colored carbonaceous phyllite with variegated (purple, gray, green and grayish white) phyllite with interbandings of grayish white quartzite, pink to reddish brown quartzite, amphibolite lenses, reddish brown to light yellowish brown limonitic quartzite and thin bands of dolomite are found to occur in the area which belong to the Phuentsholing Formation of Buxa Group of Rocks. These rocks are highly weathered and intensely fractured giving rise to development of numerous joint sets at diverse directions.

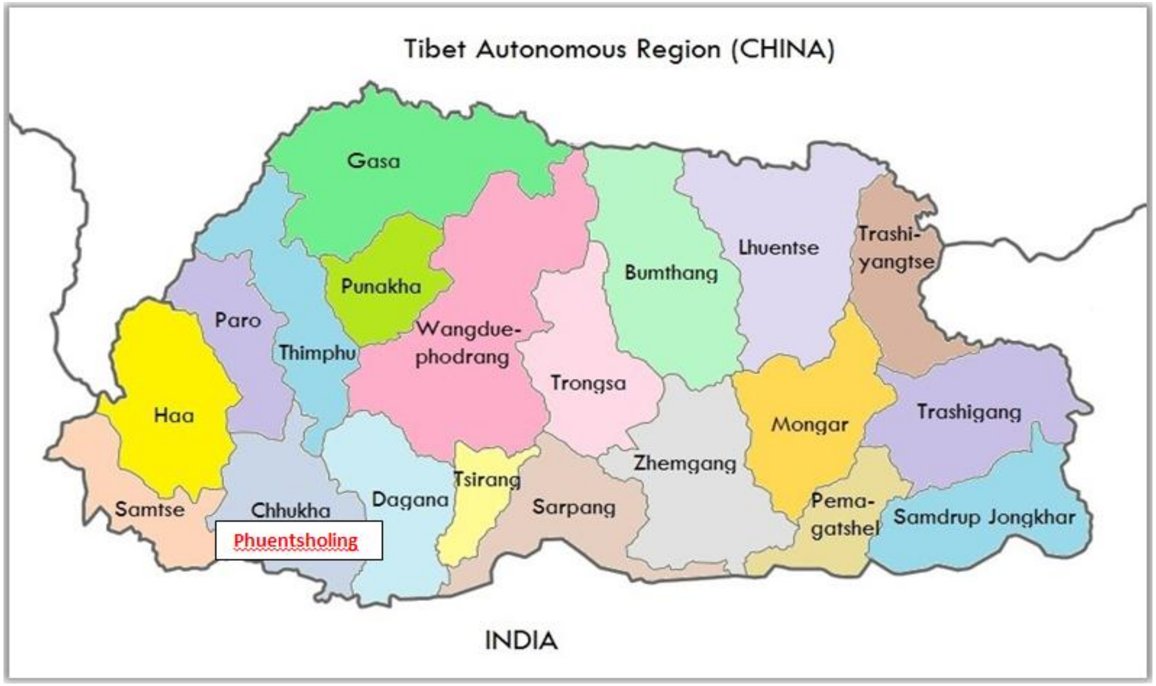


Figure 4: Location map of the critical landslides under Phuentsholing Thromde (southern Bhutan)

Figure 5: showing built up areas at the potentially dangerous landslides

Figure 6: Highly weathered and folded gray phyllite

Figure 7: Karst in dolomite

1.4 Problem related to landslides

The landslide have both short term and long term impacts on society and environment inlcuding loss of life and property at the site and also landscape changes that can be permanent, including loss of cultivable land and environmental impact in terms of erosion and soil loss, leading to relocation of settlements. The landslides also reduce the capacity and effective life of hydroelectric and multipurpose projects by adding enormous amount of silt load into the reservoirs.

The triggering factors are invariably excessive water, earthquakes, and ruggedness of the topography. Landslides triggered by heavy rain have been constant sources of destruction of property and loss of lives. Dormant as well as active slides are threat to human life and property. Their study and monitoring has become imperative to safeguard against destruction by them. Developmental activities to be sustainable must be confined away from landslides prone and landslide affected locations. However Bhutan being a rugged country, finding a suitable location for human settlement is a challenge.

A large number of human settlements on the Himalayas are situated either on old landslide masses or on landslide-prone areas (**Fig. 8)**

Figure 8: Human settlement in landslide prone areas in Bhutan

National infrastructures such as roads, bridges, dams, hydropower stations, canals, buildings repeatedly suffer landslide and flood damages. A rapid rise in construction of infrastructures including roads, hydropower, and dams with inadequate or little consideration against the natural hazards has considerably contributed to triggering of landslides in the mountainous areas.

Figure 9: Heavy rainfall causes several road blocks (Gelephu-Zhemgang highway)

Figure 10: Artificial lake formed due to landslide which blocked the streams (Eastern Bhutan)

1.5 Causes of landslides

The causes of landslides in Bhutan can be put in four categories: (i) geological causes (weak, weathered, sheared materials, and contrast in permeability of materials); (ii) morphological causes (fluvial, erosion of slope toe, tectonic uplift, erosion of marginal sides; (iii) physical causes (intense rainfall, prolonged or exceptional precipitation, earthquake, and snowmelt); and (iv) human causes (deforestation, irrigation, road construction, water leakage, land use changes).

In Bhutan, intense rainfall may be regarded as the main triggering factor for landslides because most landslides in the region occur during monsoon period when the region receives more rainfall than it can accommodate.

2. CLIMATE CHANGE SCENARIOS

2.1 Introduction

Changes in the climate occur as a result both of internal variability within the climate system and external factors (both natural and anthropogenic). The major influence of external factors is related to the increasing concentrations of greenhouse gases which affect the atmospheric absorption properties of long wave radiation, thereby leading to increased radioactive forcing that tend to warm the lower atmosphere and the earth's surface (Solomon et al. 2007). The temperature increase will be accompanied by changes in cloud cover, precipitation, air humidity, radiation, wind and other meteorological elements. These effects will lead to changes in the land phase of the hydrological cycle with impacts on glacier mass balance, snow storage, soil moisture in the unsaturated zone, groundwater storage, evaporation and runoff.

Bhutan is experiencing visible impact of climate change on agriculture, biodiversity, health, infrastructure and water resources. Although the country is committed to a high level of environmental protection, it remains at significant risk of localized impacts caused by climate change. While Bhutan is a net carbon sink, it suffers from a human development challenge that is not of its own making.

Nowhere is the challenge of responding to the varied impacts of climate change more daunting than in the Hindukush-Himalaya region. IPCC's Fourth Assessment Report designated this region as a "white spot" because of the limited number of scientific studies conducted in this region, including Bhutan. While temperature is likely to go up in the region, precipitation will be more erratic in the future implying increasing uncertainty with regard to floods and landslides.

Realizing these undaunted challenges the Royal Government of Bhutan has sought to strengthen its capacity to manage climate change risks, for example, through the development of its National Adaptation Programme of Action (NAPA) and various Climate Change strategies. These exercises highlighted the need to develop targeted tools to incorporate climate change risk management in development planning. Each of the line ministries in Bhutan has an increasing understanding that changes in climate patterns are impacting their sectors, but little is known on how to address these issues in a more sustainable and systematic manner.

2.2 Precipitation in Phuentsholing

Climate of Bhutan is extremely varied and controlled by the monsoonal winds and the regional geomorphology. It ranges from seasonably humid subtropical to semiarid alpine. In Bhutan, monsoon is the major source of rainfall in summer and approximately 90% of the total annual precipitation takes place from June to September. Travelling from south towards North, variation in the climate can be experienced as being hot, warm, cool, cold, and very cold. Based on this climatic variation, Bhutan can be divided into six climatic zones: tropical, subtropical, warm temperate, cool temperate, alpine, arctic or tundra.

The monsoon enters Bhutan during the first week of June and it brings extreme rain until September. The duration of the monsoon and amount of rain varies across Bhutan. The monsoon is longest and wettest in the southern part of the country.

The measured values of mean annual precipitation in Bhutan range from a low of approximately 250 mm at a few areas on the north of the Himalaya to many areas exceeding 6,000 mm especially in and around Phuentsoling area. The annual rainfall in the capital city of Thimphu (Capital of Bhutan) generally exceeds 1,350 mm. The mean annual rainfall varying between 1,500 mm and 2,500 mm predominate over most of the country. Daily distribution of precipitation during the rainy season is also uneven. Sometimes, 10% of the total annual precipitation can occur in a single day while 50% of the total annual rainfall can also occur within 10 days of the summer. This type of uneven distribution of precipitation plays an important role in triggering landslides in Bhutan. The orographic effect of the mountains is also the main cause of extreme rainfall in Bhutan during monsoon.

The studied area falls in the sub-tropical climate zone with warm to hot summer and pleasant to cold winter. From the past records the mean annual rain fall varies. There is a drastic fluctuation in annual rainfall. The maximum rain fall was recorded 6699mm during the year 1998 and the minimum was in 2006 where the total rain fall recorded was 1996mm. The variation of precipitation during monsoon months (May-Aug) over the past 16 years (1996-2012) is provided below.

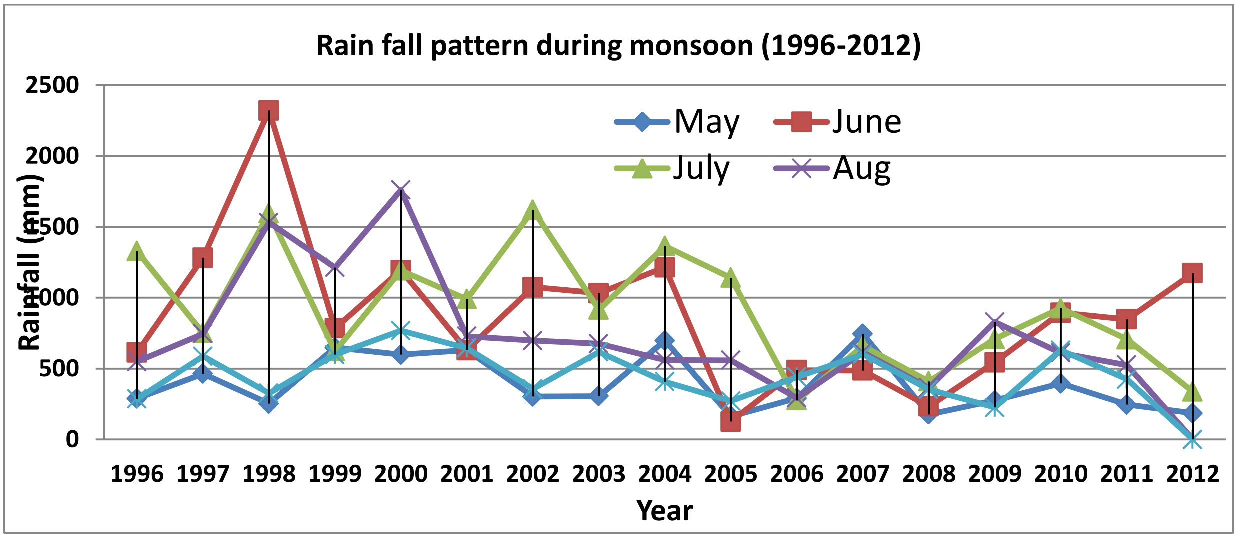


Figure 11: Variation of rainfall pattern during monsoon season from 1996-2012 (DHMS, MoEA)

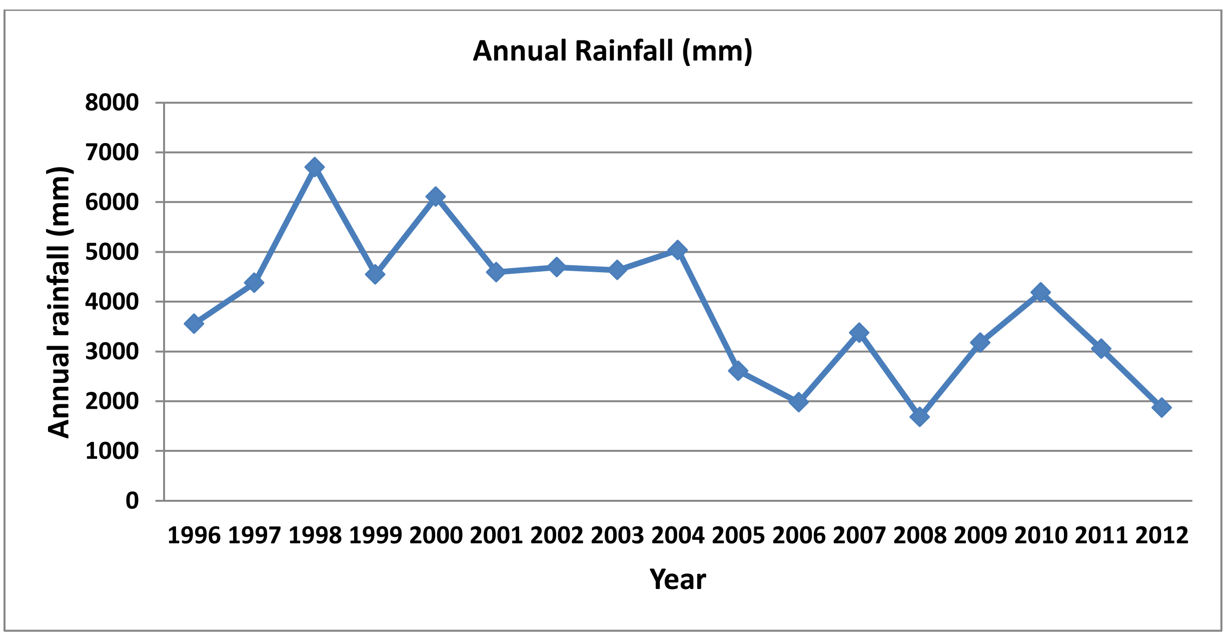


Figure 12: The annual rainfall pattern in P/Ling from 1996 till 2012 (DHMS, MoEA)

The rainfall in the year 1998 was more than 3 times than the 2008 rainfall indicating drastic variations in rainfall patterns. The precipitation pattern found to vary from one year to another. The overall erratic rainfall patterns induced due to the so called climate change phenomena may dramatically increase landslide incidents through weakening of a slope through saturation by unusually heavy rainfall (higher intensity rainfall within short duration). The hillsides which are lying at the critical angle of slope stability may be disturbed by adding the weight by the amount of rainfall which is higher than the normal amount at a particular event.

Table 4: Causes and preventive measures

Causes	Preventive measures
Factors Related to Increased Forces	
Slope gradient (steeper slopes are more prone to mass movement)	Reduce slope (e.g. constructing benches and retaining walls along road cuts and coastal cliffs)
Factors Related to Decreased Resisting Forces (Reduced Strength of Mass)	
Lateral support removed by erosion or construction	Reinforce base of slope with retaining wall or by grouting
Moisture content (increased to the point of the slope material behaving more like a liquid than a solid)	Seal surface cracks to prevent infiltration; drain surface water from potential mass movement material with ditches; install subsurface drainage system
Vegetation (roots of vegetation provide much strength to materials on hill slopes; vegetation absorbs water and minimizes the accumulation of water in the soil)	Replant slopes immediately after removal of vegetation during logging or development; protect slopes with cover or mulch while seedlings become established
Nature of geologic materials (i.e. highly weathered; or rock layers inclined parallel to slope)	Construct pilings through mass; avoid building on slopes with rocks layers parallel to the slope

3 METHODOLOGY

The following methodologies were adopted to carry out the technical assessment for the four critical landslides under the extended Township of Phuentsholing Thromde. Large scale topographical survey was done in all the critical landslide areas. Geological and engineering geological mapping were also carried out to know their structures, material characteristics, ground water etc. Numerous trial pits were excavated in different locations particularly near the periphery of the active landslide areas to know their soil profile and also to collect the soil samples for determining their index, shear strength and other properties in the geotechnical laboratory.

3.1 Literature review (stock taking of past research and initiatives)

Bhutan Unit, Geological Survey of India had carried out the geological studies in the past and they have identified major lineaments/faults cross cutting nearby these areas. Some of the geologist from Japan had also identified the active neo-tectonic activities in these areas. Studies for mitigation for these landslides have been done by Department of Geology and Mines, Department of Roads (DoR), Ministry of Agriculture and Ministry of Economic Affairs (MOEA). DoR and Phuentsholing Municipality have done the mitigation measures in the Rinchending Goenpa landslides, Kharbandi Check post landslides in the past. The Kharbandi check post mitigation did not work because the flexible retaining structures are either washed away by erosive water while the landslides below the Rinchending Goenpa has been found to stabilize to some extent with the growth of vegetation. The proprietor of the Reldri Higher Secondary School also claimed to have done some protection works and bio-engineering however the landslides could not be contained.

3.2 The Topographical survey

Detailed topographical survey on the scale of 1:1000 with 2m contour interval was carried out using the Total Station (TS803), which enabled the team to prepare a topography map, geological & engineering geological map and remedial measure map respectively.

3.3 Control Points

Control points are used in DruRef_03 coordinate system which was established by the Phuntsholing Thromde.

Table 5: Table showing the control points used as references

NAME	EASTING	NORTHING	ELEVATION
SSM1011	190802.145	2970927.884	410.934
SSM27	190287.787	2970720.48	377.556
SSM58	189843.929	2970709.798	350.096
SSM59	189513.951	2970712.66	334.156

3.4 Data Acquisition

A traverse was also run to populate the control points to ease and simplify during data/feature collection. Throughout the survey the horizontal accuracy of less than 10mm and vertical accuracy of less than 1mm was maintained while providing control points. Field data was collected or acquired using Leica Total Station, roughly maintaining 2m grid between the points.

3.5 Other Data Used

Field data acquired during 2008-2009 field season by the department of Geology and Mines was used beyond our area of interest which doesn't have any landscape changes till now to prepare the map outside the area of interest. The field data was downloaded from Total Station in Liscad and than exported to Arc Map. The final map was prepared and produced in Arc Map (ArcGIS 9.3.1).

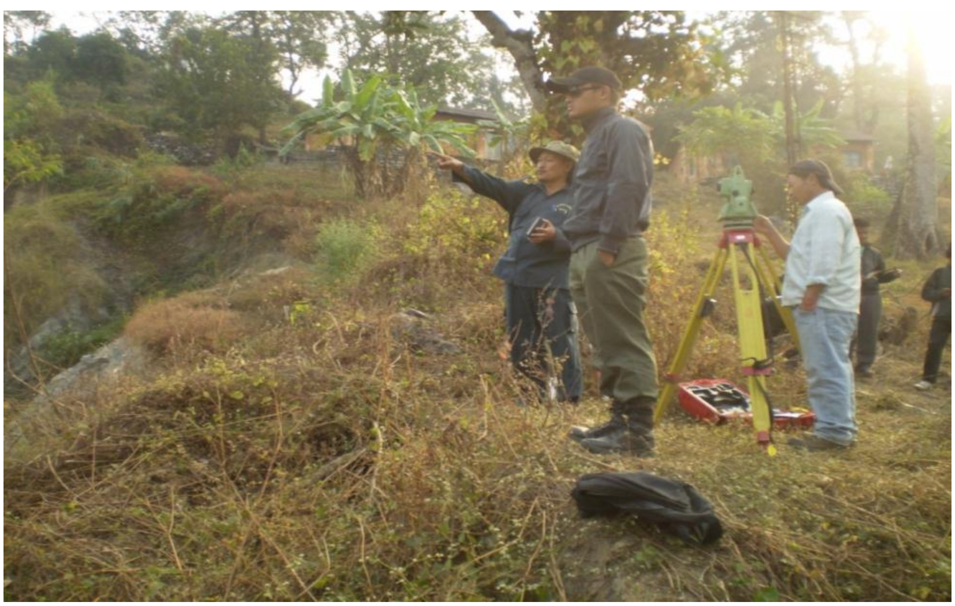


Figure 13: Detailed topographical survey on the crown of active landslide in between Old Hospital (MSD) and RBA family colony

3.6 Geological and engineering geological mapping

In general, the rock of the Phuentsholing formation strikes to the NW to SE and dip towards NE ranging their dip from 15° to more than 60°. There is also a local variation in their dip which might due to slight warping locally.

Engineering geological studies were conducted to determine the geotechnical parameters of the ground by observation of their mode of deposition. Although there is an aerial extent of the predominantly variegated phyllite exposures, owing to their fragile nature, the area of study is prone to landslides if timely attention is not given.

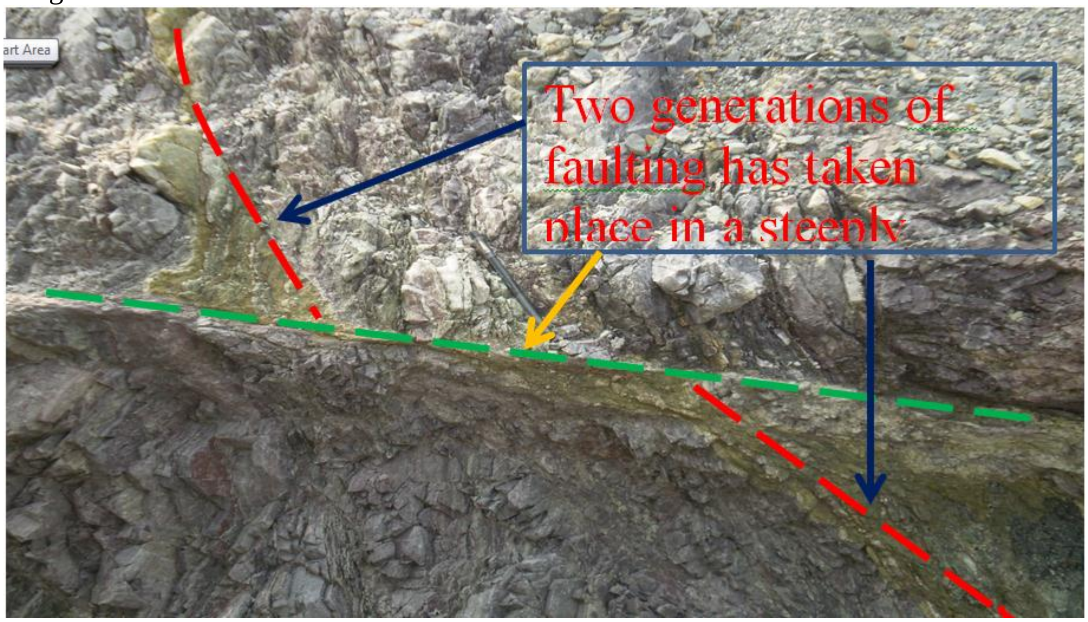


Figure 14:Photograph showing the low angle fault has displaced the older one

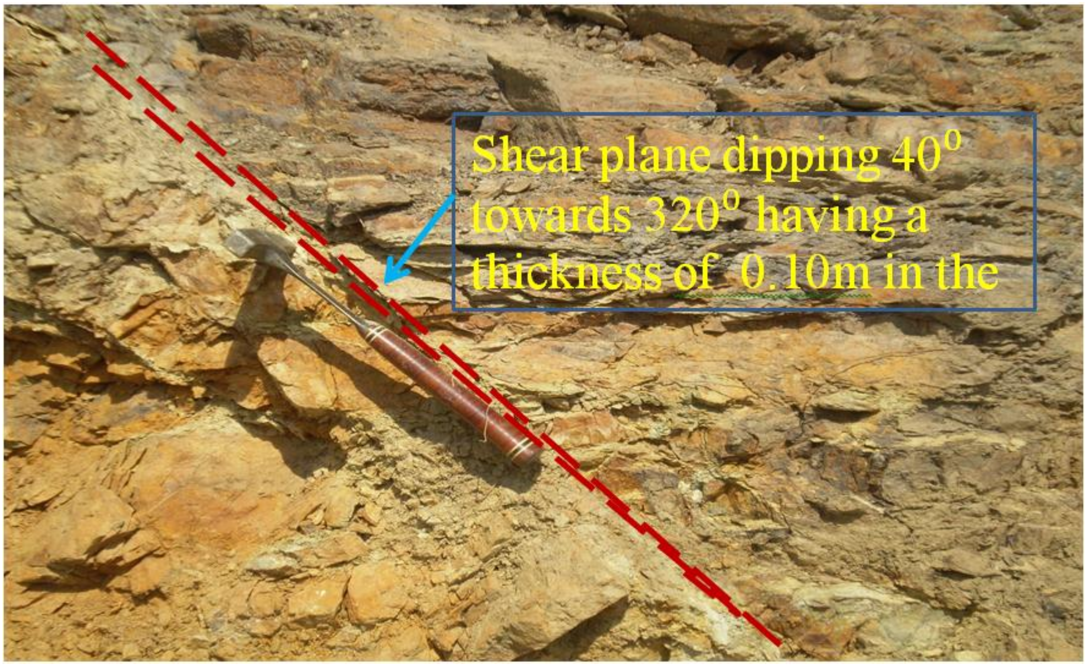


Figure 15: Shear plane in a grayish brown ferruginous quartzite

Figure 16: Photograph showing the active landslides due to toe scouring and rapid incision of the Stream/gully bed especially during peak monsoon.

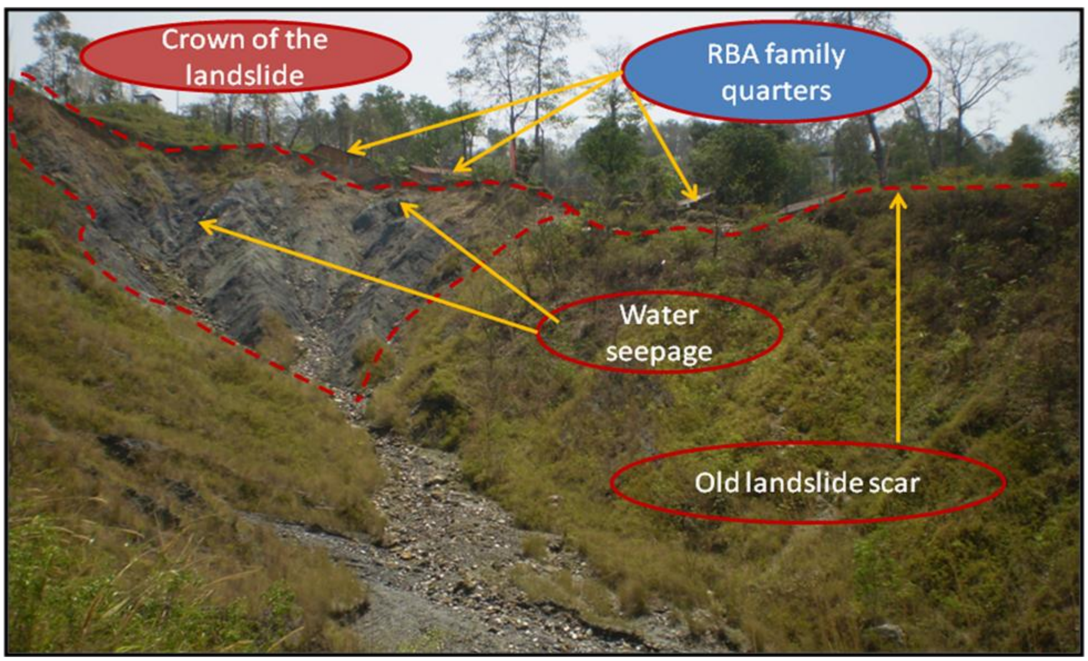


Figure 17: Photograph showing the propagating landslide near the RBA family colony

Figure 18: Flexible check dams and retaining structures constructed by Phuentsholing thromde To control the landslide

Figure 19: Active landslide to the west of reldri Higher Secondary School

Basically colluvial , fluvial and residual are the three types of soil found in the area under study. Rocks are highly to completely weathered and intensely fractured and some of the phyllites have been decomposed to residual soil. Ferruginous quartzite and phyllite are also turned to clayey soil/limonitic soil. Water seepages are most common within landslide areas.

3.7 Excavation of test pits and soil description

Nine numbers of test pits were excavated in different locations of the critical landslide areas to determine their sub-surface soil profile, material composition and their relative density. Pit loggings were done and the soil samples were collected for laboratory analysis. The description of the soil profiles of the various test pits are shown in the table below:

Table 6: Table showing the soil profile description in the Pit No.1 (HR-PIT/1)

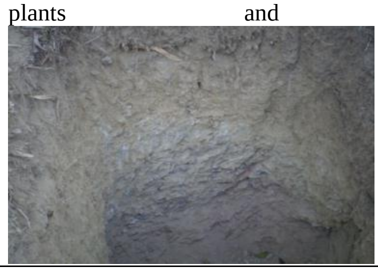
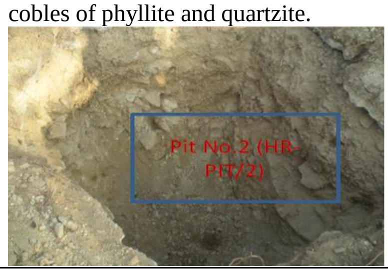
From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution: Particle size		%	Soil description
0.00	0.15	0.15	Boulder		0	Gray to slightly dark gray top soil (humus) which is slightly loose and friable in nature with roots of plants and trees. 
			Cobble		0	
			Gravel		5	
			Sand	Coarse	20	
				Medium	20	
				Fine	25	
			Silt		20	
			Clay		15	
0.15	2.00	1.85	Boulder		5	Slightly light yellowish brown colored clayey soil (Residual soil) with occasional presence of angular boulders, cobbles and gravels of phyllite and quartzite. The soil is slightly dense towards the bottom. The phyllite has been found to decompose to residual soil.
			Cobble		10	
			Gravel		15	
			Sand	Coarse	10	
				Medium	15	
				Fine	20	
			Silt		10	
			Clay		15	

Table 7: Description of soil profile in the Pit No.2 (HR-PIT/2)

From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution: Particle size		%	Soil description
0.00	0.20	0.20	Boulder		5	Graysih brown top soil with angular boulders and cobles of phyllite and quartzite. 
			Cobble		5	
			Gravel		5	
			Sand	Coarse	20	
				Medium	20	
				Fine	20	
			Silt		10	
			Clay		15	
0.20	0.60	0.40	Boulder		5	Graysih brown to slightly light yellowish brown clayey soil with angular boulders and cobbles of gray phyllite which are highly weathered and oxidized. The soil is slightly loose In nature.
			Cobble		10	
			Gravel		15	
			Sa	Coarse	10	
				Medium	15	

			n d	Fine	20	
			Silt		10	
			Clay		15	
0.60	2.00	1.40	Boulder		5	Grayish brown to slightly light yellowish brown clayey soil (residual soil) with occasional presence of highly to completely weathered and oxidized phyllite. The soil is found slightly dense in nature towards the bottom.
			Cobble		5	
			Gravel		10	
			S	Coarse	20	
			a	Medium	20	
			n	Fine	20	
			d			
			Silt		10	
			Clay		10	

Table 8: Description of soil profile in the Pit No.3 (RG-PIT/1)

From (m)	To (m)	Total (m)	Visual estimation for grain size distribution			Soil description
			Particle size		%	
0.00	0.25	0.25	Boulder		0	Grayish brown top soil with occasional presence of angular cobbles and gravels of phyllite. The soil is friable in nature. 
			Cobble		5	
			Gravel		5	
			S	Coarse	20	
			A	Medium	20	
			N	Fine	25	
			D			
			Silt		15	
			Clay		10	
0.25	0.90	0.65	Boulder		0	Grayish brown gravelly Clayey SAND with poor exposure of phyllite which is highly to completely weathered and decomposed to residual soil. Inter-layering of gray and brown colored residual soil is observed at depth. Roots of the bamboos are observed at this depth of the pit.
			Cobble		5	
			Gravel		15	
			S	Coarse	15	
			A	Medium	15	
			N	Fine	20	
			d			
			Silt		10	
			Clay		20	
0.90	2.00	1.10	Boulder		0	Gray to grayish brown phyllite, which is highly weathered, fractured, sheared and oxidized .The foliation of the phyllite is found to dip at an angle of 25° towards 45°. Roots of the bamboos are seen upto this depth.
			Cobble			
			Gravel			
			S			
			A			
			N			
			D			
			Silt			
			Clay			

Table 9: Description of soil profile in the Pit No.4 (RG-PIT/2)

From (m)	To (m)	Total (m)	Visual estimation for grain size distribution			Soil description
			Particle size		%	
0.00	0.35	0.35	Boulder		5	Grayish brown top soil with occasional presence of angular boulders, cobbles and gravels of dolomite and phyllite. The soil is slightly friable in nature. Roots of the plants and trees are abundantly found at this depth of the pit.
			Cobble		5	
			Gravel		5	
			S	Coarse	20	
			A	Medium	20	
			N	Fine	20	
			D			
			Silt		15	
			Clay		10	

						
0.35	1.45	1.10	Boulder		0	Grayish brown sandy slit CLAY with occasional presence of cobbles and gravels of phyllite and dolomite. The soil is slightly densenand plastic in nature.
			Cobble		5	
			Gravel		10	
			S	Coarse	15	
			A	Medium	15	
			N	Fine	20	
			d			
			Silt		15	
			Clay		20	
1.45	2.00	0.55	Boulder			Gray to dark gray phyllite, which is highly weathered, fractured and oxidized and at places decomposed to residual soil.. The phyllite shows it inclination of 21° towards 360°.
			Cobble			
			Gravel			
			S			
			A			
			N			
			D			
			Silt			
			Clay			

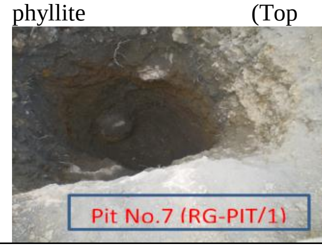
Table 10: Description of the soil profile in the pit No.5 (KCP-PIT/1)

From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution			Soil description
			Particle size		%	
0.00	0.20	0.20	Boulder		0	Grayish brown top soil with presence of angular cobbles and gravels of phyllite. 
			Cobble		5	
			Gravel		5	
			Sand	Coarse	20	
				Medium	25	
				Fine	25	
			Silt		10	
			Clay		10	
0.20	0.60	0.40	Boulder		5	Grayish brown clayey silty SAND with angular boulders, cobbles, gravels of phyllite. The soil is loose and slightly friable in nature.
			Cobble		5	
			Gravel		5	
			Sand	Coarse	15	
				Medium	20	
				Fine	20	
			Silt		15	
			Clay		15	
0.60	1.80	1.20	Boulder			Grayish brown gravelly SAND with little fines. Phyllite is exposed with 0.08 to 0.10m thick quartz vein intrusion parallel to the foliation. The phyllite is oriented to 030°/32°.It is highly weathered, fractured and also oxidized and at places decomposed to residual soil. The crack angle of the slip face is observed to 070°/62°.
			Cobble			
			Gravel			
			S	Coarse		
			a	Medium		
			n	Fine		
			d			
			Silt			
			Clay			

Table 11: Description of soil profile in the Pit No.6 (KCP-PIT/2)

From (m)	To (m)	Total (m)	Visual estimation for grain size distribution: Particle size		%	Soil description
0.00	0.50	0.50	Boulder		5	Grayish brown,boulder, cobbler, gravelly SAND with little fines. The soil is highly friable and loose in nature. Roots of thye plants are observed upto this depth. 
			Cobble		5	
			Gravel		10	
			S	Coarse	20	
			A	Medium	20	
			N	Fine	20	
			D			
			Silt		10	
			Clay		10	
0.50	1.60	1.10	Boulder			Highly disturbed gray phyllite with thin layers of grayish brown sand which is highly friable and loose in nature. The phyllte is oriented in diverse direction.
			Cobble			
			Gravel			
			S	Coarse		
			A	Medium		
			N	Fine		
			d			
			Silt			
			Clay			

Table 12: Description of the soil profile in the pit No.7 (RD-PIT/1)

From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution: Particle size		%	Soil description
0.00	1.00	1.00	Boulder		5	Grayish brown to pre-dominantly dark grayish brown colored clayey silty SAND with angular boulders, cobbles and gravels of quartzite and phyllite (Top soil). 
			Cobble		5	
			Gravel		10	
			Sand	Coarse	15	
				Medium	15	
				Fine	20	
			Silt		15	
			Clay		15	
1.00	1.70	0.70	Boulder		5	Grayish brown clayey silty SAND with occasional presence of angular boulders, cobbles and gravels of quartzite and phyllite.
			Cobble		10	
			Gravel		15	
			Sand	Coarse	10	
				Medium	15	
				Fine	20	
			Silt		10	
			Clay		15	
1.70	1.85	0.15	Boulder			Gray to ash gray gravelly sandy CLAY which is saturated and plastic in nature.
			Cobble			
			Gravel		15	
			Sand	Coarse	10	
				Medium	10	
				Fine	10	
			Silt		25	
			Clay		30	

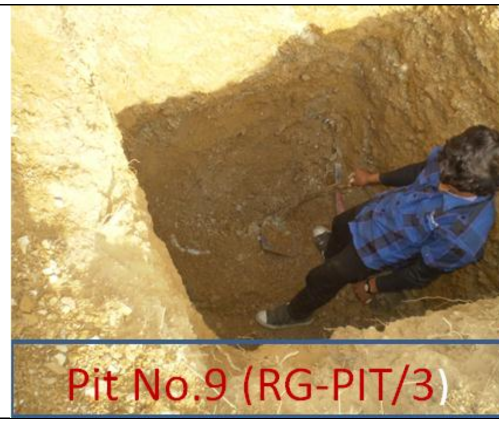
1.85	2.10	0.25	Boulder		0	Grayish brown gravelly SAND.
			Cobble		0	
			Gravel		15	
			Sand	Coarse	20	
				Medium	20	
				Fine	25	
			Silt		10	
			Clay		10	

Table 13: Description of the soil profile in the pit No.8 (RD-PIT/2)

From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution			Soil description
			Particle size		%	
0.00	0.80	0.80	Boulder		5	Grayish brown gravelly SAND with occasional presence of angular boulders of phyllite. The soil is saturated and plastic in nature. 
			Cobble		0	
			Gravel		20	
			Sand	Coarse	15	
				Medium	15	
				Fine	15	
			Silt		15	
			Clay		15	
0.80	1.25	0.45	Boulder		0	Dark gray colored carbonaceous phyllite decomposed to carbonaceous clay. The soil is slightly plastic in nature.
			Cobble		0	
			Gravel		10	
			Sand	Coarse	15	
				Medium	20	
				Fine	20	
			Silt		15	
			Clay		20	
1.25	1.60	0.35	Boulder		0	Ash gray colored talcose phyllite decomposed to clay which is highly plastic in nature with water at the bottom.
			Cobble		0	
			Gravel		10	
			Sand	Coarse	10	
				Medium	10	
				Fine	15	
			Silt		25	
			Clay		30	

Table 14: Description of the soil profile in the pit No.9 (RD-PIT/3)

From (m)	To (m)	Total length (m)	Visual estimation for grain size distribution		Soil description
			Particle size	%	
0.00	1.35	1.35	Boulder		Grayish brown top soil with highly disturbed gray phyllite. Layerings are seen but at diverse directions/ orientations. Some grayish brown limonitic soil is also seen upto a thickness of 0.10m.
			Cobble		
			Gravel		

			Sand	Coarse		
				Medium		
				Fine		
			Silt			
			Clay			
1.35	1.75	0.40	Boulder			Grayish brown phyllite with thin residual soil. The phyllite is oriented to 035°/35° but slightly disturbed and some of them have been decomposed to residual soil.
			Cobble			
			Gravel			
			Sand	Coarse		
				Medium		
				Fine		
			Silt			
			Clay			
1.75	2.00	0.25	Boulder			Grayish white to ash gray colored gravelly clay which is highly plastic in nature.
			Cobble			
			Gravel			
			Sand	Coarse		
				Medium		
				Fine		
			Silt			
			Clay			

3.8 Soil Sampling

Soil samples were collected from the excavated test pits and two tests such as direct shear box and Proctor tests were sent to the Material testing Laboratory of the Bhutan Standard Bureau, Thimphu and rest of the samples were analyzed in the Geotechnical Laboratory of the Department of Geology and Mines to determine their index test. The results are annexed in the report.

3.9 In-situ test: Portable Penetration Test (PPT)

The Portable Penetrometer is the instrument which measures the strength of soil for the purpose of the slope stability study in the field. It is normally used in the ground consisting of sand, silt or clay. The Portable Penetration Test (PPT) was carried out in 7 (seven) different locations adjacent to the excavated pits. The number of blows required to penetrate 16mm diameter rod for 10cm by freely falling 5kg hammer from a height of 50cm which is recorded and plotted against depth to determine the allowable bearing pressure of the ground as shown in the following tables: PPT tests were performed at different places especially in or near the excavated test pits to find out the strength parameters of the soil.

The graphical representation of the results are presented below for all the seven different locations. From the PPT test it is deduced that the soil is less dense as a result, PPT could be driven from 1.10m to 5.00 m depth.

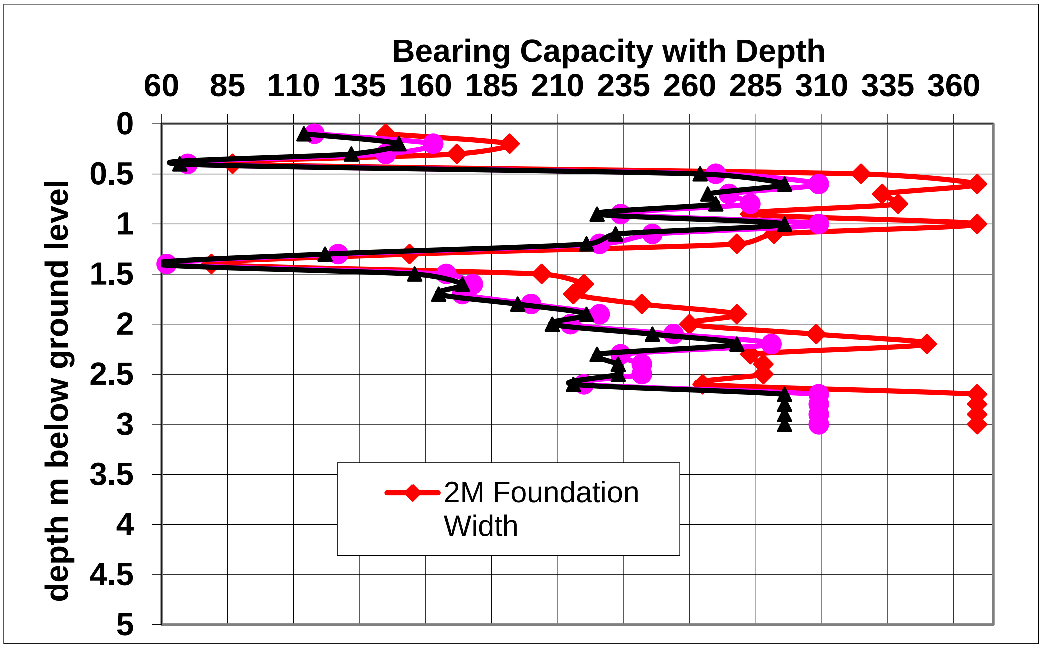


Figure 20: Plot of graph from the PPT test of the Pit No.1 (HR-PIT/1)

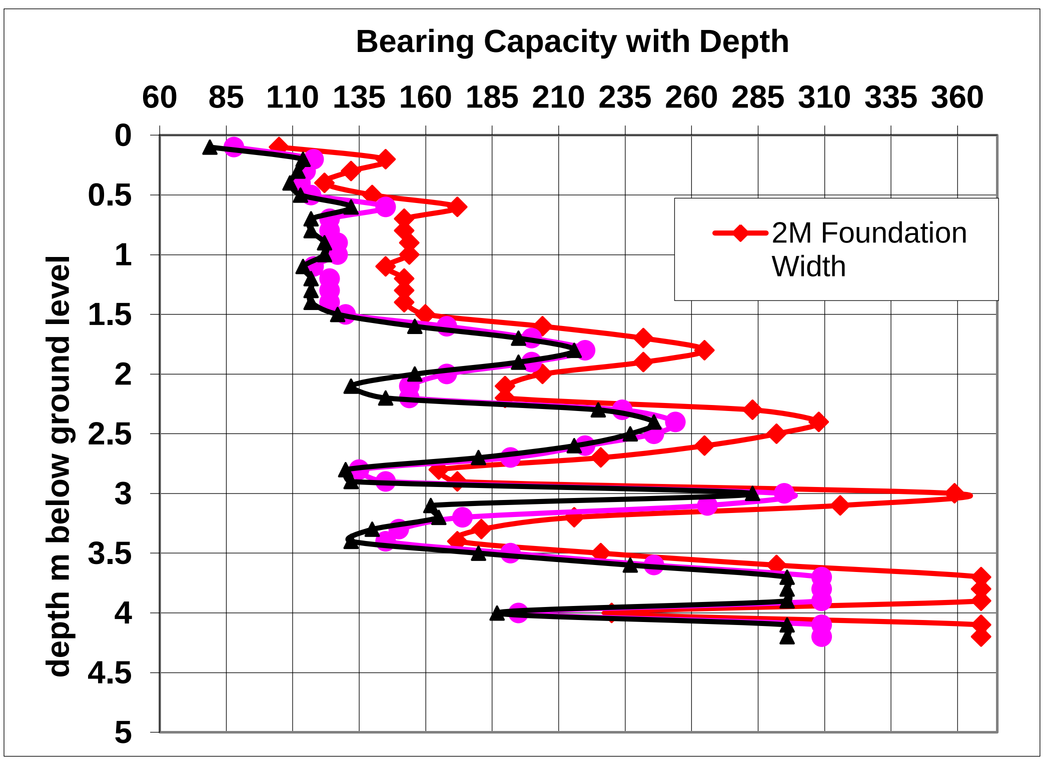


Figure 21: Plot of graph from the PPT test of the Pit No.2 (HR-PIT/2)

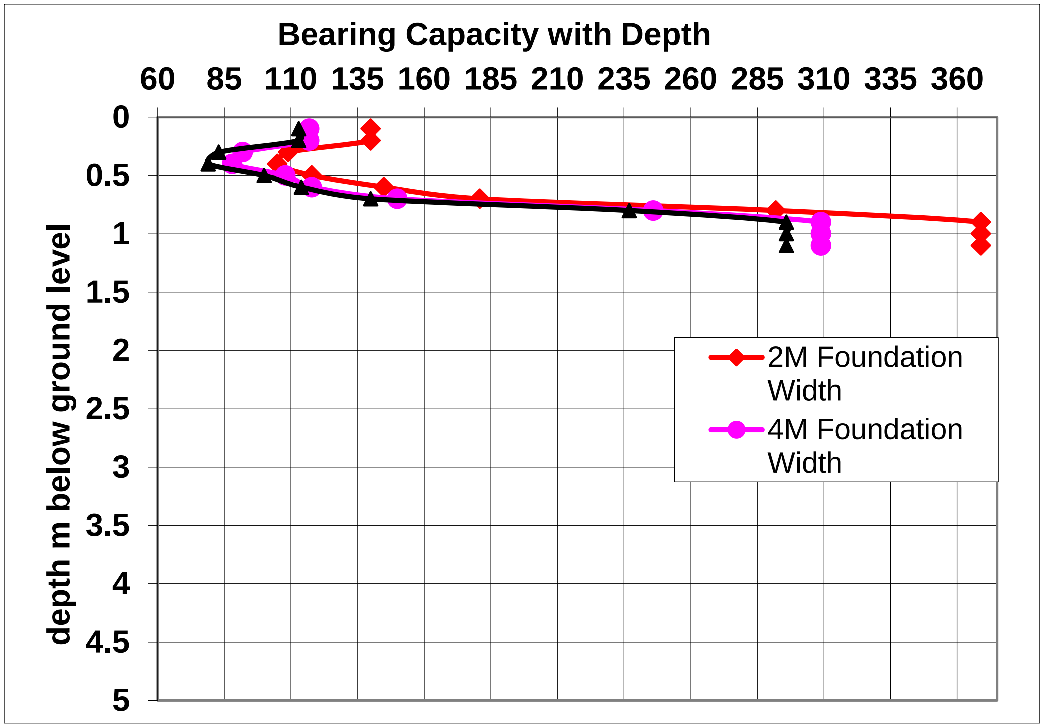


Figure 22: Plot of graph from the PPT test of the Pit No.3 (RG-PIT/1)

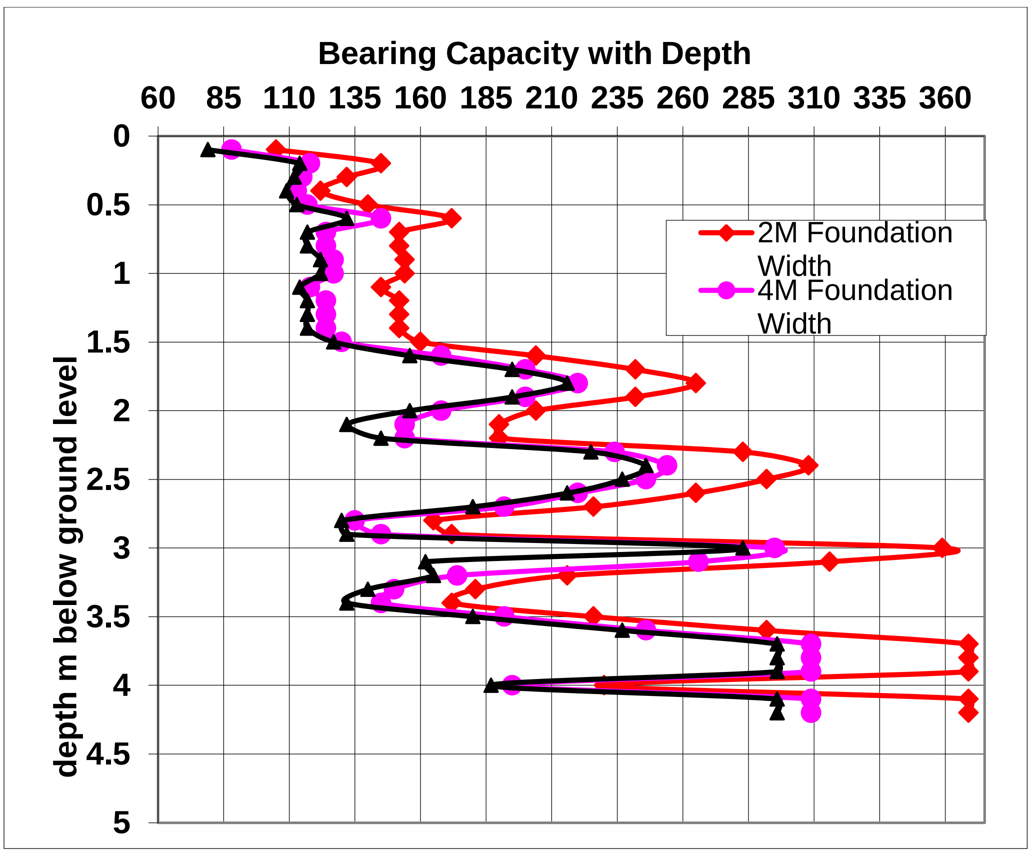


Figure 23: Plot of graph from the PPT test of the Pit No.4 (RG-PIT/2)

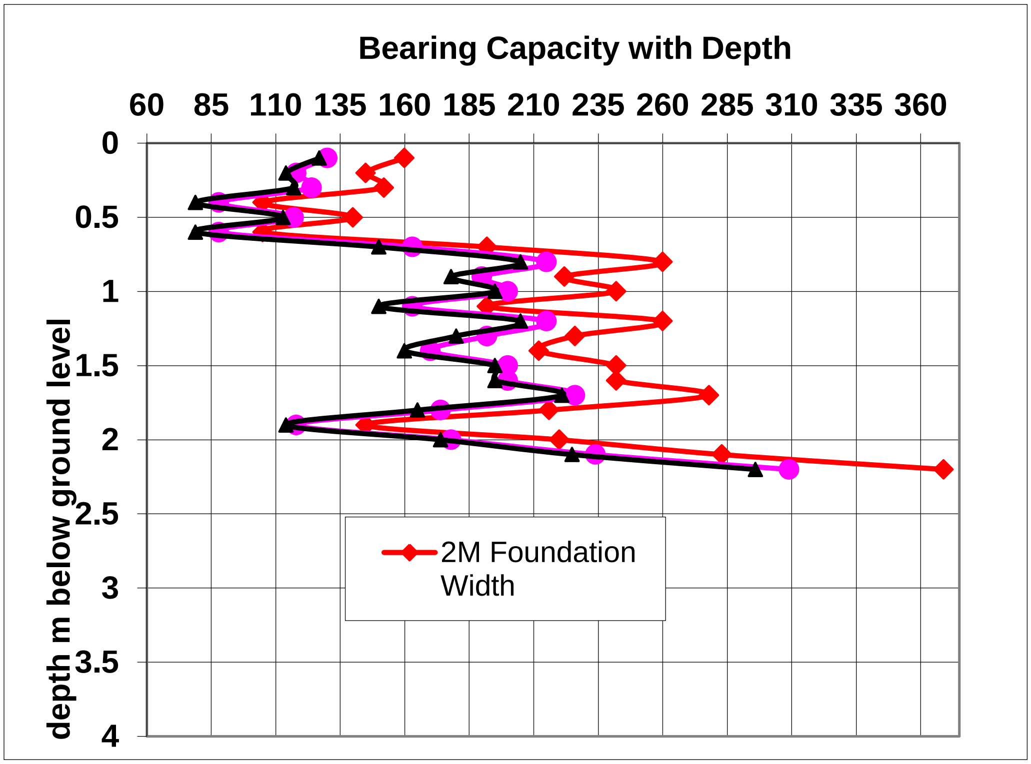


Figure 24: Plot of graph from the PPT test of the Pit No.5 (KCP-PIT/1)

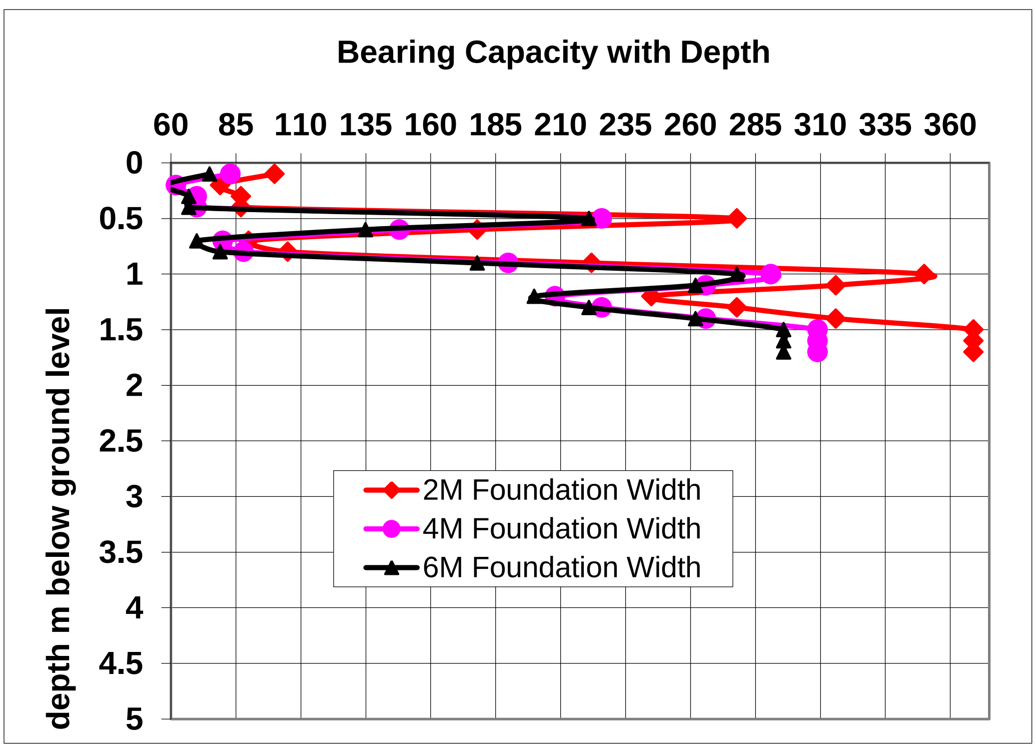


Figure 25: Plot of graph from the PPT test of the Pit No.6 (KCP-PIT/2)

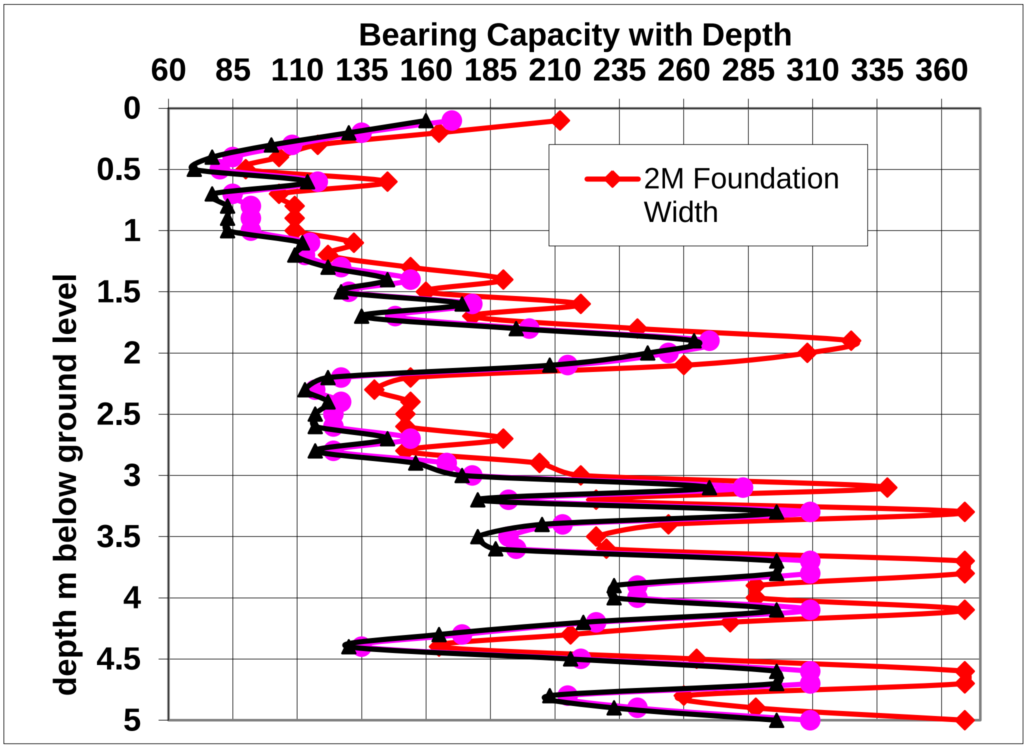


Figure 26: Plot of graph from the PPT test of the Pit No.9 (RD-PIT/3)

4 SELECTION OF FOUR CRITICAL AREAS

The technical assessment was carried out for the following critical landslide areas and descriptions are briefly given below:

1) Landslide in between Old Hospital and RBA family colony
2) Landslide of the Rinchending Goenpa area
3) Kharbandi Check Post Landslide area
4) Landslide to the West of Reldri Higher Secondary School

4.1 Landslides in between Old Hospital (MSD) and RBA family colony

The landslide is very active and propagating to North East, South East and also North West. It has a steep slope face angle of more than 50⁰ facing 280⁰ (NW). This is one of the major landslides which have an approximate area of 28.39 acres. The top 2 meters thick of reddish brown residual soil followed by intensely fractured and crumpled carbonaceous phyllite with variegated colored (gray, purple, green) phyllite and thin lenses of clay are the main rock types present in this active slide zone. Seepages of water were seen at number of places. Numerous tension cracks are developed with ground subsidence of more than 10cm all along the foot trail (Railing) leading to Old General Hospital (MSD). Even the foot path is seen to tilt 10⁰ towards 055⁰ (NE).

Figure 27: Photograph showing the active and dormant landslide

Figure 28: Active landslide propagating towards the east of the Old Hospital area (MSD)

4.1.1 Identification of landslides

The active landslide is propagating further as the SSM68 (eroding more than 5m) has been already eroded by these landslide which were very much present during the 2008-2009 Hazard assessment of extended Phuentsholing Township from Kabreytar east to Ahalay-Toribari areas. Slope movement of this landslide is also very complex, as the processes involved appears to be multiple. Numbers of cracks were seen developing on the plinth areas of FQ7, FQ8 & FQ9. Some of the old landslide scars are presently in a dormant state with vegetation cover.

Figure 29: Subsidence of the foot trail leading to old Hospital (MSD) area

Series of tension cracks, subsidence of the ground and foot trail and tilting of the trees are seen along the foot trails leading to Old Hospital (MSD); i.e on top of the active landslide. This landslide is found to propagate towards North easterly direction and one of the survey station which existed during the 2009 Hazard Assessment is no more visible.

4.1.2 Material type

The area mainly consists of predominantly carbonaceous phyllite, variegated (purple, green, gray and grayish white) phyllite with interbandings of gray and ferruginuous quartzite and thin cover of light reddish brown residual soil. The rock types are highly fractured and jointed with their diverse orientations. Occasional presence of water seepages were seen particularly near the RBA family colony. The phyllite is highly crumpled, weathered and at places decomposed to residual soil. The carbonaceous phyllite band shows the numerous deep cracks quite persistently which appears to be due to drying of the clay mineral associated in the phyllite.

4.1.3 Causes of the landslide

The cause of this landslide appears to be due to toe scouring by the accumulated water during prolonged and heavy precipitation. Since the rock types in the area are predominantly carbonaceous phyllite, variegated phyllite with thin bands of grayish white quartzite which are highly weathered and fractured with development of numerous discontinuities. In some places the phyllite have been found to changed to plastic clay which also aggravates the stability of the slope due to its inherent property of absorbing water during wet season and shrinking during dry periods. Ground water table also rises up suddenly during heavy precipitation which leads to decrease in shear strength of the soil or fragile rocks thereby initiation of the mass movement takes place particularly where the terrain is steep to very steep. The occurrence of intense fracturing, highly weathering, folding and faulting of the rock types of the Phuentsholing Formation may be due to the presence of Main Boundary Thrust (MBT) and neo-tectonic activities nearby. In addition to the above, over grazing and cutting down of the plants and trees for firewood by the people from across the border further adds to the slope instability. The erratic pattern of the climatic conditions of the area also appears to accelerate slope instability due to sudden wetting and drying processes.

Figure 30: Photograph showing the people from Jaigaon fetching firewood from these landslides areas

Cutting down of the trees for firewood and over grazing also further triggers the slope instability in the landslide prone areas. Landslide areas will be amplified in such places if such activities are not prohibited by the local authorities. Further, dumping the excavated materials downhill/ old landslide areas will also accelerate the mass movement under wet condition.

Figure 31: Excavated materials stacked on the edge of the slope near the Old Hospital

4.1.4 Proposed remedial measures

Catch/garland drain should be constructed on top of the crown of the active landslide all along the old foot trail leading to Old Hospital (MSD) and from existing fair weather road to down wards (in front of) the FQ11,FQ12 & FQ13 (RBA Family quarters) almost parallel to the left flank of the landslide. The tension cracks have to be filled by fine materials and seal it properly so as to avoid infiltration of the surface run off during precipitation. Check dams and also retaining structures are recommended to construct as shown in the Plate No.2 (Remedial measure map). Some of the drains have to be re-aligned (or course of the river/.stream have to be changed) so as to control active erosion and incision of the stream/river bed. Water seepages from the landslide areas are properly collected and safely channeled preferably to the natural gully or depressions. Sub-horizontal perforated either HD Pipe or perforated NX casing should be in place for drawing the sub-surface water from the landslide. Bio-engineering with suitable species of trees/plants and grasses should be done just before the onset of monsoon. Cutting down of trees/plants and over grazing should be prohibited in these areas. Landscaping (1:2 ratio) of the slope (maintaining the required slope angle) will help to reduce the slope instability to some extent. Application of suitable geotextile method should be adopted especially where soil cover is thick as shown in the remedial measure map.

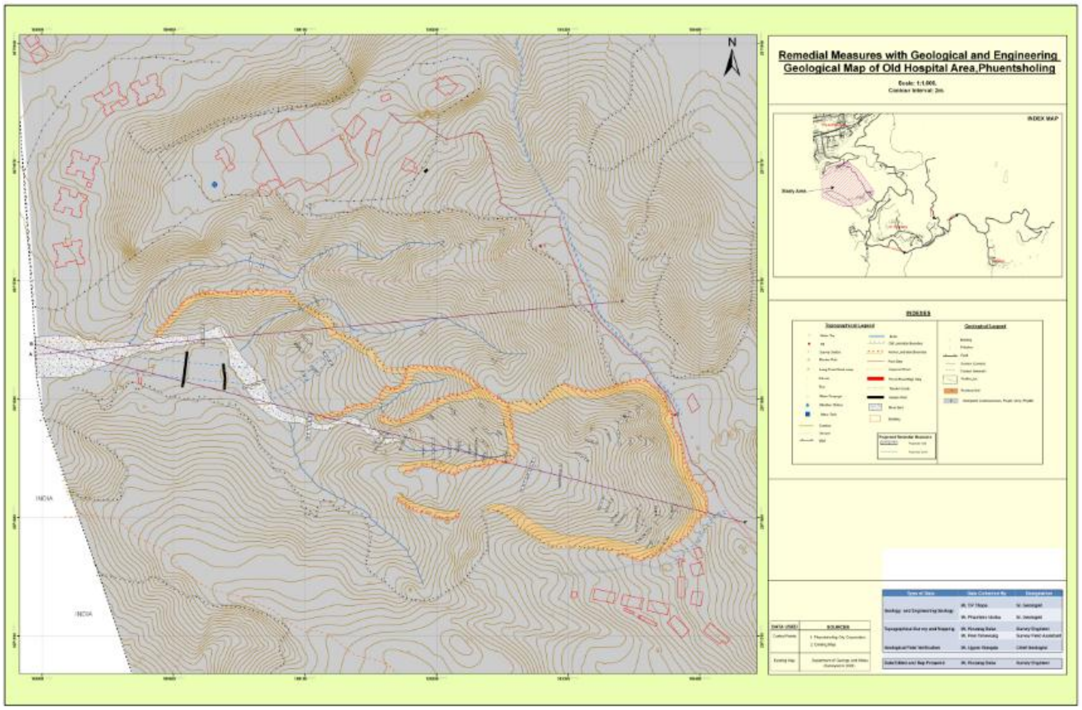


Figure 32: Remedial measures with geological and engineering geological map for Old Hospital area

4.1.5 Status of past landslide mitigation measures

Table 15: Status of the gabion wall in between Old Hospital and RBA family colony landslides

Sl. #	Layer	Status	Location	Remarks
1.	2	Half damaged	Base of the landslide	Lower most
2.	2	Half damaged	Do	Lower most
Total	2 nos.			

4.2 Landslide of the Rinchending Goenpa area

This landslide was encroaching to Rinchending Goenpa in the past which has an area of 16.83acres. Currently this landslide is propagating towards NNW. This is one of the very active landslides with complex phenomenon. This has a more than 10m slip face at the crown. Numerous remedial measures were done in the past to contain the landslide. However, the landslide appears to be in a dormant state especially in the left flank (Fif. 38) most probably due to counter measures as applied by the Department of Roads and the Phuentsholing Thromde in the past and also further supported by the growth of vegetation. The rock types observed in the area is predominantly carbonaceous phyllite with intercalations of variegated phllyite and thin bands of grayish white quartzite. These rock units are overlain by dark gray colored, fine to medium grained dolomite band. The thickness of dolomite band ranged from 2m to 10m for a strike length of 500m. But this dolomite band gradually pinches towards the north western section of the area. No water seepages were observed near the crown of the landslide, but these rock units appear to hold water reservoir especially during rainy season.

Figure 33: Photograph showing the active landslide during 2009

Figure 34: Photograph showing the propagation of landslide during 2012-2013

4.2.1 Identification of landslides

Minor cracks near the edge of the vehicle parking area and cracks on the wall of Rinchending Goenpa area are the first sight indications and identification of the mass movement in the area. This is followed by numerous tension cracks and subsidence of the ground particularly near the edge of the crown of the landslides. Tilted trees were observed and some of them have been already uprooted due to active mass movement.

Figure 35: Photograph showing the different stages of landslide in the NW of Rinchending Goenpa area

4.2.2 Material type

The material is dominantly carbonaceous phyllite intercalated with variegated (gray,green, purple) phyllite and thin bands of grayish white to ferruginous quartzite. Unlike the other areas, it has a grayish to ash gray colored, fine grained dolomite band ranging its thickness from 2.5m to 10.0m for a strike length of about 500m which is the top most units in the area. Light reddish brown clayey soil having a thickness of about 5m also overlies all rock units in the area. The phyllite, as a whole, is also fractured, but not to that extreme.

4.2.3 Causes of the landslide

The main causes for triggering landslide in these areas appear to be due to toe scouring by the prolonged and heavy precipitation during the monsoon. Secondly, easy infiltration of the rain water into the highly crumpled phyllite zone and gradually erodes the phyllite down stream. Thirdly, due to cutting down of the trees/plants around these unstable areas. The overburden soil are porous and permeable in nature which allows the rain water infiltration causing decrease in shear strength of soil and highly crumpled phyllite adding the weight due to saturation and thereby leads to mass movement.

4.2.4 Proposed remedial measures

The rain water should be collected around the main Goenpa and residential areas and should be channeled safely to natural gullies. Catch drain should be constructed on top of the crown of the active landslide with safe disposal. The tension cracks have to be filled by fine materials and seal it properly so as to avoid infiltration of the surface run off during precipitation. Check dams and also retaining structures are recommended to construct as shown in the Plate No.5 (Remedial measure map). Drainage system should not be straight since the velocity of turbulent water starts scouring the toe of slides. Sub-horizontal perforated either HD Pipe or perforated NX casing should be in place for drawing the sub-surface water from the landslide. Bio-engineering with suitable species of trees/plants and grasses should be done just before the onset of monsoon. Cutting down of trees/plants and over grazing should be prohibited in these areas. Landscaping of the slope in 1:2 (Vertical: Horizontal) ratio will help in reduction of slope instability to some extent. Application of suitable geotextile method should be adopted especially where soil cover is thick as shown in the remedial measure map.

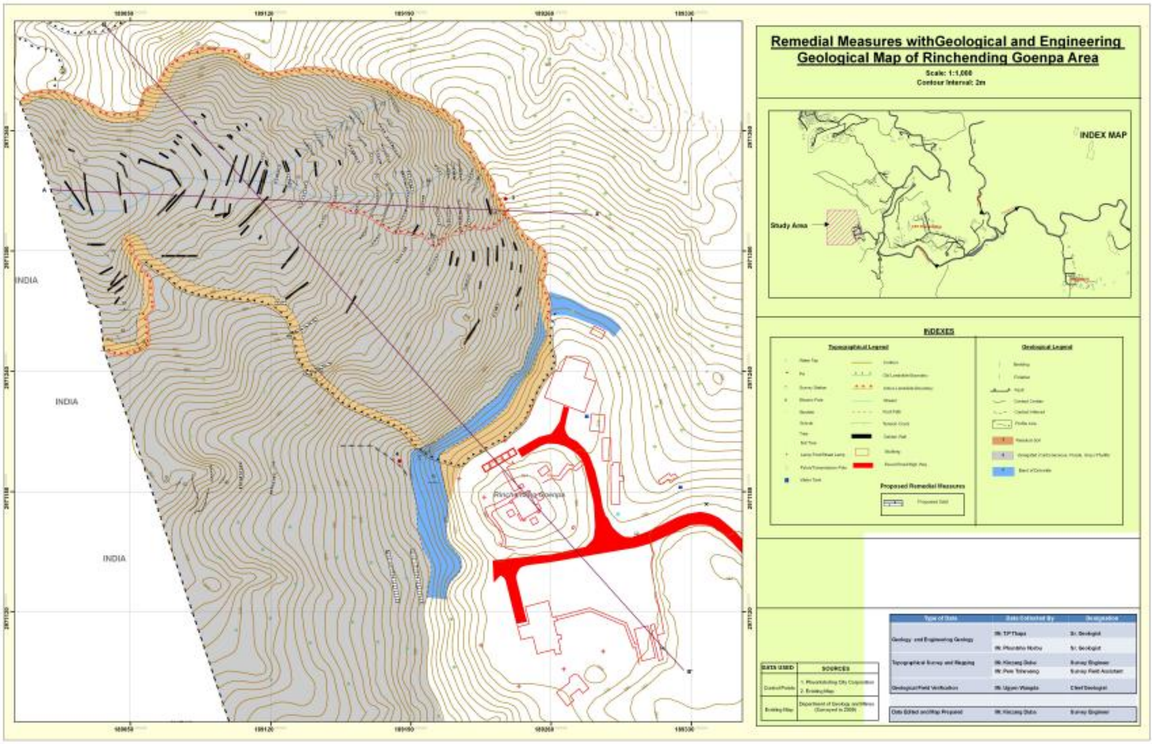


Figure 36: Remedial measures with geological and engineering geological map for Goampa area

4.2.5 Status of past landslide mitigation measures

Table 16: Gabion wall at Rincheding Goenpa Landslides

Sl.No.	Layers	Status	Location	Remarks
1.	1	Slightly bulged (New)	Below the Goenpa (eastern flank of the landlside)	Topmost gabion wall
2.	1	-do-	Do	5 m length
3.	4	Slightly bulged (old) towards N20^{o}E	Do	20 m length, still in good condition
4.	6	Top layer bulged and damaged (Old)	Do	35 m length
5.	3	Bulged and partially damaged(Old)	Do	10m (middle section)
6.	3	Slightly bulged (Old)	Do	20m
7.	3	Slightly bulged (Old)	Do	15m
8	2	Slightly bulged (Old)	Do	12m
9	1	Slightly bulged (Old)	Do	2
10	2	Slightly bulged(new)	Do	8m
11	4	Damaged in the middle section(Old)	Do	30m
12	4	Damaged (Old)	Do	25m
13	3	Slightly damaged (New)	Do	
14	2	Slightly damaged (New	Do	
15	1	Slightly bulged (Old)	Do	5m
16	3	Slightly bulged (New)	Do	

17	3	Slightly bulged (New)	Do	Damaged at the basal part
18	2	Slightly bulged (New)	Do	Do
Total	18 Nos.			

Sl.No.	Layers	Status	Location	Remarks
1.	2	Damaged (Old)	Near the International Boundary wall, Jharna	Top 2m
2.	2	Damaged(New)	Do	
3.	2	Slightly bulged (New)	Do	
4.	2	Do	Do	
5.	2	Do	Do	
6.	2	Slightly damaged (Old)	Do	
7.	1	Middle section of the gabion wall damged (Old)	Do	
8	2	Slightly damaged(New)	Do	
9	1	Damaged (New)	Do	
10	1	Do	Do	
11	2	Slightly bulged	Do	Lower most gabion wall
Total	11 Nos.			

Sl.No.	Layers	Status	Location	Remarks
1.	1	Fully damaged	Rinchending Geonpa area	Upper most in the western flank of the Goenpa landslide
2.	1	Parly damagaed	Do	Do
3.	1	Good condition	Do	Do
4.	2	Do	Do	Do
5.	2	Partly damaged	Do	Do
6.	1	Fully damaged	GG-A-7	Middle_East
7.	1	Partly damaged		Do
8	2	Partly damaged		Do
9	2	Fully damaged		Do
10	5	Partly damaged		Do
11	2	Partly damaged		Middle -West
12	1	Do		Do
13	1	Good condition		Do
14	3	Do		Do
15	1	Fully damaged		Do
16	2	Partly damaged		Do
17	2	Fully damaged		Do
18	2	Good condition		Do
Total	18 Nos.			

4.3 Kharbandi Check Post Landslides

This is the biggest landslides in the area and propagating NW. Few small landslides are found re- activated even in the north east of the Kharbandi Check Post. It has an area of 38.65 acres approximately. This landslide has a high slip face angle ranging from 55° to more than 70°.

Figure 37: Photograph showing the active landslide near the Kharbandi Check Post

4.3.1 Identification of landslide

Numereous tension cracks followed by subsidences of the ground are the main indicator of active mass movement. The tension cracks are widely opened and are as deep as 1.5m to 2m deep. The retaining walls are found to bulged and other structures are seen tilted.Even the trees around these areas are found to tilt to some angle.

Figure 38: Picture showing the ruined office of the Revenue and Custom due to landslide

Figure 39: Picture showing the bulged retaining wall with wide open tension cracks

4.3.2 Material type

Predominantly carbonaceous phyllite is exposed intercalating with variegated (gray, green,purple) phyllite and slaty phyllite with thin bands of ferrugenous quartzite. The crabonaceous phyllite and the variegated phyllites are highly to completely weathered and intensely crumpled. At times these phyllites are found to decompose to residual soil especially on the crown of the landslide. This type of intense weathering may be contributed by presence of shallow ground water table and also owing to sudden rise and fall of tempareatures in the area. The phyllites exhibit steep foliation plane. Shearing and minor dispalcement are common in this area.

4.3.3 Causes of the landslide

Due to very poor management of the darinage system in the area, mass movement is actively taking place. The collected water from the road side drain enters directly onto the crown of the landslide (Fig. 45) Cutting down of the trees in the unstable slope is also found to be another factor for slope instability.

Figure 40: The rain water drains into the landslide crown

The fact that the soil is very loose, fraible and porous in nature allows rain water to penetrate the soil, which decreases the shear strength of the soil or crumpled rocks. Such process in due course of time leads to incision of the either banks and bed of the gullies or stream.

Figure 41: Picture showing the incision of the river/stream bed by storm water

4.3.4 Proposed remedial measures

Raising of the drainage/channel bed (Fig. 45) should be done and simultaneously diverted to other side of the slope (i.e towards western slope). The tension cracks should be sealed by fine materials. Removal of the small mounds (i.e near the present Revenue & Custom Office) and the RBP watch tower has to be done to some extent in order to reduce the deadload on the crown of the landslides. Landscaping in the 1:2 (Vertical:Horizontal) ratio has to be done and plantation of the appropriate trees have to be done. Sub-horizontal HD pipe should be inserted to draw the ground water lying near the crown of the landslide.Check dams and retaining gabion strutures should be built as shown in the Remedial measure map. Raising of the river/stream/gully bed should be done to protect the toe of the slope. Application of appropriate geotextile method should be adopted particularly around the landslide crown areas.

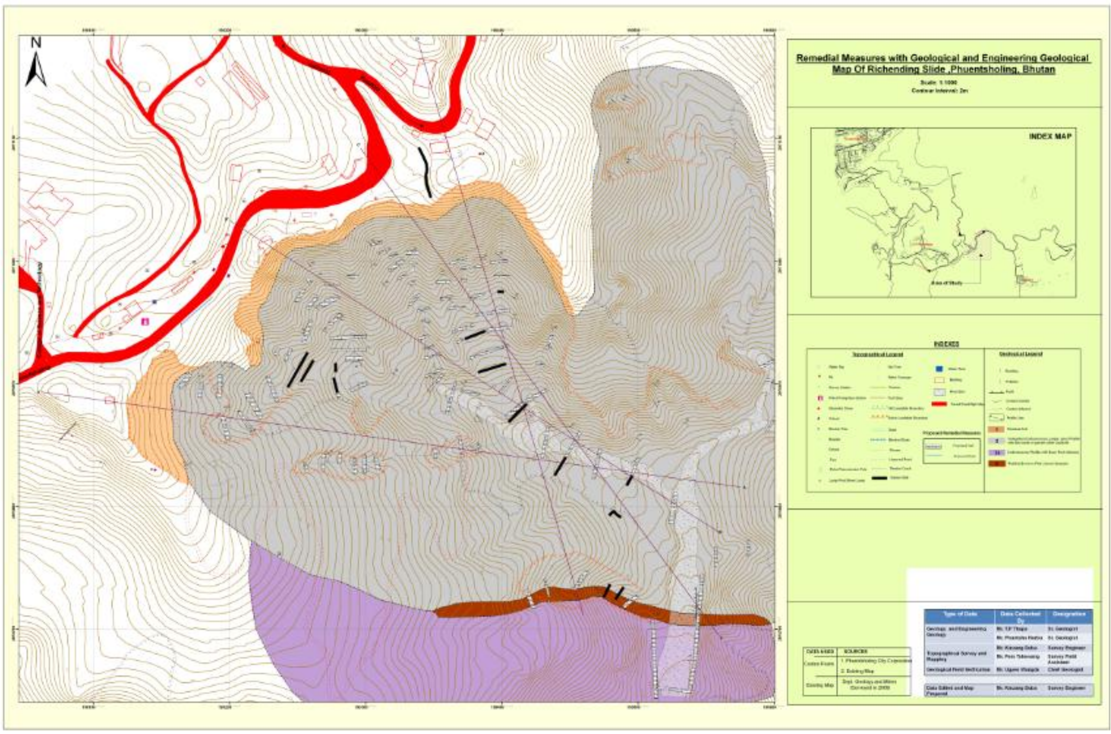


Figure 42: Remedial measures with geological and engineering geological map for Kharbandi area

4.3.5 Status of past landslide mitigation measures

Table 17: Status of the gabion structures at Kharbandi Check post Landslides

Sl. #	Layer	Status	Location	Remarks
1.	2	Damaged & bulged	Just below the water tank on right bank of Jogi Khola	Again replacement/ renovation has to be done
2.	4	Wire mesh were found rusted and broken	At the base of small landslide of the main Kharbandi check post	Extension on either sides has to be carried out
Total	2 Nos.			

Sl.No.	Layers	Status	Location	Remarks
1.	3	Partially damaged towards North and top layer wire mesh is cut	Near Stn. D-3 Kharbandi check post landslide base	More than 20 m length still eists.
2.	5	Partially damaged	Just below Stn.D-3	

		towards North and found bulged		
3.	5	Southern and Northern edges of the gabion wall has been damaged totally where as middle portion still remains intact	Near the big boulder	Base width is 2.50m and top width is 1m. The main nala has damaged the southern edge of the gabion wall.
4.	6	Wire mess totally cut but the gabion wall still remains intact		Water flows from the base.
5.	1	Almost filled by debris		A small portion is seen intact.
6.	4	Some of the wire mess is cut but remain intact.	KG-19	Western and eastern part of the gabion wall has been eroded by water and the middle portion is filled by debris.
7.	5	Remnant of the gabion wall exists only as it is totally damaged	KG-30	
8	3	Eastern edges totally damaged	KG-35	Proposed gabion wall KG-35 to Kg-35
9	5	Bulged, damaged and moved	KG-37	
10	4	Completely damaged	KG-39	
11	4	Middle portion completely damaged	Just above the KG-40	
12	4	Western edge is totally damaged	KG-51	Check dam
13	2	The gabion wall is partilly eisted	KG-52	
14	5	Middle portion of the gabion wall is eroded	KG-67	
15	5	Southern edges of the gabion wall is damaged and the wire mesh is rusted	KG-69	
16	4	Do as above	KG-70	
Total	16 Nos. + 2 Nos. =18 Nos.			

4.4 Landslide on West of the Reldri Higher Secondary School

Unlike the other landslides, this landslide is propagating towards North easterly direction threatening the infrastructure of the Reldri Higher Secondary School. It has an area of 11.78 acres approximately. Although the slip plane appears to be shallow but the mass movement is active in the process.

Figure 43: Photograph showing the active landslide to the west of Reldri Higher Secondary School

4.4.1 Identification of the landslide

No tension cracks were observed near the crown of this landslide but subsidence of the ground and slip of the particularly left flank of this landslide were observed during the course of field work. Seepage of the water is most common in this landslide area. Tilted trees, bamboos are common phenomenon indications of the landslide in the area. The simali plants were seen uprooted at few places. No growth of vegetation particularly in the active landslide area, instead deep incision of the stream/gully bed was observed. Numerous tension cracks were also observed all along the ridge which may be due to drying of clayey material during dry season.

4.4.2 Material type

Carbonaceous phyllite is the dominant rock type in the area followed by variegated phyllite and thin band of gray quartzite. The rock types are highly to completely weathered and fractured. Clay bands were observed at number of places. The rock is found to dip to the west with some angles. Reddish brown to grayish brown residual soil were found to expose at the crown of the landslide.

4.4.3 Causes of the landslides

Although the general slope angle in this landslide area is found to be gentle, even then the mass movement is observed to be very active, most probably due to presence of water seepages at number of places. The phyllites have been disintegrated to clay due to intense weathering. Clay bands as shear zones were also encountered at number of places. Reel and gully erosions are common in this landslide. Deep gullies with steep side slopes were formed in the area.

4.4.4 Proposed remedial measures

Catch drain should be constructed all along the edge of the road and water should be channeled towards eastern slope. Series of gabion check dams have to be constructed and simultaneously the stream/gully bed should be raised to some extent. Landscaping will help to reduce the steep slope angle and also deadload. Bio-engineering with suitable species may be encouraged. The ground water should be withdrawn using perforated HD pipe. Application of appropriate geotextile method should be adopted particularly around the landslide scarp.

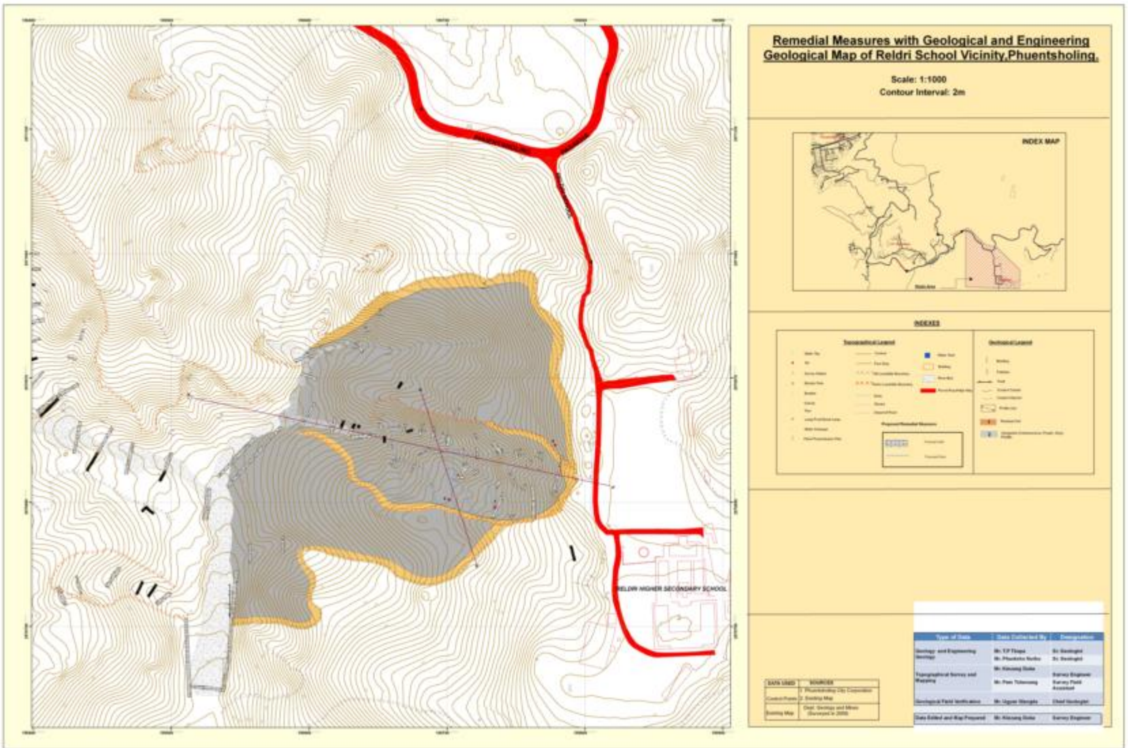


Figure 44: Remedial measures with geological and engineering geological map for Reldri school areas

4.4.5 Status of past landslide mitigation measures

Table 18: Status of the gabion structures at Reldri Landslide area

Sl. #	Layer	Status	Location	Remarks
1.	1	Completely damaged	Above the big boulder	Reldri landslide
2.	1	-do-	Below the big boulder	-do-
3.	1	-do-	-do-	-do-
4.	2	¾ completely damaged	Just above the confluence	-do-
5.	2	-do-	-do-	-do-
6.	1	Remnant only remained	-do-	-do-
7.	1	50% of the gabion wall completely damaged	-do-	-do-
Total	7 Nos.			

5 LABORATORY RESULTS AND OTHER ANALYSIS

Soil samples were collected from each excavated test pit at different places in area under study. This was done to know the index, physical and strength parameters of the soil through laboratory analysis.

From the gradation curve of the sieve analysis, the soils range from well graded, gap graded and poorly graded in their classifications. The coefficient of uniformity (C_u) ranges from 3.64 to 23.04 whereas the Coefficient of curvature (C_c) ranges from 0.40 to 2.19.The Atterberg limit tests show their plasticity Index (I_p) ranging from 13.20 to 22.02%. Water content **(**ω**)** of the soil ranges from 7.26% to 18.30%. The soil ranges from 2.28 to 2.60 from the specific gravity (Sp.gr) test. The bulk density **(**ρ**)** of the soil sample gave their ranging from 1.27 to 2.10g/cm^3. Void ration **(e)** of the soil samples assumed to rages from 0.52 to1.14. Porosity (η) of the soil samples computed ranging from 39.26 to 53.19%. The degree of saturation (**S**) ranges from 21.25 to 66.68%.

From the direct shear Box Test the cohesion and the internal friction angle of the soil samples ranges from 0 kPa to 16kPa and 24^0 to 32^0 respectively. From the Standard Proctor Test , the Maximum Dry Density of the soil sample ranges from 0.648 to 0.968gm/cc and the Optimum Moisture Content ranges from 10.33 to 16.95% respectively.

The density of the soil are found to be less dense as per the PPT test near the vicinity of the landslide areas.The rainfall of 1998 was more than 3 times than the 2008 rainfall indicating drastic variations in rainfall patterns. Geological, engineering geological, slope and remedial maps were prepared. Also geological cross sections and longitudinal sections were prepared to estimate the approximate thickness of soil cover, thickness of lithological units and depth of ground water table.

6 CONCLUSIONS

The Bhutan Himalaya has never been and will never be free from ambiguity of weak geology, slope instability, frequent seismicity, soil erosion etc. mainly due to natural causes as well as a result of climate change, in particular high intensity rainfall. These adverse conditions in tandem can exacerbate the existing fragile and vulnerable ecosystem. So far disaster caused by landslides, earthquake, flood etc. have not led to large scale human tragedy in Bhutan in the recent memory. However, there is ever increasing human demand of natural resources, especially land for urban development and mega dams in an apparently unsustainable manner, making some of the residents to adapt and survive at dangerous margins. The emerging crisis can be minimized by combination of indigenous knowledge base and modern technological interventions. To safeguard against accelerated degradation and to improve the living standard of people, the Government (Local Government and Thromde) needs to address specific issues through systematic and effective integration of all development planning and climate induced disaster risk management. Without appropriate policy directives from the government to address urban development in hilly slopes, the threat from devastating landslides, earthquake, flood etc. will always remain.

7 RECOMMENDATIONS

Landslides may be corrected or controlled by one or any combination of four principle measures: modification of slope geometry, drainage, retaining structures and internal slope reinforcement. The following information provides the requirements for construction of Check dams and retaining walls:

- The foundation of the structures particularly gabion check dams and retaining walls should be laid on the bed rock or hard soil wherever deem feasible (not on the loose soil or disturbed exposures).
- The fill material should be compacted to a minimum of 95% proctor density.
- The fill material should be of a standard specification i.e suitable compressive strength and durable to resist the loading, as well as the effects of water and weathering.
- Usually 3 to 4 inches clean, hard stone must be specified.
- A well graded stone fill increases density.
- The length of the gabion check dams or retaining structures should not be more than ten (10) lengths.
- The gabion walls should be stepped front face(slope side)
- Geophysical survey using resistivity profiling should be carried out where there are suspected clayey layers and water seepages.
- A special attention should be focused to study/analyze the trend of the rainfall and temperature variations patterns of these areas.
- Bio-engineering with suitable species of plants are recommended to plant prior to onset of the rainy season.

- Landscaping by benching and gentle sloping should be done particularly in the steep slope (1:2 ratios).
- Application of the geo-textile may be done near the crown of the landslides on highly to completely weathered rock and soil.
- Excavation to unload the upper part of landslide may be done.
- Lime/cement columns should be negotiated where ever feasible.
- No excavated materials should be dump downhill.
- Quarrying from the river bed should not be allowed because it will :
  (a) weaken the intact rock strength;
  (b) cause incision of the river bed very rapidly
- No explosives should be used during excavation or breaking of large boulders because it:
  (a) makes soil and rock more prone to slide
  (b) may cause the blockage and fluctuation of the ground water.
  (c) weakens the shear strength of soil or rock.
- Cutting down of plants and trees should be strictly prohibited because:
  (a) Some of the roots are very long and penetrates deep into the ground.
  (b) The roots of the plants and trees acts as anchors as a result soil erosion will be controlled.
- The karst/cavern (as shown in Fig. 7) in the dolomite just below the Rinchending Goenpa should be plugged by cement grouting.

Appendix

Portable Penetration Test (PPT) results from various test pits

Table 19: Computation of allowable bearing pressure from PPT test of the Pit No.1 (HR-PIT/1)

Penetration in depth (m)	No of blows	Allowable bearing pressure (kN/m^2) for the foundation width		
		2m	4m	6m
0.1	13	145	118	114
0.2	22	192	163	150
0.3	18	172	145	132
0.4	3	87	70	67
0.5	43	325	270	264
0.6	50	369	309	296
0.7	44	333	275	267
0.8	45	339	283	270
0.9	36	283	234	225
1	50	369	309	296
1.1	38	292	246	232
1.2	35	278	226	221
1.3	15	154	127	122
1.4	2	79	62	58
1.5	23	204	168	156
1.6	26	220	178	174
1.7	25	216	174	165
1.8	30	242	200	195
1.9	35	278	226	221
2	33	260	215	208
2.1	40	308	254	246
2.2	47	350	291	278

2.3	36	283	234	225
2.4	37	288	242	233
2.5	37	288	242	233
2.6	34	265	220	216
2.7	52	369	309	296
2.8	53	369	309	296
2.9	67	369	309	296
3	93	369	309	296

Table 20: Computation of allowable bearing pressure from the PPT test of the Pit No.2 (HR-PIT/2)

Penetration in depth (m)	No of blows	Allowable bearing pressure(kN/m^2)for the foundation width		
		2m	4m	6m
0.1	16	160	130	127
0.2	13	145	118	114
0.3	9	118	108	100
0.4	3	87	70	67
0.5	6	103	85	77
0.6	8	109	92	83
0.7	13	145	118	114
0.8	18	172	145	132
0.9	16	160	130	127
1	15	154	127	122
1.1	18	172	145	132
1.2	17	165	135	130
1.3	11	132	115	112
1.4	16	160	130	127
1.5	12	140	117	113
1.6	19	178	148	135
1.7	30	242	200	195
1.8	29	230	195	187
1.9	19	178	148	135
2	17	165	135	130
2.1	18	172	145	132
2.2	20	181	150	140
2.3	26	220	178	174
2.4	23	204	168	156
2.5	41	316	266	262
2.6	39	300	249	242
2.7	35	278	226	221
2.8	28	226	192	180
2.9	26	220	178	174
3	26	220	178	174
3.1	18	172	145	132
3.2	19	178	148	135
3.3	33	260	215	208
3.4	27	222	190	178
3.5	22	192	163	150
3.6	23	204	168	156
3.7	23	204	168	156

3.8	24	212	170	160
3.9	26	220	178	174
4	20	181	150	140
4.1	50	369	309	296
4.2	51	369	309	296
4.3	27	222	190	178
4.4	22	192	163	150
4.5	23	204	168	156

Table 21: Computation of allowable bearing pressure from the PPT test of the Pit No.3 (RG-PIT/1)

Penetration in depth (m)	No of blows	Allowable bearing pressure(kN/m^2)for the foundation width		
		2m	4m	6m
0.1	12	117	113	140
0.2	11	117	113	140
0.3	8	92	83	109
0.4	7	88	79	105
0.5	9	108	100	118
0.6	13	118	114	145
0.7	20	150	140	181
0.8	38	246	237	292
0.9	62	309	296	369
1	96	309	296	369
1.10	104	309	296	369

Table 22: Computation of allowable bearing pressure from the PPT test of the PIT No.4 (RG-PIT/2)

Penetration in depth (m)	No of blows	Allowable bearing pressure(kN/m^2)for the foundation width in		
		2m	4m	6m
0.1	7	105	88	79
0.2	13	145	118	114
0.3	11	132	115	112
0.4	10	122	113	109
0.5	12	140	117	113
0.6	18	172	145	132
0.7	14	152	124	117
0.8	14	152	124	117
0.9	15	154	127	122
1	15	154	127	122
1.1	13	145	118	114
1.2	14	152	124	117
1.3	14	152	124	117
1.4	14	152	124	117
1.5	16	160	130	127
1.6	23	204	168	156
1.7	30	242	200	195
1.8	34	265	220	216
1.9	30	242	200	195
2	23	204	168	156
2.1	21	190	154	132
2.2	21	190	154	145

2.3	36	283	234	225
2.4	40	308	254	246
2.5	38	292	246	237
2.6	34	265	220	216
2.7	28	226	192	180
2.8	17	165	135	130
2.9	18	172	145	132
3	48	359	295	283
3.1	42	316	266	162
3.2	25	216	174	165
3.3	20	181	150	140
3.4	18	172	145	132
3.5	28	226	192	180
3.6	39	292	246	237
3.7	75	369	309	296
3.8	74	369	309	296
3.9	33	369	309	296
4	29	230	195	187
4.1	51	369	309	296
4.2	81	369	309	296

Table 23: Computation of allowable bearing pressure from PPT test of the Pit No.5 (KCP-PIT/1)

Penetration in depth (m)	No of blows	Allowable bearing pressure for the foundation width in kN/m^2		
		2m	4m	6m
0.1	16	160	130	127
0.2	13	145	118	114
0.3	14	152	124	117
0.4	7	105	88	79
0.5	12	140	117	113
0.6	7	105	88	79
0.7	22	192	163	150
0.8	33	260	215	205
0.9	27	222	190	178
1	30	242	200	195
1.1	22	192	163	150
1.2	33	260	215	205
1.3	28	226	192	180
1.4	24	212	170	160
1.5	30	242	200	195
1.6	30	242	200	195
1.7	35	278	226	221
1.8	25	216	174	165
1.9	13	145	118	114
2	26	220	178	174
2.1	36	283	234	225
2.2	130	369	309	296

Table 24: Computation of allowable bearing pressure from PPT test of the Pit No.6 (KCP-PIT/2)

Penetration in depth	No of blows	Allowable bearing pressure for the foundation width in kN/m^2

(m)		2m	4m	6m
0.1	5	100	83	75
0.2	2	79	62	58
0.3	3	87	70	67
0.4	3	87	70	67
0.5	35	278	226	221
0.6	19	178	148	135
0.7	4	90	80	70
0.8	7	105	88	79
0.9	27	222	190	178
1	47	350	291	278
1.1	42	316	266	262
1.2	31	245	208	200
1.3	41	278	226	221
1.4	42	316	266	262
1.5	50	369	309	296
1.6	93	369	309	296
1.7	157	369	309	296

Table 25: Computation of allowable bearing pressure from the PPT test of the PIT No.9 (RG-PIT/3)

Penetration in depth (m)	No. of blows	Allowable Bearing Pressure for the foundation width (kN/m^2)		
		2m	4m	6m
0.10	24	212	170	160
0.20	17	165	135	130
0.30	9	118	108	100
0.40	6	103	85	77
0.50	5	100	83	75
0.60	3	87	70	67
0.70	5	100	83	75
0.80	8	109	92	83
0.90	8	109	92	83
1.00	8	109	92	83
1.10	11	132	115	112
1.20	10	122	113	109
1.30	15	154	127	122
1.40	21	190	154	145
1.50	19	178	148	135
1.60	26	220	178	174
1.70	19	178	148	135
1.80	30	242	200	195
1.90	43	325	270	264
2.00	40	308	254	246
2.10	33	260	215	132
2.20	15	160	130	127
2.30	12	140	117	113
2.40	15	132	115	112
2.50	14	152	124	117
2.60	14	152	124	117

2.70	21	190	154	145
2.80	14	152	124	117
2.90	23	204	168	156
3.00	26	220	178	174
3.10	45	339	283	270
3.20	28	226	192	180
3.30	63	369	309	296
3.40	32	254	213	205
3.50	28	226	192	180
3.60	29	230	195	187
3.70	54	369	309	296
3.80	72	369	309	296
3.90	37	288	242	233
4.00	37	288	242	233
4.10	51	369	309	296
4.20	35	278	226	221
4.30	25	216	174	165
4.40	17	165	135	130
4.50	34	265	220	216
4.60	61	369	309	296
4.70	59	369	309	296
4.80	33	260	215	208
4.90	37	288	242	233
5.00	61	369	309	296