ROLE OF GEOLOGICAL STRUCTURES AND CLAY MINERALS IN THE OCCURRENCE OF LANDSLIDES ALONG MUGLING-NARAYANGHAT HIGHWAY SECTION

A DISSERTATION

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1 NOV 2010

Recommendation

Date: 15 Kartik 2067
1 Nov 2010

It is certified that Mr. BHUPATI NEUPANE has worked satisfactorily for his Master's Degree dissertation under my guidance and supervision. He has worked enthusiastically with sincere interest. The dissertation entitled –ROLE OF GEOLOGICAL STRUCTURES AND CLAY MINERALS IN THE OCCURRENCE OF LANDSLIDES ALONG MUGLING-NARAYANGHAT HIGHWAY SECTION‖ embodies the candidate‘s own work. I, hereby, recommend the dissertation for approval.

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Date: 28 Kartik 2067

14 Nov 2010

The dissertation presented by Mr. BHUPATI NEUPANE entitled –ROLE OF GEOLOGICAL STRUCTURES AND CLAY MINERALS IN THE OCCURRENCE OF LANDSLIDES ALONG MUGLING-NARAYANGHAT HIGHWAY SECTION‖ has been accepted as the partial fulfillment of requirement for the Master‘s Degree of Science in Geology.

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ABSTRACT

Each year Mugling-Narayanghat Highway section suffers from numerous landslides and debris flow. Geological structures and clay mineral content in soils have been investigated to understand their roles in the occurrence of landslides along Mugling-Narayanghat Highway section. In this section 13 large landslides in the Lesser Himalaya and the Siwaliks were investigated in detail and mapped to prepare landslide distribution map. From the landslides 11 soil samples were collected in the field, sieved and the finer fraction was subjected to X-ray diffraction analysis. X-ray analysis reveals that illite, chlorite and kaolinite were the main clay mineral in the soil. The main finding of the study is that in addition to the role of geology, geological structures and human activities, clay mineral content, particularly Illite, has significant role for the observed activity of the landslides in the study area.

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CHAPTER - 1
INTRODUCTION

General

Geologically and tectonically, the Himalayan range is a very dynamic region in the world. Due to the dynamic nature of the Himalaya, Nepal Himalaya also experiences landslides commonly during monsoon season. Landslide, as a form of mass movement, is one of the principal processes of hill slope erosion, and it happens along most part of the roads and highways in Nepal, where they cause extensive damage to property and occasionally results in loss of lives. The temporal distribution of slope movements is determined by the occurrence of triggering factors such as rainfall, rapid snowmelt, volcanic eruption, earthquakes and human activity (Dai et al., 2002). Concerning the role of water in slope stability, it causes a decrease in shear strength either by reducing the apparent soil cohesion or through the potential slip surfaces, a fact directly related to intense or long-lasting rainfall events (Gostelow, 1991).

Location and accessibility

Location

The Mugling-Narayanghat Highway is located in Chitwan Districts, Narayani Zone, and Central Nepal as a part of the Gorkha-Narayangadh Highway. The study area lies within longitude 84º 25' 00" E to 84º 32' 30" E and latitude 27º 45' 00" N to 27º 50' 00" N (Figure 1) that falls within the topographical map 2784-03C (Mugling) and 2784-02D (Jugedi Bajar) (Survey Department, Government of Nepal 1995).

Accessibility

The study area lies at 111 km southwest of Kathmandu, the capital city of Nepal. It lies at 5 km southwest from the Mugling Bazaar. The Prithivi Highway joins Mugling with Kathmandu, which is 111 km and the Gorkha-Narayangadh Highway connects the study area with the Mugling Bazaar (Figure 1). A number of the newly build earthen roads and many tracks connect local villages that make the area well accessible.

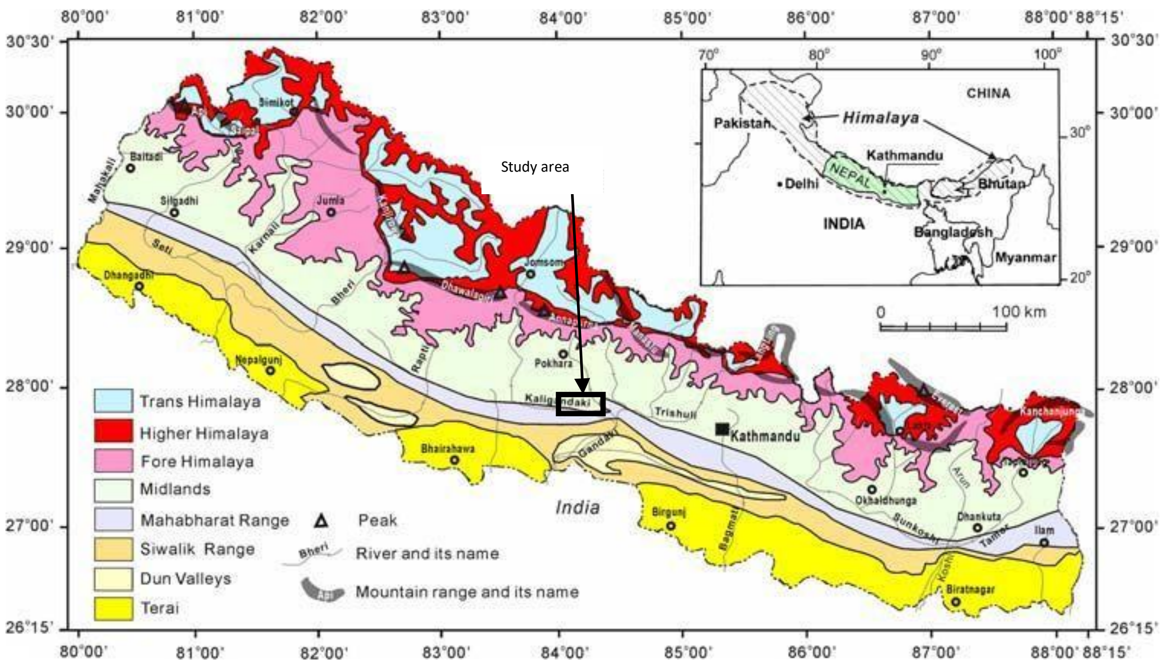


Figure 1: Location Map of the study area (after Hagen 1969, Upreti 1999 and Dahal and Hasegawa 2008)

Topography

The study area is characterized by mountain topography of the Mahabharat range and the Siwaliks. In the study area, medium to hard rock such as quartzite, schist, dolomite and dolomitic limestone forms moderate to steep slope. The soft rock such as slate and phyllite forms gentle slope. Large scale landslide scarps are dominant in the study area.

Climate and Vegetation

The physiographic characteristic and altitude influences the climate in the area. The area experiences sub-tropical to temperate climate. The temperature ranges from 5–40 ºC. As in other parts of Nepal, summer monsoon is dominant from June to the end of September in the study area. The region receives approximately 80 % of the annual rainfall during the Monsoon period (June-September). Rainfall intensities vary throughout the basin with maximum intensity occurring on the south facing slopes. During the monsoon period, relative humidity reaches at their maximum and the temperatures are lower compared to the pre-monsoon period. The mean annual precipitation map of the country shows that the annual precipitation in the area ranges 1500–2000 mm.

This area has sub-tropical, deciduous and evergreen trees. Most of the hillsides are covered with forest. Dense mixed forests to sparsely vegetal are found in the area. The forest is covered with trees as well as herbs and shrubs. The gentle slope and flat land is cultivated. Most of the pastures and grassland is coupled with deciduous, coniferous forest, and shrubs. The Sallo (*Pinus roxburghii*), Sal (*Shorea robusta*), Chilaune (*Schirna wallichi*), Uttis (*Alnus nepalensis*) are dominant species on the forest.

CHAPTER - 2
OBJECTIVE AND METHODOLOGY

Objectives

The main objectives of the study are to

- Study the geological and engineering geological condition of the study area.
- Find out the role of geological structures and clay minerals in the occurrence of landslides.

Methodology

To achieve the objectives, the methodology adopted during the study is desk study, field study, laboratory work and data processing, and interpretation and report preparation. They are discussed below.

Desk study

Topographic maps, published and unpublished reports and literatures, journals, field manuals and established theories related to the present study were collected from the various sources such as internet, library and personal communications. Topographical maps of 1:25,000 scale published by the Survey Department, Government of Nepal, were collected. The toposheets 2784-02D (Jugedi Bajar) and 2784 03C (Mugling) were used for the study. Published and unpublished papers, reports and dissertation available on Central Department of Geology (CDG) provide a concept on geological and engineering geological conditions of the study area. Based on available information, an investigation program was scheduled for the fieldworks.

Field study

The field investigation was carried out for 15 days to locate active landslide along the highway and mountain slopes in different parts of the study areas. Landslide mapping was done with the measurement of its dimensions. Geological data was collected in the field and updated the existing data. Soil samples were collected for clay mineral analysis from 11 active landslides in the area.

a) Geological mapping

The Brunton compass, geological hammer, GPS, altimeter, magnifying glass, measuring tape, Hydrochloric acid, topographical map and the different stationary items were the tools used during the field study. Topographical maps 2784-02D (Jugedi Bajar) and 2784 03C (Mugling) were used for the geological mapping. Geological traverses were made along the Sindhure Khola, Kamere Khola , Bangesal, Das Khola, Dumre Khola, Virkuna Gaira, Ch 27+300, Padhera Khola, Ch 23+760, Gaighat Khola Kerabari Khola, and along numerous other streams and gullies along the roads, trails and spurs. Lithological characteristics were studied in outcrop with the help of hand lens and using hydrochloric acid. Lithological unit as well as geological contact between different rock units was carefully depicted in topographic map. The attitude of bedding/foliation plane and joints were measured on the exposed bedrock. Geological structures like fault and fold were delineated in topographic map and finally geological map was prepared at 1:25,000 scale.

b) Landslide Distribution mapping

For the landslide mapping traverses were made along the Mugling-Narayanghat Highway section, including drainage basins and mountain slopes. The engineering properties of the rock and soil were noted. On the rocky outcrop, the rock type, discontinuities, infilling materials, weathering grade, strength, and seepage condition were the major properties of concern. The soil was classified according to their origin and geologic feature, i.e. alluvial, colluvial or residual soil. The Brunton compass, geological hammer, GPS, altimeter, magnifying glass, measuring tape, 10% Hydrochloric acid, topographic map and the different stationary items were the tools used for this purpose.

Laboratory work, data processing, interpretation & report writing

The laboratory test of soil samples was done in full form lab. Grain size analysis was done to prepare samples for X-Ray analysis. There are two separate procedures for obtained the grain size distribution of soils: sieve analysis and sedimentation analysis (hydrometer, pipette, or buoyancy analysis) (Carig, 1987). One of the most fundamental methods for determining particle size is to pass the material through a series of sieves of standard sieve (Figure 2) of decreasing size and the percentage passed of the finest size.

Figure 2: Collected soil samples after sieving

Figure 3: Sieving equipment ready to use

Dry sieving was performed using the following meshes: 4.75 mm, 2.00 mm, 850 µm, 425 µm, 250 µm, 106 µm and 75 µm. Before sieving, the samples were placed in different bowls (plates), wrapped with perforated gelatinous sheet and dried under the sun for five days.

The fine sediments <75 µm were then subjected to sedimentation analysis as shown in Figure 3 to obtain the finest sediments of <2 µm. The samples were put into the hydrometer containing water in a fixed level and the time period for sample was fixed (for 10cm column it takes 11 hours, for 8cm column it takes 8.54 hours).

The samples after sedimentation were removed with the help of pipe as illustrated in Figure 4, and were collected in different jugs. The settled samples were centrifuged with a spin of 1300 rpm (Figure 5). The centrifuged samples were taken out and placed on the slide with the help of pipette (dropper) in a circle of diameter 1 cm as shown in Figure 6 and a slide of thickness approximately. 3 mg/cm^2.Were left until it got dry. This slide then was ready for X-ray diffractometer study (Figure 7).


Figure 4: Fine clay fraction are cursing in bowls


Figure 5: Crushed samples placed in jugs for settlement

The working formula during the process is

$$V = \frac{(\rho_p - \rho_f)g}{18\eta} \times R^2$$

Where, V = settling velocity. (m/s)

ρp = particle density (kg/m3)

ρf = density of fluid (kg/m3)

R = particle radius (m)

η = viscosity of water (kg/ms)


Figure 6: Samples removed from hydrometer


Figure 7: Samples removed from centrifuging unit

The following values were used for the calculation purpose:

ρ_p = 2.6gm/cm^3

ρf = 999.85kg/m3

g = 9.8m/s2

R = 0.0002m

η = 0.001346kg/ms

Settlement formula is $V = \frac{h}{t}$

Where, h = height of water

t= time of settlement

Diffractometer Setting

The instrument for X-ray diffraction was Advanced D8 diffractometer. It has Cu cathode, Ni filter and utilizes 40 kV tube Voltage, 30 mA current. The diffractometer setting was constant for all samples, i.e. time constant = 2 second, scatter silt = 1^0, receiving silt = 0.2 mm, divergence silt = 1^0.

Figure 8: Sample placed in slide for X-Ray analysis


Figure 9: Slide placed in X-Ray Diffractometer

All data and information obtained during desk study, field investigation and laboratory testing were then refined and analyzed. The interpretation and presentation of collected data are facilitated by computer software. The final report was prepared in accordance with the guidelines provided by Central Department of Geology, Tribhuvan University by incorporating all the analysis, results and data collected in the field.

CHAPTER - 3

GEOLOGY AND LANDSLIDES OF THE STUDY AREA

Geologically and tectonically, the Nepal Himalaya is divided into five major tectonic zones, namely, Terai, Sub-Himalaya (Siwaliks), Lesser Himalaya, Higher Himalaya and Tibetan-Tethys Himalaya (Gansser 1964; Upreti 1999). From South to North these tectonic zones are separated by major thrusts and faults of the Himalaya: South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) from north to south. The Himalaya was formed as a result of a collision between the northward moving Indian continent and the Asian landmass. Continued activity is manifested in present day northward movement of the Indian plate at a rate of 5cm per year and in occurrence of frequent seismic events along the mountain range and in its surroundings (Seeber and Armbruster, 1981; Pandey et al., 1995; Bilham et al., 1997, 1998). As a result, the rocks of the Himalaya are moving upwards as well as horizontally towards south along the major thrusts (Upreti, 2001). Steep slopes and deeply eroded river valleys are the outcomes of such movement in the Higher Himalaya. The erosion rate in the Himalayans about 3-4 mm/yr (Gupta, 1997), suggests that such a high rate may be caused by frequent occurrence of big landslide. Many investigations have disclosed that movement along the MCT ceased by around 18 Ma (Copeland et al., 1991; Hodges et al., 1996). Such movement caused Higher Himalayan rocks to slide horizontally towards south about 120 km over the young Lesser Himalayan rocks. Thus, it is believed that once upon the geological time much of the Lesser Himalaya must have been covered by the rocks of the Higher Himalayan crystalline rocks like a bedspread. In eastern Nepal, the MCT is still in south and only opens as window in the Arun River valley and Taplejung areas. But most of the parts of Higher Himalayan crystalline rocks are already eroded in other area. Although it is presumed that the MCT became inactive and the movement along this thrust practically ceased by 18 Ma, it has been found that MCT was reactivated during a period 6–8 million years ago (Harrison et al., 1997), and the Higher Himalaya again revitalized. As a result, normal fault system, STDS, developed as gravitational collapse structure, which is now considered as a tectonic boundary between the Tibetan- Tethys Zone and the Higher Himalayan Zone.

A brief review of the Nepal Himalaya

The Nepal Himalaya is located in the central part of the 2,400 km long Himalayan arc and extends for about one third (800 km) of its total length running from the Mechi River to the Mahakali River (Gansser, 1964). It is divided into five major tectonic zones. From south to north they are Terai, Sub Himalaya, Lower Himalaya, Higher Himalaya and Tethys Himalaya (Gansser, 1964). These zones extend approximately parallel to each other, each characterized by their own lithology, tectonics, structures and geological history. It is also divided into four transverse geological zones namely Eastern Nepal, Central Nepal, Western Nepal and Far western Nepal separated by a major river from East to West.

Terai

This zone represents the southernmost tectonic unit of the Nepal Himalaya. The Himalayan Frontal Thrust (HFT) separates this foreland basin with the Sub-Himalaya to the north. The Pleistocene to Recent alluvial deposits cover the Terai plain and rests on the Siwaliks which in turn rest over the Precambrian and the Gondwana rocks of the Eocene-Oligocene age (Sharma, 1990). The average thickness of deposit is 1500 m. Geomorphologic ally, the Terai zone is sub-divided into Northern (Bhabhar), Middle and Southern zones.

Sub Himalaya (Siwaliks)

The Churia range, synonym for this zone, represents low hills and is bounded by the MBT to the north separating it from the Lesser Himalaya. It is composed of fluvial deposits of the middle Miocene to early Pleistocene age containing vertebrate fossils (Corvinus, 1988). This zone is sub-divided into the Lower Siwalik, the Middle Siwalik and the Upper Siwalik (Auden, 1935). The Lower Siwalik comprises ash grey and red-brown, fine-grained sandstone with pseudo conglomerate containing pebbles of Siwalik fragments, inter-bedded with purple, grey mudstone and siltstone. A few vertebrate fossil remains have been reported from central and central west Nepal (West et al., 1978, 1981; Munthe et al., 1983). The Middle Siwalik comprises relatively coarse, arkosic to lithic, grey sandstone with small proportion of green and grey mudstone and siltstone. Sandstone is salt-and-pepper type in appearance and is thick-bedded and cross-laminated toward the top. Occasionally it consists of conglomerate beds in the middle and upper part of the sequence. Coalified plant logs, leaf impressions and some molluscs are found in sandstone, mudstone and siltstone (West et al., 1975; Corvinus, 1988). The Upper Siwalik represents dominant coarse conglomerate beds with minor sandstone and mudstone beds. Conglomerate consist of pebble, cobble and boulder of gneiss, schist, granite and quartzite of the Higher Himalaya, limestone, phyllite, slate and sandstone of the Lesser Himalaya and sandstone of the Lower and Middle Siwaliks.

Lesser Himalaya

It is separated from the Higher Himalaya to the north by the MCT. It is mostly made up of non-fossiliferous sedimentary and metasedimentary rocks such as shale, sandstone, conglomerate, slate, phyllite, schist, quartzite, limestone and dolomite ranging in age from the Precambrian to the Oligocene (Bordet, 1961; Hagen, 1969; Valdiya, 1995, Sakai 1983, 1985; Le Fort et al. 1999). The geology is complicated due to folding and normal and thrust faulting (Stöcklin, 1980). There are also some remarkable granitic intrusions in this zone. Tectonically, the entire Lesser Himalaya consists of two sequences of rocks. They are allochthonous, and autochthonous-parautochthonous units with various nappes, klippes and tectonic windows. From east to west, the Lesser Himalaya shows much variation in stratigraphy, structures and magmatism.

Higher Himalaya

It generally begins at the top of the Lesser Himalaya and extends to the bottom of the Tethys Himalaya, separated by the MCT and STDS, respectively. It is made up of the Precambrian rock unit, mainly the high grade metamorphic rock and granitic gneiss. It comprises mainly kyanite-sillimanite bearing gneiss, schist and marble and granite. This crystalline unit extends continuously along the entire length of the country (Heim and Gansser, 1939) commonly called as the Higher Himalayan Crystalline Series (HHCS). Bordet et al. (1972) sub divided the HHCS into kyanite-sillimanite gneiss, Pyroxenic gneiss and marble, Banded gneiss and Augen gneisses in the ascending order. However, Le Fort (1975) divided this zone into three formations as the Formation I, Formation II and Formation III in the ascending order. The Formation I consists of kyanite to sillimanite garnet, two-mica banded gneiss of pelitic to arenaceous composition. The presence of augen gneiss, remobilization (migmatization) and intercalation of lime silicate rock and quartzite characterize the upper part of the formation. The Formation II often begins with a coarse quartzite beds several tens of meters thick. It is mainly composed of alternation of pyroxene (amphibole) calc-gneiss and marble.

Tethys Himalaya

It is made up of the Late Precambrian–Early Paleozoic to the Upper Cretaceous (Colchen et al., 1980), richly fossiliferous clastic and carbonate sediments deposited in the Tethys Ocean. It extends to the north into Tibet, separated by the Indus-Tsangpo Suture Zone (ITS). It is composed of shale, limestone and sandstone. These rocks are well developed at the Thak Khola (Mustang), Manang and Dolpa.

The study area lies in the Lesser Himalaya of Central Nepal.

Review of the previous works in the study area

A number of geological investigations are being carried since 1875 in Central Nepal at regional and local scale. The brief description of the geological works is given below. Medlicott (1875) took a traverse from Amlekhgunj through Kathmandu to Nuwakot. He was the first to discover the Chandragiri-Phulchauki fossiliferrous beds. He described the sedimentary and the low grade metamorphic rocks to the south and gneiss and the high grade rocks to the north of Kathmandu.

Auden (1935) carried the first systematic geological investigation in Nepal, who visited some parts of the Eastern and the Central Nepal. He gave a fairly good account of the geology of this part of the Himalaya. He studied the fossils from limestone of Chandragiri and assigned the Ordovician age to these rocks. He noticed superposition of the high grade metamorphic rocks over the low grade metamorphic rocks in the Mahabharat Range.

Gansser (1964) compiled the geology of Nepal and tried to reconstruct the comprehensive and total geological configuration of the Himalaya. In his work, he has tried to give a regional tectonic outline of the whole Himalaya including Nepal.

Hagen (1969) worked the first most important and extensive study on the Nepal Himalaya. He developed the concept of nappe structures in the Nepal Himalaya. The distinction of the Kathmandu Nappe and the Nawakot Nappe was based on conspicuous differences in composition, metamorphic grade and age.

Stöcklin and Bhattarai (1977) studied the geology of the Kathmandu area and Mahabharat range based mainly on the photogeological interpretations supported by field works. They developed the stratigraphy of the Central Nepal. Apart from the Tertiary Siwalik and Quaternary deposits, they grouped the rocks into two largest units, Nawakot Complex and Kathmandu Complex. These complexes are further sub-divided into formations and members.

Landslides in the Himalaya are scale-dependent, from massive extent of whole mountain ranges (gravity tectonics) through failure of single peaks to very minor slope failures (Shroder and Bishop 1998; Shang et al. 2003). However, only few studies have been done to understand the Nepal Himalayan landslide mechanisms and processes (e.g., Laban 1979; Wagner 1983; Upreti and Dhital 1996; Chalise and Khanal, 2001) and there are still lack of research publications related to the mechanisms and processes of large scale landsliding in the Lesser Himalaya. However some few works have been done in Mugling-Narayanghat section (e.g., Udas 2005; Hasegawa et al. 2006; Adhikari 2007).

Udas (2005) analyzed the slopes in the Narayanghat-Mugling Highway with the help of Arc View GIS 3.2 and concluded that the mean critical internal frictional angle and the critical slope angle for the three steady state increases against the saturation of the rock more than 45% of the study area falls in unstable condition and only 1.28% of the study area is stable in saturated condition. Thus, it can be concluded that the study area is the most prone site for rock slide and it‘s more susceptible to the slope failure.

Hasegawa et al. (2008) studied slopes along the major highways of Central Nepal namely the Prithivi Highway, Narayanghat-Mugling Road and Tribhuvan Highway which are considered of large-scale landslides.

Adhikari (2007) worked along the Narayangarh-Mugling section and has studied with the help of landslide distribution map and structural maps. He has suggested the method of mitigating the water induced disaster due to landslides in the study area.

Regional Geology and Geological structures

Regional Geology

The Mugling-Narayanghat section in the north belongs to the Mahabharat Range of the Lesser Himalaya and that in the south belongs to the Siwaliks. The Lesser Himalayan rocks in this area are part of the Lower Nuwakot Group of the Nuwakot Complex. Stratigraphically, the Lower Nuwakot Group is considered as an overturned sequence with the Kunchha Formation at the bottom and the Dhading Dolomite on the top. The Dandagaun Phyllite, Nourpul Formation and Dhading Dolomite appears in some parts, and the reason is tectonic rather than stratigraphic. The Benighat Slate is the only rock formation of the Upper Nuwakot Group exposed in the area. The Siwalik Group consists of boulder beds, conglomerate, and some sandstone. The rock formations are briefly described below.

The Lesser Himalaya

Kunchha Formation

The Kunchha Formation is exposed around Mugling area and continues to the south for about 2 km along the road as illustrated in Figure 10. It consists of an alternation of phyllites, phyllitic quartzites and phyllitic gritstones, and the areas represented by the Kunchha Formation have low mountains and relatively gentle slope. An especially noteworthy feature of the Kunchha Formation is a strong lineation, predominantly in N or N-NE direction, seen in nearly all outcrops. Generally, the rocks are highly weathered and deep colluvial and residual soil is developed on it, but landslides and debris flow deposits were uncommon along the road section.

Fagfog Quartzite

South from the Kunchha Formation, about 500 m thick band of the Fagfog Quartzite is exposed along the road section, and it extends both east and west of the Trishuli River (Figure 10). It is made up of thickly bedded white quartzite with ripple marks and cross beddings. The beds are generally almost vertical to steeply dipping and as the rocks are jointed, some rock falls and slides can be seen at places. The Fagfog Quartzite can be easily distinguished even from some distance because it usually makes high mountains due to the hard nature of the rock.

Table 1 Stratigraphic sub-division of Central Nepal (Stöcklin and Bhattarai, 1977; Stöcklin, 1980)

COMPLEX	GROUP	FORMATION	MAIN LITHOLOGY	APPROX. THICKNESS (m)	AGE
Kathmandu	Phulchauki	Godavari Limestone	Limestone	300	Devonian
		Chitlang Formation	Slate	1,000	Silurian
		Chandragiri Limestone	Limestone	2,000	Cambrian-Ordovician
		Sopyang Formation	Slate, calc-phyllite	200	Early Cambrian or Late Precambrian
		Tistung Formation	Meta-sandstone, phyllite	3,000	
	Transitional				
	Bhimphedi	Markhu Formation	Marble, schist	1,000	Precambrian
		Kulikhani Formation	Quartzite, schist	2,000	
		Chisapani Quartzite	White quartzite	400	
		Kalitar Formation Jurikhet Conglomerate Pandrang Quartzite Bhimsen Dolomite Member Lower Schist Member	Schist, quartzite , partly garnetiferous	2,000	
		Bhainsedobhan Marble	Marble	800	
		Raduwa Formation Chak Quartzite beds	Garnet schist, quartzite	1,000	
Mahabharat Thrust (MT)					
Nawakot	Upper Nawakot	Robang Formation with Dunga Quartzite beds	Phyllite, quartzite	200-1,000?	Paleozoic
		Malekhu Limestone	Limestone, dolomite	800?	
		Benighat Slates Boulder beds Jhiku carbonate beds	Slate, argill. dolomite	500-3000?	
	Unconformity (?)				
	Lower Nawakot	Dhading Dolomite	Stromatolitic dolomite	500-1,000	Late Precambrian
		Nourpul Formation Purebesi Quartzite	Phyllite, quartzite, Dolomite	800	
		Dandagaon Phyllites	Phyllite	1,000	
		Fagfog Quartzite	White quartzite	400	
		Kuncha Formation Ladbi Phyllite Member Banspani Quartzite Member	Phyllite, quartzite, gritstone, conglomerate	3000+	
Main Boundary Thrust (MBT)					
Siwalik			Sandstone, mudstone, conglomerate	Several km.	Neogene

Dandagaun Phyllite

The Dandagaun Phyllite consists of uniform argillaceous to finely quartzitic phyllites of dark blue-green color. In weathered condition the rock often displays reddish tints.

Green, fine-grained, sericitic or chloritic quartzite occurs in places as thin intercalations in phyllites. The exposure in the north of Purebesi Village along the road section is about 1 km thick and reappears again as a thrust slice in the west of Trishuli River, opposite of the Dumrebesi Village, but it is missing in the east. Slopes are relatively stable in this rock.

Nourpul Formation

The Nourpul Formation is extensively distributed along the Mugling-Narayanghat Highway section from about Ch 32+00 in the north (close to Purebesi Village) to Ch 16+700 in the south (~2 km south from Gaighat) as shown above in Figure 10. It has a mixed lithology of phyllitic, quartzitic, and calcareous rock types. Purebasi Quartzite – light pink to white in color, overlying the Dandagaun Phyllites, forms the basal part of the formation. It is followed by an intercalation of red-purple, grey-green, and dark-grey slates, phyllite and quartzite in the middle part, and dolomites and dolomitic quartzites become more abundant in the upper part, i.e. in the downstream section. The uppermost boundary of the formation is marked by a thrust fault, and two more thrust faults, with a common root, run in the Nourpul Formation from south-east to north-west direction. The rocks are folded, faulted and sheared, and particularly the quartzites are jointed and intensely fractured. Thick collapsed deposits with a wide range of particle sizes from clay to blocks, but dominated by coarse fractions, are common. Most of the instabilities in the Mugling-Narayanghat Road section lie in this formation. The formation is widely exposed in the study area. Representative dips strike 275/68NW.

In the Yakrang area (Figure 10), outcrop of amphibolite (metamorphosed basic igneous rock) rests over the thrust faults within the Nourpul Formation. A separate outcrop of the Formation (< 1 km) reappears around the Sayoli area in the south in contact with the Main Boundary Thrust (MBT). The Nourpul formation in some part of the Mugling-Narayanghat road section forms the lowermost part of the Lesser Himalaya.

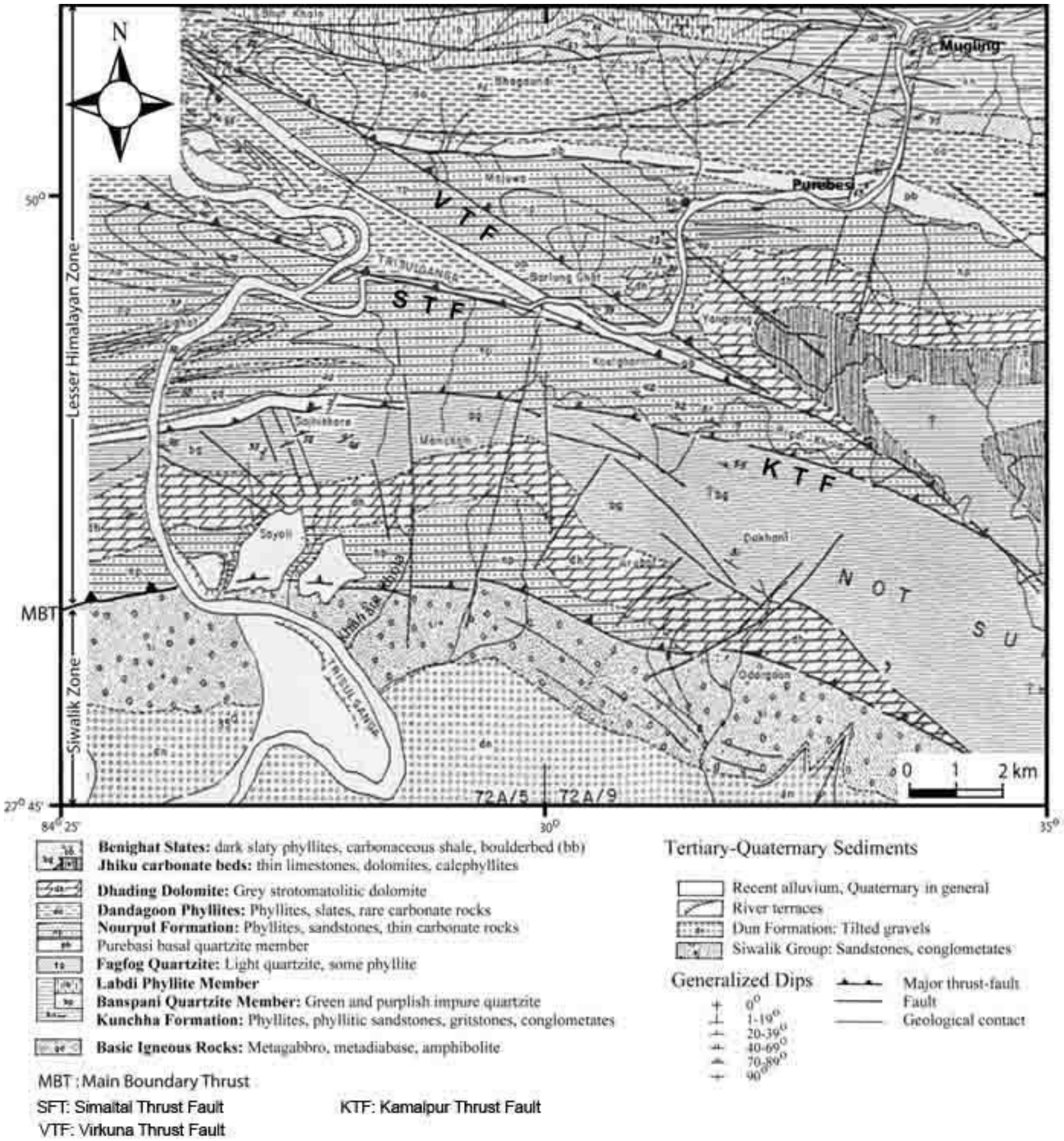


Figure 10: Regional geological map of the Narayanghar-Mugling area (modified after Stocklin and Bhattarai, 1977, modified by Adhikari, 2007)

Dhading Dolomite

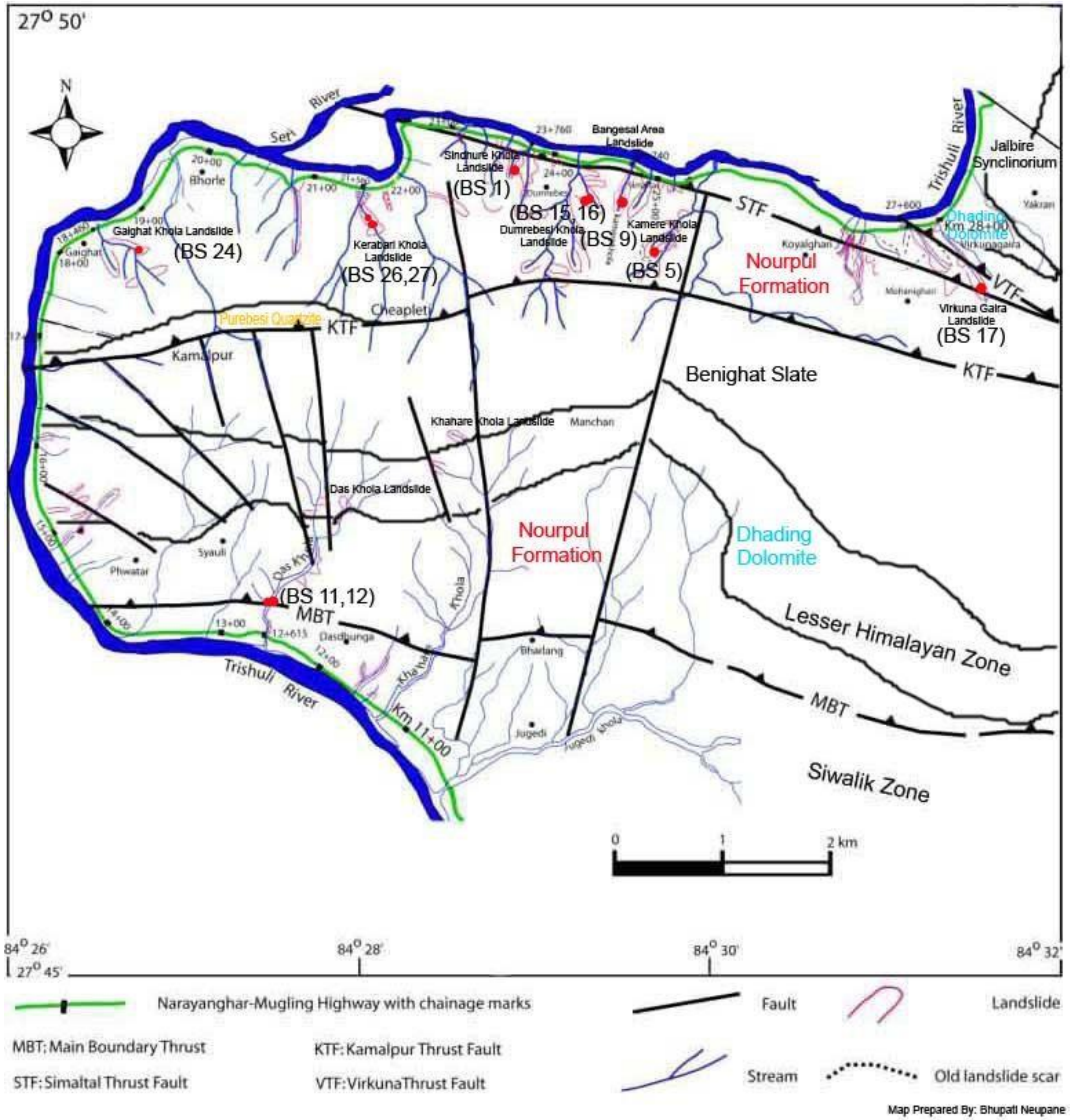
The Dhading Dolomite crops out south of Gaighat as shown in Figure 10, and forms a continuous band both to the east and west of the Trishuli River, and there is a separate outcrop around Yakrang area in the east. The rock is characteristically fine crystalline or dense and light blue-grey in color. It is thinly bedded and platy in the basal part and the beds are thick to massive with common occurrence of columnar stromatolite in some parts. There are also few bands of black slate intercalated with the dolomite. As the Dhading Dolomite is hard and resistant to weathering, it makes high hills and ridges with distinct topographic features and abrupt topographic rise as can be seen north from the Jugedi area. In the vicinity of the MBT, the rock is intensely fractured and brecciated, making the slope marginally stable to unstable. In some places, it forms vertical cliffs with bare rock faces.

Benighat Slate

Although the Benighat slates rests over the Dhading Dolomite and occupy the uppermost position in the Lesser Himalayan stratigraphic column in Mugling-Narayanghar area, tectonic repetitions of some formations as mentioned above make the sequence complicated. The Benighat Slates along the road section crops out between Ch 16+200 and Ch 16+800, and distributed around Sajikhore and Mancham, and gets thicker in the east. It consists of dark grey to black slates and phyllites, subordinately siliceious or finely quartzitic. Particularly characteristic of the Benighat Slates are black ―carbonaceous‖ slates containing much graphitic matter, occurring as intercalated zone up to several tens of meters of thick. Generally, the rocks are weathered and the color is much lighter, showing lead-grey, silver-grey, pinkish, and pale green. Frequently, the slate is highly cleaved. There are also a few carbonate bands intercalated in the slates and they are known as the Jhiku Calcareous bed. A sharp thrust fault separates the Benighat Slate to the south from the Nourpul Formation in the north. There is some instability in this formation.

The Siwalik Group

Beds of conglomerate of the Upper Siwalik and sandstone of the Middle Siwalik are exposed south of the Mahabharat Hills in the Das Khola, Khahare Khola, and Jugedi Khola Valleys. Outcrops of these rocks can be observed on the road side north of the Das Khola. The thickness of the rocks is less than 1 km. The sandstone is medium-grained and grey colored, and is moderately weathered in some locations. As the Siwalik rocks in the area have formed low ridges, they are covered by colluvium derived from the Lesser Himalayan rocks. The sandstone hosts some landslides on the stream sides, while the ridges are stable.



Sample Location	Landslide	Formation	Lithology	Clay Minerals
BS 17	Virkuna Gaira	Nourpul Formation	Light grey phyllite	Illite, Chlorite
BS 5	Kamere Khola	Nourpul Formation	Milky White Feldspar with phyllite	Illite, Kaolinite, Chlorite
BS 9	Bangesal Area	Nourpul Formation	Light grey phyllite	Illite, Chlorite
BS 15	Dumrebesi Khola	Nourpul Formation	Light grey phyllite with feldspar	Kaolinite, Chlorite
BS 16			Light grey phyllite	Illite, Chlorite
BS 1	Sindhure Khola	Nourpul Formation	Light grey phyllite with quartzite	Illite, Kaolinite, Chlorite
BS 26	Kerabari Khola	Kunchha Formation	Light green amphoblite	Kaolinite, Chlorite
BS 27				
BS 24	Gaighat Khola	Nourpul Formation	Light grey phyllite with feldspar	Illite, Kaolinite, Chlorite
BS 11	Das Khola	Siwalik Zone	Reddish brown sample	Unidentified

Nourpul Formation

Dhading Dolomite

Benighat Slate

Siwalik Zone

Figure 11: Distribution of landslides and the faults and thrusts faults in the Mugling-Narayanghar section. (After Adhikari, 2007)

Geological Structures

The Main Boundary Thrust (MBT), a major thrust which separates the Lesser Himalaya to the north and the Siwaliks to the south, crosses the Narayanghat-Mugling Road around Ch 14+00, south of Phwatar and runs east-west. As the MBT is one of the major thrusts in the Himalaya, it plays an important role on slope instabilities. In the Narayanghar-Mugling section, instabilities along the Das Khola, Khahare Khola and Jugedi Khola valleys are mostly located in the MBT zone and immediately north of it. Kamalpur Thrust Fault (KTF), Simaltal thrust fault (STF), and Virkuna Thrust Fault (VTF) (Figure 11) are some local Thrust Faults observed in the study area are (Adhakari , 2007). In this study they are named as: The Kamalpur Thrust Fault (KTF), which crosses the highway at Ch 16+700 and passes to the east through the Kamalpur and Chepleti areas; the Simaltal Thrust Fault (STF), which crosses the highway at Ch 23+00 and passes to the south-east through the Simaltal area and; the Virkuna Thrust Fault (VTF), which cross the highway at Ch 27+600 and passes to the south-east along the Virkunagaira and meets the STF somewhere south of Yakrang. The late two has a common root zone.

Most of the instabilities on the road side and in the stream catchment areas between Ch 16+00 and Ch 28+00 are largely, directly or indirectly, due to the thrust faults and the normal faults mentioned above Figure 10. The area has also undergone local folding of different scales at places, which have locally controlled slope stability. Another major geological structure in the road section is the western closure of the Mahabharat Synclinorium. It is a huge syncline in the Mahabharat Range of the central Nepal, and is locally known by the Jalbire Syncline. It has also some roles in the stability of the slope along the road section around Jalbire area. The brittle rocks, especially dolomite, quartzite, and amphibolite are jointed and intensely fractured, making the slope vulnerable to rock falls and slides. Phyllites and slates have undergone high degree of weathering and have some ductile deformation at places.

Landslides

General features of Landslides

A landslide is defined as a down-slope movement of a mass of soil, rock, and other material (Cruden, 1991). This broad definition includes a variety of failure modes and is not limited to slow-moving, slide-type failures. Mass movement, mass wasting, and slope movement (Varnes, 1978) are alternate terms for landslides as broadly defined. Four types of movement are found in the study area—falls, topples, flows, and slides as given in Table 2.

Table 2: Schematic landslide classification adopting the classification of Varnes 1978 and taking into account the modifications made by Cruden and Varnes, in 1996.

<table>
<tr><td rowspan="3" colspan="3">Type of movement</td><td colspan="3">Type of material</td></tr>
<tr><td>Bedrock</td><td colspan="2">Engineering soils</td></tr>
<tr><td></td><td>Predominantly fine</td><td>Predominantly coarse</td></tr>
<tr><td colspan="3">Falls</td><td>Rockfall</td><td>Earth fall</td><td>Debris fall</td></tr>
<tr><td colspan="3">Topples</td><td>Rock topple</td><td>Earth topple</td><td>Debris topple</td></tr>
<tr><td rowspan="3">Slides</td><td>Rotational</td><td></td><td>Rock slump</td><td>Earth slump</td><td>Debris slump</td></tr>
<tr><td rowspan="2">Translational</td><td>Few units</td><td>Rock block slide</td><td>Earth block slide</td><td>Debris block slide</td></tr>
<tr><td>Many units</td><td>Rock slide</td><td>Earth slide</td><td>Debris slide</td></tr>
<tr><td colspan="3">Lateral spreads</td><td>Rock spread</td><td>Earth spread</td><td>Debris spread</td></tr>
<tr><td rowspan="3" colspan="3">Flows</td><td>Rock flow</td><td>Earth flow</td><td>Debris flow</td></tr>
<tr><td>Rock avalanche</td><td></td><td>Debris avalanche</td></tr>
<tr><td>(Deep creep)</td><td colspan="2">(Soil creep)</td></tr>
<tr><td colspan="3">Complex and compound</td><td colspan="3">Combination in time and/or space of two or more principal types of movement</td></tr>
</table>

The landslides in the study generally fall in the classes Rock Fall (Kerabari Khola), Earth Fall (Kamera Khola), Debris Avalanche (Kerabari Khola) and Topples (Sindhure Khola).

Triggering factors of Landslide

There are many trigging factor which is the cause of landslide occurrence. The main triggering factors are:

- Cloud burst(200-1000mm per day)
- Uncontrolled flow of water on slope.
- Toe cutting by river.
- High strength quake.
- Blasting vibration.
- Flash flood.
- Failure of landslide dams.

The most common triggering factors in the Narayanghat-Mugling areas are intense monsoon rainstorms, prolonged periods of sustained rainfall, seismic shaking, and slope undercutting. The triggering threshold varies with the inherent stability of the terrain and therefore the spatial differences in the value of triggering thresholds can provide a relative measure of the geographic distribution of terrain susceptibility to landslide occurrence. It is also clear that in some situations the triggering threshold for a given terrain is not a constant but varies temporally as a result of landslide occurrence. As susceptible material is successively removed from hill slopes there is a residual strengthening of the terrain and the triggering threshold rises. This phenomenon is referred to as ‗event resistance'. A similar phenomenon can be observed with debris flow occurrence. The activation of debris flows depends not only on the magnitude of the triggering event but also on the availability of transportable material. For example, if all source material is removed by a rainfall-triggered debris flow, further rainstorms of the same magnitude are unlikely to generate flows.

Landslides of the study area

Lesser Himalayan Areas

Virkuna Gaira and Koyalghari area - Area between Ch 28+00 to Ch 26+00

The rock unit around the Virkuna Gaira and Koyalghari area belongs to the Nourpul Formation, which consists of alternate beds of quartzite, phyllites and some carbonate beds. The general attitude of of the rocks is S50^{o} E/30^{o} NW. It forms the southern limb of the Jalbire Syncline. The Virkuna Thrust Fault (VTF) passes along the Virkuna Gaira as shown in Figure 12. The rocks are fresh to highly weathered, and are intensely fractured, jointed and deformed. The dip slope is mantled by thick (> 5 m) collapsed deposits consisting of coarse soil with domination of boulders and blocks and younger colluviums on the top. The collapsed deposit is believed to have formed during or following the formation of the VTF.

Figure 12: View of Virkuna Gaira Landslide (Ch 26+00) as seen from the highway

As the soils are coarse and loose, they are highly porous. Plane rock failures and planer soil sliding and flowing in the dip slopes and the rock falls and rock slides in the counter dip slopes are the main type of instabilities. The intersection of the bedding plane (dip slope) and the joints (counter dip slope) forms wedges and wedges failures, along which the Virkuna Kholsi flows. It is completely dry but experiences big flood in monsoon time, during which slope undercutting triggers more instabilities. The topography has made a series of dip and counter dip slopes, and most of the instabilities in this area are concentrated on the dip slopes because the disposition of the rocks are favorable for this type of failure.

The landslide debris in the down slope areas were seen mobilized into debris flows, which is the main cause of road blocking and damage. In some areas, phyllites and slates have undergone intense deformation and weathering and have facilitated hillslope failures without any undercutting actions of seasonal gullies. At the base of the hill slopes adjacent to the road, small slides are common between Ch 27+00 and Ch 27+500, and from some elevated areas, isolated landslides can be seen in the upper slopes. Seepage of groundwater was observed on the breast wall all along the road side. In some parts, the land is used as slopping terrace for maize; mustard, millet and oilseed cultivation, and some parts are degraded forest and shrub lands. Sample of BS17 was collected on active side as shown in Figure 12.

Orientation of the bed rocks, the presence of rock discontinuities, and availability of the thick coarse soils on the hill slopes have already pre-disposed the slope to failure. Thrusting and other rock deformations, weathering, stream erosion, deforestation and slope farming, and tectonic uplift are some of the preparatory factors converting the stable slope into marginally stable conditions; and the monsoon rains, groundwater, and the slope under cutting are the landslide triggers, which finally make the slope moving. Field investigations, therefore, revealed that the area is vulnerable for landslide and debris flow occurrence when there is extreme precipitation of short duration or sustained rainfall of longer period.

Some of the major landslides observed on this area are:

- *Ch: 28+00 kholsi*: Active landslide, rocks are highly disturbed and highly jointed. Dimensions are: length (L) 30 m, breadth (B) 10 m, height (H) 15 m.
- *Ch: 27+300*: Light grey- to white, highly weathered, some grit of phyllite. Soil horizon 50 cm. Dimension of this landslide was: L = 20 m, B 12 m, H 10 m.
- *Ch: Pandhere Khola*: Milky white, wet, completely weathered, seepage, origin of spring. Dimensions are: length 10 m, breadth 8 m, height 8 m.
- *Ch: 23+760*: Light grey, slightly weathered, wet, soil horizon depth 2 m. Dimensions are: length 8 m, breadth 4 m, height 5 m.
- *Ch: 26+00*: Black-to grey, weathered, wet, and soil horizon depth 1m. Dimensions are: length 15 m, breadth 9 m, height 5 m

Pachchis (25) Kilo Kholchi (Ch: 24+860)

The rocks around the Pachchis Kilo Kholsi are interbeded quartzite, phyllites and slate of the Nourpul Formation. As in Virkuna Gaira-Koyalghari area, the quartzite is highly jointed and fractured, and folded (Figure 13) in some parts. In undisturbed outcrops, bedrocks dip along the hill slope and the stream, and the attitude is 110/50^{o} N. Soil in the area is thick (>5 m) and coarse fraction dominates the size. There are a large number of landslides all along the stream, which are rock falls, rock slides (plane failure), and soil slides and soil falls, and soil flow in some areas. Code Figure in appropriate place.

Figure 13: Pachchis Kilo Kholsi Slide Ch: 24+860)

The Simaltal Thrust Fault (STF), which crosses the stream and the landslide, has a sheared zone consisting of some rock fragments with fine clays. Field evidence in the wet part of the sheared zone revealed that the materials have aggravated the slope stability because they serve as a lubricant. The landslides in the area are largely due to the thrust induced instabilities triggered by undercutting and monsoon precipitation. As in other parts of the Mugling- Narayanghat section, the Pachchis Kilo Kholsi is prone to landslides in the upper parts and the resulting debris flow in the lower parts and the highway.

Kamere Khola (Ch: 24+740)

The rocks around and along the Kamere Khola constitute interbedded quartzite, phyllites and slate of the Nourpul Formation. The quartzite is highly jointed and fractured, and the phyllites and slate are weathered and crushed (Figure 14). On the right side, a recumbent fold and boudinage structures were observed, which indicate that the area represents a compressional stress regime. The undisturbed outcrops dip parallel to the hill slope with an attitude of 275/68^o N. Thick (>5 m) coarse soils characteristics of collapsed deposits overlie the bedrock and some finer colluvial soils are on the surface.

Figure 14: Upper part of the Kamere Khola Slide observed from the highway

Some old and several interconnected new slides appeared in 2006 were evidenced in the field. The whole Kamere Khola Valley represent as a multitier expanding landslide with domination of translational movements both in the soil mass and bed rocks. The Simaltal Thrust Fault (STF) runs across the landslide, and this is the preparatory factor of the instabilities. As in the other parts of the area, geological and engineering geological conditions are the main causes of the landslides and the monsoon rain and stream undercutting act as the trigger. The potential threat of the landslide is that all the landslide debris displaced from the upper slopes could mobilize as debris flow downward and it could destroy the road as that happened in 2006. As the landslide is expanding each year, some houses and cultivated lands are under high risk of damage and destruction. Despite some counter measures, the area is prone to landslide and highly hazardous for debris flow in monsoon. Sample of BS5 were collected middle part of failure zone.

Bangesal area (Ch: 24+600)

The rocks around and along the Bangesal area constitute interbedded, phyllites and quartzite, dominant of quartzite, and slate of the Nourpul Formation. The quartzite is highly crushed area lies in thrust zone. Rill erosion and gullies are developed as illustrated in Figure 15. Few years back there was slight depression. Now a day here is large landslide. It has powder like substance of quartzite and phyllite.

The undisturbed outcrops dip parallel to the hill slope with an attitude of 265/59^{o} N. Thick (>4 m) coarse soils characteristics of collapsed deposits overlie the bedrock and some finer colluvial soils are on the surface. The Simaltal Thrust Fault (STF) runs across the landslide, and this is the preparatory factor of the instabilities. Sample of BS 9 were collected lower part of failure zone.

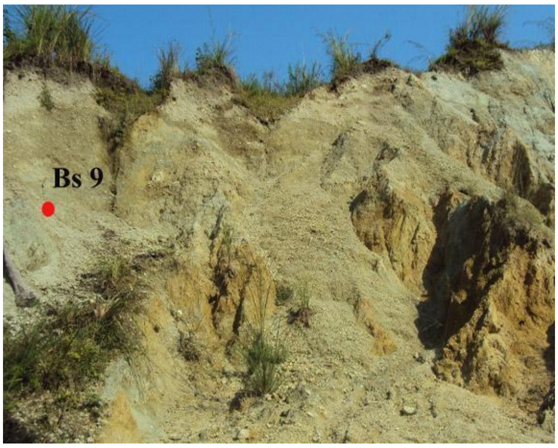


Figure 15: Bangesal landslide (Ch: 24+600) with weathered rock mass

Dumrebesi Khola (Ch: 24+300)

The geology around Ch: 24+300 is similar to that of Kamere Khola as described above. A small stream that meets the Highway at 24+300 has a landslide (L = 155 m, B = 60 m, D = >5 m) in its upper reaches. The thick colluvial soil (> 5m) dominated by gravel-size fraction with lots of fines overlying phyllite have undergone soil falling and sliding as shown in Figure 16.

Figure 16: Dumrebesi Khola slide with rock fall

Unlike the soils observed along the Kamere Khola, it is free from fractions coarser than gravel. It is actively retreating toward the cultivated land and threatening the houses up slope. It was triggered by the heavy precipitation of 2006 monsoon and, is prone to further more sliding and falling, which in turn could generate debris flow and damage the highway. Samples of BS 16 and BS 17 were collected in this location.

Sindhure Khola (Ch: 23+00)

The rocks around the Sindhure Khola, as is consist of interbedded quartzite, phyllites and slate of the Nourpul Formation. The quartzite is highly jointed and fractured, and the phyllites and slate are weathered and crushed into soils (Figure 17). On the lower left side of the landslide, quartzite is intensely fractured, separating the outcrops into number of unstable blocks. Phyllite is exposed on the right side, which is highly weathered and behaves either like a soil or unusually fractured and jointed when it is fresh. The attitude of the foliation in undisturbed outcrop is dominant 78^{o}/62^{o} NW and the attitude of the major joint is 210^{o}/61^{o} NW. Some fold structures are also seen on the slate and phyllite.

Figure 17: Sindhure Khola slide seen from road side

Figure 18: View of the landslide in the upper-right part

The STF is the major geological structure. In the lower part, soils are sandy gravel with lots of fines and some boulders and blocks, and the thickness varies from <1 m to >8 m. A major landslide initiated a couple of years ago in the lower part of the Sindhure Khola is expanding into a huge slide with components of rock falls on the right side as illustrated in Figure 18 and, as the thick soil mass is resting over the bedrock on the dip slope, soil slides and flow is dominant in the western part. The land use around the slide is dry cultivated land, where new tension cracks are propagating beyond the slide each year. There is some seepage in different levels even in the dry season, and addition of water, especially during monsoon time, could easily trigger landslides, and that in turn could mobilize in the form of debris flow below. As the STF passes across the landslide, all the instabilities are linked to it. Although some engineering structures are at places, and are protecting the slope from failure to some extent in some parts, the landslide still seems active and highly hazardous both for the village located up slope and road below. In the upper reaches of the Sindhure Khola there, the nature of the bed rocks is unchanged but soils get thinner and coarser. There are small slides almost all along the stream sides, but they are potential source of debris to generate debris flow in the lower part. The sample for BS 1 was collected 3m bottom of failure zone.

Kerabari Khola (Ch: 21+560)

The rock unit around the Kerabari Khola area is the Kuncha Formation, but a body of amphibolites (metamorphosed basic igneous rock) crops out in the valley and dominates the lithology. In the section along the stream, a highly weathered and deformed phyllites and slate are in the basal part, some quartzite beds on the top and the amphibolites is between the phyllite and quartzite. The quartzite is slaby and jointed, suitable to produce big blocks. Unlike the amphibolites seen in other parts of the Himalaya, it has 3-4 sets of joint, and is extremely fractured and fragmented into sizes from gravel to blocks as shown in Figure 19.

Figure 19: Kerabari Khola slide with rock debris

Figure 20: Rock and soil falls on Kerabari Khola slide

The debris in the valley looks like a rock glacier (Adhikari, 2007), where the size is smaller in the lower part and gets coarser up slope. There is no soil in the lower part but a thick fine colluvial soil overlies the bed rock in the head part of the stream (Figure 20), where the land is used for dry cultivation. Below the cultivated field is forest. A landslide characterized by a combination of rock falls, rock slide and wedge failures has wrecked the area. It is about 300 m long, 30 m wide and the depth varies from 5-8 m. As the amphibolites is heavily fractures and jointed, the valley walls are prone to rock failure. Pore water pressure in the discontinuities can easily trigger failures. The rock debris generated by the landslides was mobilized into a disastrous debris flow in 2006 summer and damaged the Highway Bridge and created a lot of problem. The field observations suggest that the area is prone to future landslide and debris flow. The samples BS 26 and BS 27 were collected from the active site.

Gaighat Khola (Ch: 18+450)

The rocks around the Gaighat Khola constitute interbedded quartzite, phyllites and slate of the Nourpul Formation. The quartzite is highly jointed and fractured, and the phyllites and slate are weathered and crushed (Figure 21). The undisturbed outcrops dip parallel to the hill slope with an attitude of 190/55° N. Thick (>3 m) coarse soils characteristics of collapsed deposits overlie the bedrock and some finer colluvial soils are on the surface. The sample BS 24 was collected in this location.

Figure 21: Rock falls and soil slides on the right side of the Gaighat Khola

The Simaltal Thrust Fault (STF) runs across the landslide, and this is the preparatory factor of the instabilities. As in the other parts of the area, geological and engineering geological conditions are the main causes of the landslides and the monsoon rain and stream undercutting act as the trigger. As the landslide is expanding each year, some houses and cultivated lands are under high risk of damage and destruction. Despite some counter measures, the area is prone to landslide and highly hazardous for debris flow in monsoon. Sample were collected upper part of failure zone.

The Siwalik Zone

Das Khola Valley

The headwaters of the Das Khola lie in the Mahabharat Range in the Lesser Himalaya, where Dhading Dolomite makes high hills and steep slopes in the upper reaches and the quartzite and slates of the Nourpul Formation, which rests over the MBT, expose at the base of the mountains. South of the MBT is the Siwalik zone, which in the area consists of sandstone and conglomerate beds of various thickness with thick colluvial cover on the surface (Figure 22). The MBT is marked by a wide zone with intense jointing, fracturing, and breciation of rocks (dolomite, quartzite and slates) and presence of shearing features and fault gauges (Figure 23). Facilitated by all these features together with steep stream gradient, active erosions have undergone on the stream beds and it has made deep trench in the MBT zone and north of it. All these features have made the upper reaches of the Das Khola vulnerable to rock falls and rock slides as shown in some of the photographs.

Figure 22: Thick terrace deposit in the head part of Das Khola

Figure 23: Fault gauge in Das Khola

Within the MBT zone and north of it, there are thick Quarternary sediments consisting of both hill slopes derived and stream deposits and pockets of historical debris flow deposit with, sometimes, domination of coarse fraction like boulders and blocks of dolomite at places. As in the Siwaliks, these materials on the surface are covered by younger colluvial deposits. The weathered sandstones and the overlying colluvium have created a number of landslides in the Siwaliks and the removal of forest covers has further aggravated the instabilities in some places.

Figure 24: Discontinuity in rock in Das Khola

Figure 25: Gorge in upper reaches of Das Khola (MBT zone)

During summer monsoon, saturation of the soils creates some instabilities and the flooded stream easily undercuts the loose soils on the sides and generates more landslide. Some of the landslides are vertical soil falls capable of displacing disproportionately huge amount of sediments. The growing sediment loads to the stream (Das Khola) by all these processes could generate huge debris flow like that occurred in 2006 monsoon time and easily wash away the settlement on the terraces and the highway bridge over the Das Khola. Field observations suggest that jointing, fracturing and shearing of the bed rocks, and availability of the thick soils have pre-disposed the Das Khola Valley slopes to incipient instabilities; thrusting, faulting (Figure 24), tectonic uplift, stream erosion (Figure 25) and deforestation are the preparatory factors; monsoon rains (both concentrated and sustained) and slope undercutting are the trigger; and monsoon rains and the material availability are the sustaining factors of the landslides. The upper part of the Das Khola is therefore prone to landslides and the lower part is vulnerable to catastrophic debris flow events. The samples BS 11 and BS 12 were sampled from this location.

Khahare Khola Valley

The Khahare Khola valley lies in the Mahabharat Range of the Lesser Himalaya. Dhading Dolomite makes high hills and steep slopes in the upper reaches and the quartzite and slates of the Nourpul Formation. South of the MBT is the Siwalik zone, which in the area consists of sandstone and conglomerate beds of various thicknesses with thick colluvial cover on the surface as shown in the Figure 26. Therefore MBT zone is not observed clearly in the Khahara Khola area. Within the MBT zone and north of it, there are thick Quarternary sediments consisting of both hill slopes derived and stream deposits, debris flow deposit with, sometimes, domination of coarse fraction like boulders and blocks of dolomite at places. As in the Siwaliks, these materials on the surface are covered by younger colluvial deposits.

Figure 26: Thick terrace deposits in Khahare Khola Range as seen north

The weathered sandstones and the overlying colluvium have created a number of landslides in the Siwaliks and the removal of forest covers has further aggravated the instabilities in some places. During summer monsoon, saturation of the soils creates some instabilities and the flooded stream easily undercuts the loose soils on the sides and generates more landslide. Field observations suggest that jointing, fracturing and shearing of the bed rocks, and availability of the thick soils have pre-disposed the Khahare Khola Valley slopes to incipient instabilities; thrusting, faulting, tectonic uplift, stream erosion and deforestation are the preparatory factors; monsoon rains (both concentrated and sustained) and slope undercutting are the trigger; and monsoon rains and the material availability are the sustaining factors of the landslides. The upper part of the Khahare Khola is therefore prone to landslides and the lower part is vulnerable to catastrophic debris flow events.

CHAPTER - 4

CLAY MINERALS & ITS ROLE IN LANDSLIDE OCCURRENCE

Clay Minerals

The clay minerals are a part of a general but important group within the phyllosilicates that contain large percentages of water trapped between the silicate sheets. Most clays are chemically and structurally analogous to other phyllosilicates but contain varying amounts of water and allow more substitution of their cations. There are many important uses and considerations of clay minerals. They are used in manufacturing, drilling, construction and paper production. They have great importance to crop production as clays are a significant component of soils. It is the physical characteristics of clays that more so than the chemical and structural characteristics define this group.

Clay minerals tend to form microscopic to sub microscopic crystals. They can absorb water or lose water from simple humidity changes. When mixed with limited amounts of water, clays become plastic and are able to be molded and formed in ways that most people are familiar with as children's clay. When water is absorbed, clays will often expand as the water fills the spaces between the stacked silicate layers. Due to the absorption of water, the specific gravity of clays is highly variable and is lowered with increased water content. The hardness of clays is difficult to determine due to the microscopic nature of the crystals, but actual hardness is usually between 2-3 and many clays give a hardness of 1 in field tests. Clays tend to form from weathering and secondary sedimentary processes with only a few examples of clays forming in primary igneous or metamorphic environments. Clays are rarely found separately and are usually mixed not only with other clays but with microscopic crystals of carbonates, feldspars, micas and quartz. Clay minerals are divided into four major groups. These are the important clay mineral groups:

The Kaolinite Group

This group has three members (kaolinite, dickite and nacrite) and a formula of Al2Si2O5(OH)4. The different minerals are polymorphs, meaning that they have the same chemistry but different structures (polymorph = many forms). The general structure of the kaolinite group is composed of silicate sheets (Si_2O_5) bonded to aluminum oxide/hydroxide layers ($Al_2(OH)_4$) called gibbsite layers. The silicate and gibbsite layers are tightly bonded together with only weak bonding existing between the s-g paired layers.

The Montmorillonite/Smectite Group

This group is composed of several minerals including pyrophyllite, talc, vermiculite, sauconite, saponite, nontronite and montmorillonite they differ mostly in chemical content. The general formula is $(Ca, Na, H) (Al, Mg, Fe, Zn)_2(Si, Al)_4O_{10}(OH)_2$ - xH_2O, where x represents the variable amount of water that members of this group could contain. Talc's formula, for example, is $Mg_3Si_4O_{10} (OH)_2$. The gibbsite layers of the kaolinite group can be replaced in this group by a similar layer that is analogous to the oxide brucite, ($Mg_2 (OH)_4$). The structure of this group is composed of silicate layers sandwiching a gibbsite (or brucite) layer in between, in an s-g-s stacking sequence. The variable amounts of water molecules would lie between the s-g-s sandwiches.

The Illite (or The Clay-mica) Group

This group is basically a hydrated microscopic muscovite. The mineral illite is the only common mineral represented, however it is a significant rock forming mineral being a main component of shales and other argillaceous rocks. The general formula is $(K, H) Al_2 (Si, Al)_4O_{10} (OH)_2$ - xH_2O, where x represents the variable amount of water that this group could contain. The structure of this group is similar to the montmorillonite group with silicate layers sandwiching a gibbsite-like layer in between, in an s-g-s stacking sequence. The variable amounts of water molecules would lie between the s-g-s sandwiches as well as the potassium ions.

The Chlorite Group

This group is not always considered a part of the clays and is sometimes left alone as a separate group within the phyllosilicates. It is a relatively large and common group although its members are not well known. These are some of the recognized members: Amesite $(Mg, Fe)_4Al_4Si_2O_{10} (OH)_8$

- Baileychlore (Zn, Fe+2, Al, Mg)6(Al, Si)4O10(O, OH)8
- Chamosite (Fe, Mg)3Fe3AlSi3O10(OH)8
- Clinochlore (kaemmererite) (Fe, Mg)3Fe3AlSi3O10(OH)8
- Cookeite LiAl5Si3O10(OH)8
- Corundophilite (Mg, Fe, Al)6(Al, Si)4O10(OH)8
- Daphnite (Fe, Mg)3(Fe, Al)3(Al, Si)4O10(OH)8
- Delessite (Mg, Fe+2, Fe+3, Al)6(Al, Si)4O10(O, OH)8
- Gonyerite (Mn, Mg)5(Fe+3)2Si3O10(OH)8
- Nimite (Ni, Mg, Fe, Al)6AlSi3O10(OH)8
- Odinite (Al, Fe+2, Fe+3, Mg)5(Al, Si)4O10(O, OH)8
- Orthochamosite (Fe+2, Mg, Fe+3)5Al2Si3O10(O, OH)8
- Penninite (Mg, Fe, Al)6(Al, Si)4O10(OH)8
- Pannantite (Mn, Al)6(Al, Si)4O10(OH)8
- Rhipidolite (prochlore) (Mg, Fe, Al)6(Al, Si)4O10(OH)8
- Sudoite (Mg, Fe, Al)4 - 5(Al, Si)4O10(OH)8
- Thuringite (Fe+2, Fe+3, Mg)6(Al, Si)4O10(O, OH)8

The term chlorite is used to denote any member of this group when differentiation between the different members is not possible. The general formula is X4-6Y4O10 (OH, O) 8. The X represents aluminum, iron, lithium, magnesium, manganese, nickel, zinc or rarely chromium. The Y represents aluminum, silicon, boron or iron but mostly aluminum and silicon.

The gibbsite layers of the other clay groups are replaced in the chlorites by a similar layer that is analogous to the oxide brucite. The structure of this group is composed of silicate layers sandwiching a brucite or brucite-like layer in between, in an s-b-s stacking sequence similar to the above groups. However, in the chlorites, there is an extra weakly bonded brucite layer in between the s-b-s sandwiches. This gives the structure an s-b-s b s-b-s b sequence. The variable amounts of water molecules would lie between the s-b-s sandwiches and the brucite layers.

Some minerals listed above (specifically chlorite, pyrophyllite and talc) as belonging to one of the clay groups are often excluded by some minerologists. Usually the reason is that their crystal size and character due not consistently conform to those parameters that define a clay. Such minerals are listed here more for their structural similarities, however all three minerals are quite often found associated with and do behave like clays occasionally.

Role of Clay Minerals in Landslide Occurrence

The shear strength and the swelling properties of different clay minerals differ variably and have a great significance with the occurrence of landslides. The results of studies related to clay and landslide show that the illite and montmorillonite clay minerals have lower shear strength and higher swelling potentials and are more prone to landslide problem than those composed of kaolinite and chlorite clay minerals (Ohlmacher 2000).

Analysis of Clay Minerals

Working formula

$$n\lambda = 2d \sin \theta$$

Where, n= a whole number (1.00), λ = the X-ray wavelength (1.5406A), d= the distance between planes of atoms (A), and θ =the angle between a ray and an atomic plane.

Table: 3 Data for identification of clay minerals in an oriented mount using X-ray diffraction (adopted from Carroll, 1970)

Clay mineral	Untreated	Ethylene glycol	Heated to 550°C
illite	generally broad (001) reflection at approximately 8.8° 2θ (10 Å) with integral series of basal reflections including 17.7° 2θ (5 Å) and 26.75° 2θ (3.3 Å)	no change	(001) may be more intense
montmorillonite	(001) reflection variable from 6.80 to 5.89° 2θ (13–15 Å); higher-order basal reflections irrational	(001) increases to approximately 5.2° 2θ (17 Å) with integral series of basal reflections including 10.4° 2θ (8.5 Å) and 15.5° 2θ (5.7 Å)	(001) collapses to between 9.83 and 8.84° 2θ (between 9 and 10 Å) with corresponding integral series of higher-order basal reflections
chlorite	(001) reflection at approximately 6.3° 2θ (14+ Å) with an integral series of basal reflections including 12.62° 2θ (7 Å), 18.92° 2θ (4.7 Å), and 25.45° 2θ (3.5 Å).	no change	(001) reflection intensified; higher-order basal reflections disappear
kaolinite	(001) reflection at 12.38° 2θ (7.15 Å) and (002) reflection at 24.94° 2θ (3.57 Å); higher-order reflections generally too weak for recognition in samples composed of several clay minerals; disordered (poorly crystallized) kaolinite shows broader and less intense basal reflections	no change	Structure collapses to an X-ray amorphous mineral metakaolin (peaks disappear)

The above data were analyzed on the basis of the Table 3 given by Caroll, (1970) for the identification of minerals, used only by the untreated method.

CHAPTER - 5

RESULTS AND DISCUSSIONS

The Lesser Himalayan Area

Virkuna Gaira area

The landslides of Virkuna Gaira area are described in Chapter 3. The X-Ray diffractogram of the soil sample taken from Virkuna Gaira (BS 17) contains Illite peak at 2theta = 8.8, Chlorite at 2theta = 12.6 and again Illite at 2theta = 17.7.

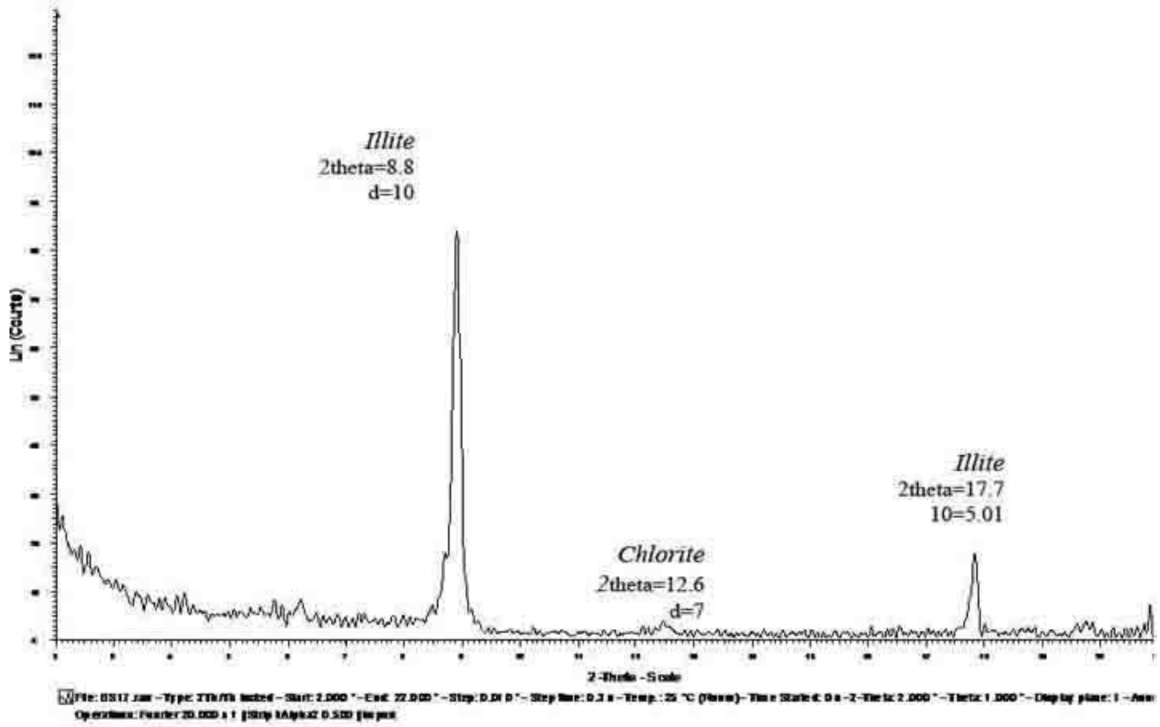


Figure 27: X-ray diffractogram of sample from Virkuna Gaira Landslide (Sample No. BS 17)

Landslides in the area are active and are interpreted partly due to the presence of Virkuna Gaira Thrust Fault (Figure 12), weathering condition of rocks, and climatic factors. X-Ray analysis suggests that the soils in the area contains abundant Illite (Figure 27), and is interpreted as the additional factor in making the landslide in this area active during rainy season as Illite has high swelling capacity.

Kamere Khola (Ch: 24+740)

The X-ray analysis of the soil sample taken from the Kamere Khola landslide (Figure 14 and sample location of BS 5) revealed the presence of Chlorite peak at 2theta = 6.3, Illite peak at 2theta = 8.8, Kaolinite peak at 2theta = 12.4 and again Chlorite at 2theta = 18.9.

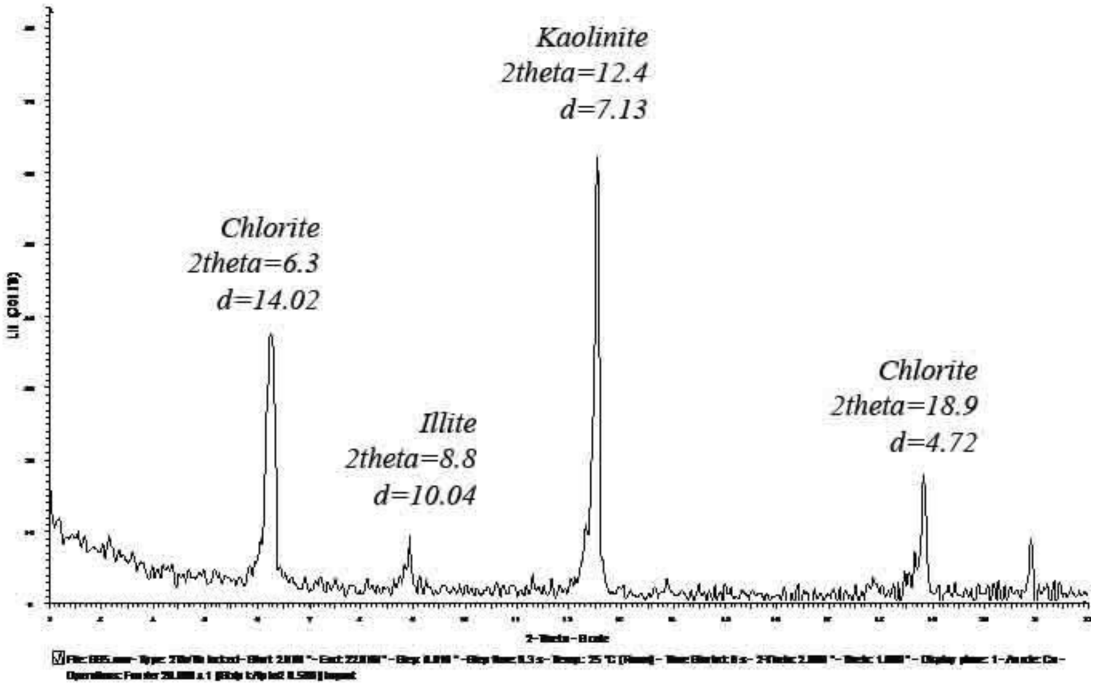


Figure 28: X-ray diffractogram of sample from Kamere Khola Landslide (Sample No. BS 5)

The landslide of this area is stablished in the lower part but active in the upper part. The overall nature of the material produced by the landslide is bouldery with shallow failure (Figure 14), and it has small or no flowing components. The activity of the landslide is largely due to the Simaltal Thrust Fault (STF) passing across the landslide (Figure 11) (Adhikari, 2007). However, the presence of little Illite and Kaolinite (Figure 28) may have played some role for sliding in this area. Compare to this landslide, the Virkuna Gaira landslide is active because it contains much Illite.

Bangesal area (ch: 24+600)

The X-Ray analysis of soil sample (BS 15) of the Bangesal area (Figure 15) shows peak of Chlorite at 2theta = 6.3, Illite at 2theta = 10.07, again Chlorite at 2theta = 12.5 and unidentified minerals in different positions.

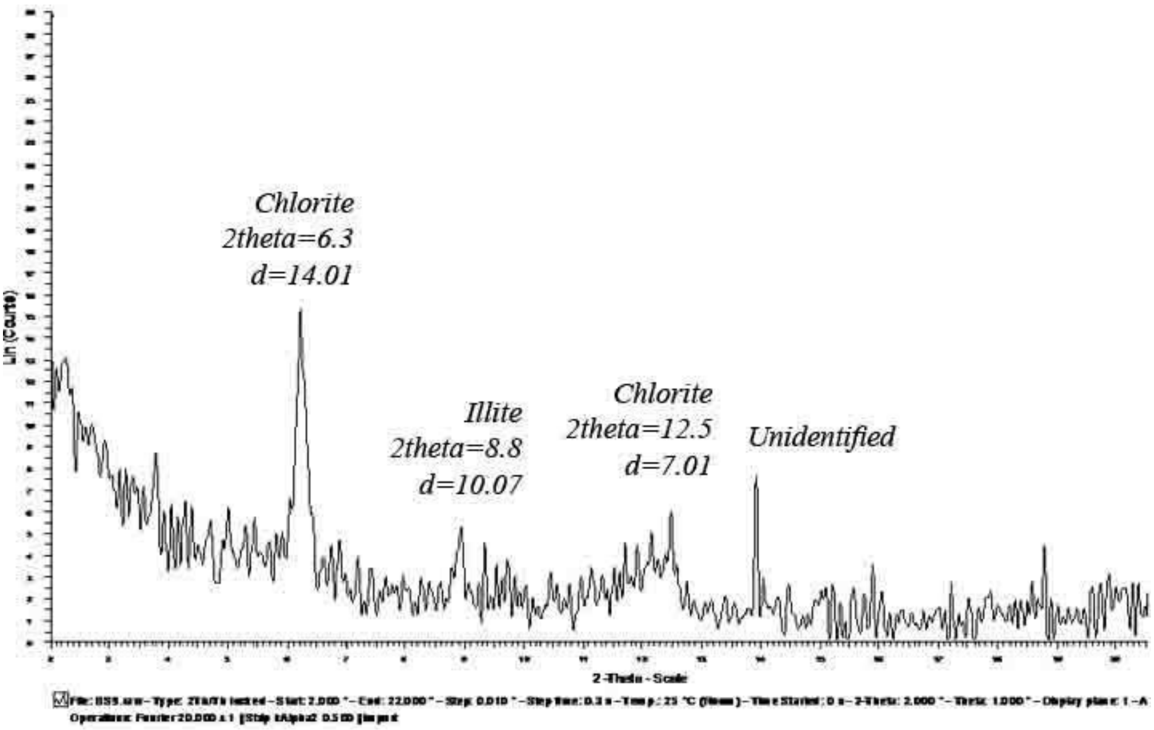


Figure 29: X-ray diffractogram of sample from Bangesal Landslide (Sample Number. BS 9

Landslides are active in this area, because of soils characteristics of collapsed deposits overlie the bedrock and some finer colluvial soils are on the surface. In this landslide also the Simaltal Thrust Fault (STF) runs across (Figure 11), and is considered as the main factor of instabilities. The presence of Illite as illustrated Figure 29 is considered as the factor for sustained sliding in the area. Compare to the Kamere Khola landslide it is not so active.

Dumrebesi Khola (Ch: 24+300)

The result of X-Ray analysis of the soil samples from Dumrebesi Khola BS 15 and BS 16 are shown in Figure 30 and 31. Sample BS 15 from inactive part of the landslide shows Chlorite peak at 2theta = 6.3, Kaolinite peak at 2theta = 12.4 and again Chlorite peak at 2theta = 18.9. In the active landslide in the adjacent part, the graph revealed Illite peak at 2theta = 18.8, chlorite at 2theta = 12.6 and again Illite at 2theta = 17.7.

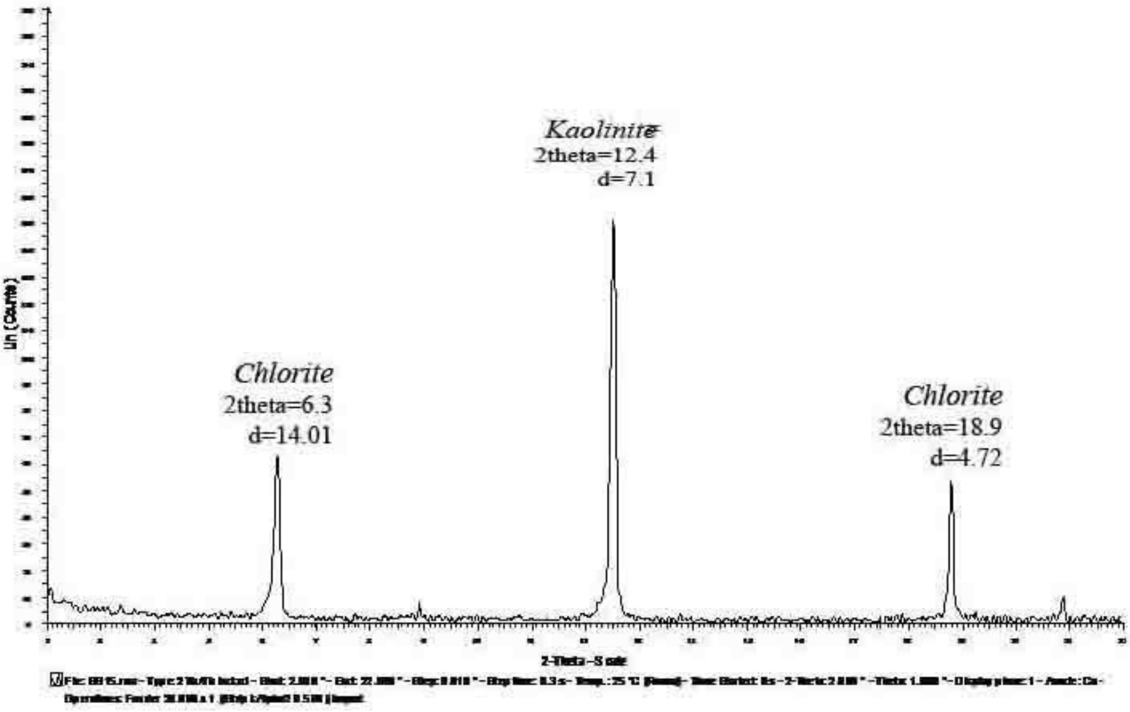


Figure 30: X-ray diffractogram of sample from Dumrebesi Khola Landslide (Sample No. BS 15)

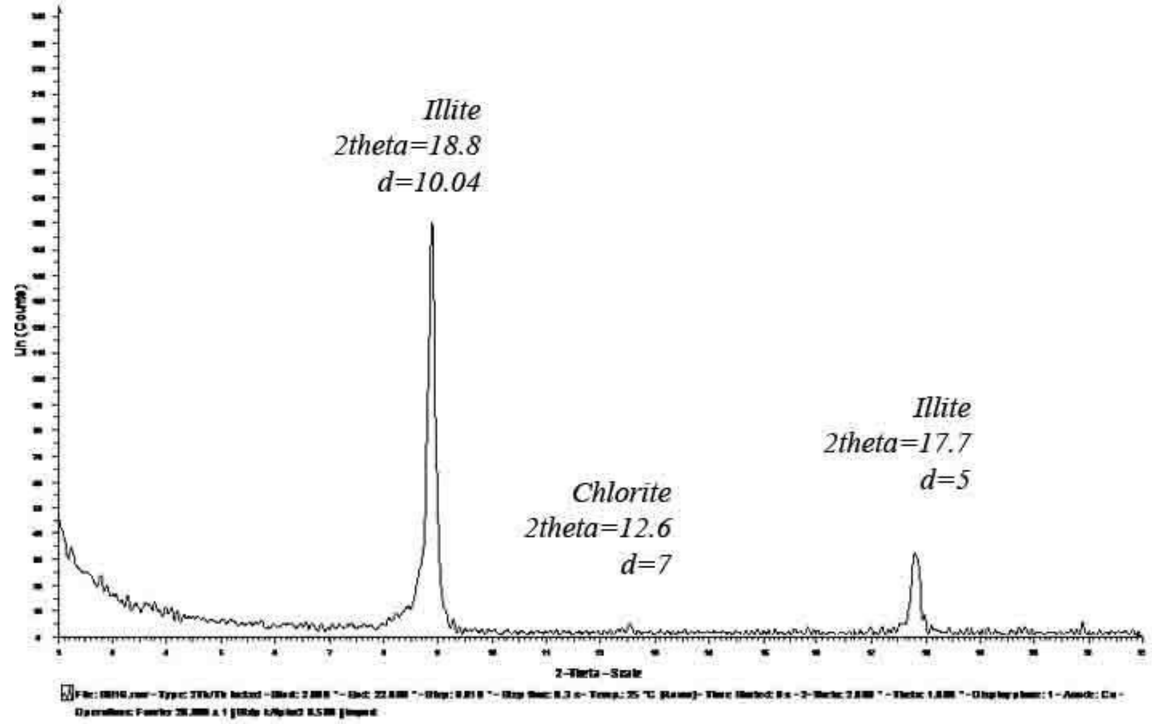


Figure 31: X-ray diffractogram of sample from Dumrebesi Khola Landslide (Sample No. BS 16)

The two samples from Dumrebesi landslide contain different clay minerals. The geology and weathering condition are similar but the X-Ray analysis shows that the active landslide contains Illite (Figure 30), whereas the inactive landslide contains only kaolinite and chlorite as illustrated in Figure 29. As the nature of Illite suggests, it is more susceptible to create landslide than in the area which contains kaolinite and chlorite. The activity of the landslide is therefore interpreted as the influence of Illite.

Sindhure Khola (Ch 23+00)

The sample (BS 1) from Sindhure Khola landslide (Figure 17) shows the following nature of graphs X-Ray Diffractogram with Illite peak at 2theta = 8.8 similarly chlorite peak at 2theta = 12.5 and Illite again at 2theta = 17.8.

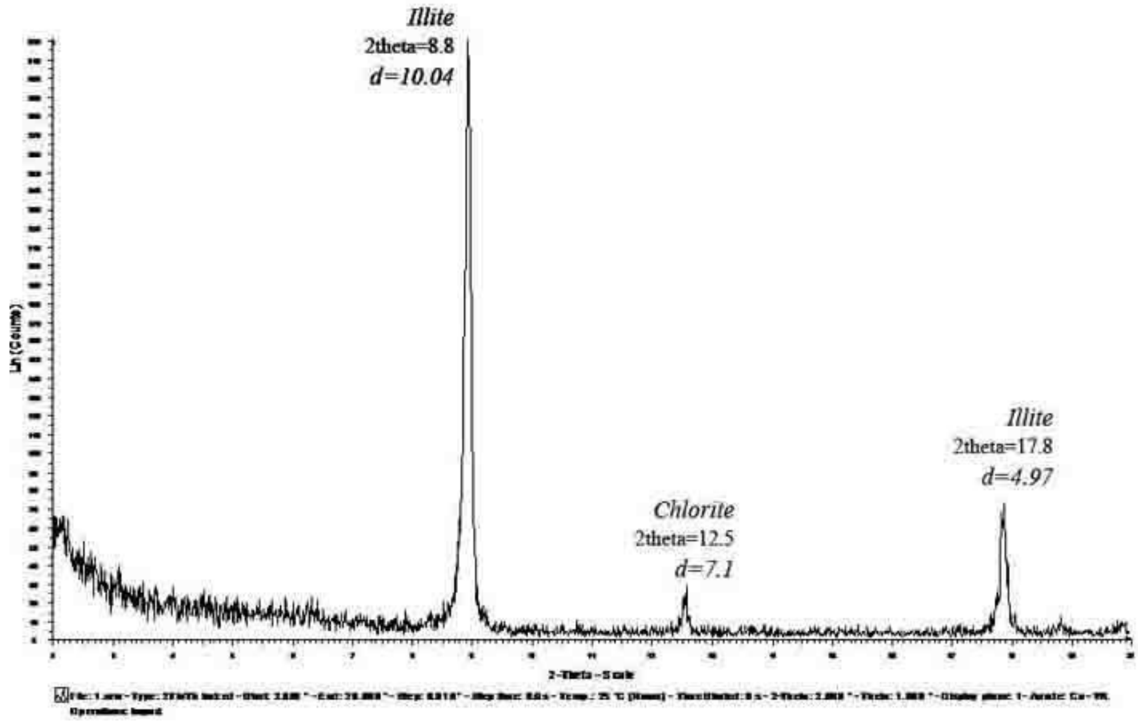


Figure 32: X-ray diffractogram of sample from Sindhure Khola Landslide (Sample No. BS 1)

As mentioned in the earlier chapters, the landslide in the Sindhure Khola is the most active in the area and sometimes occurs even in winter if it is rainy. The Simal Tal Thrust passes across the landslide (Figure 11) and the rock is highly crushed and weathered. In addition to the favorable geological condition for the occurrence of landslide, the presence of abundant Illite in the soil is interpreted as the key factor for the landslide activity. The role of Illite is therefore important in the occurrence of landslide.

Kerabari Khola (Ch: 21+560)

Highly weathered and deformed samples of the Kerabari Khola (Figure 20) shows the following nature of X-Ray graphs as in Figure 33. Two samples were analysed and both of them displayed similar results and only one graph is presented. In the graph the peak value of Chlorite at 2theta = 6.3, Kaolinite at 2theta = 12.4 and again Cholorite at 2theta = 18.9 as illustrated in Figure 32.

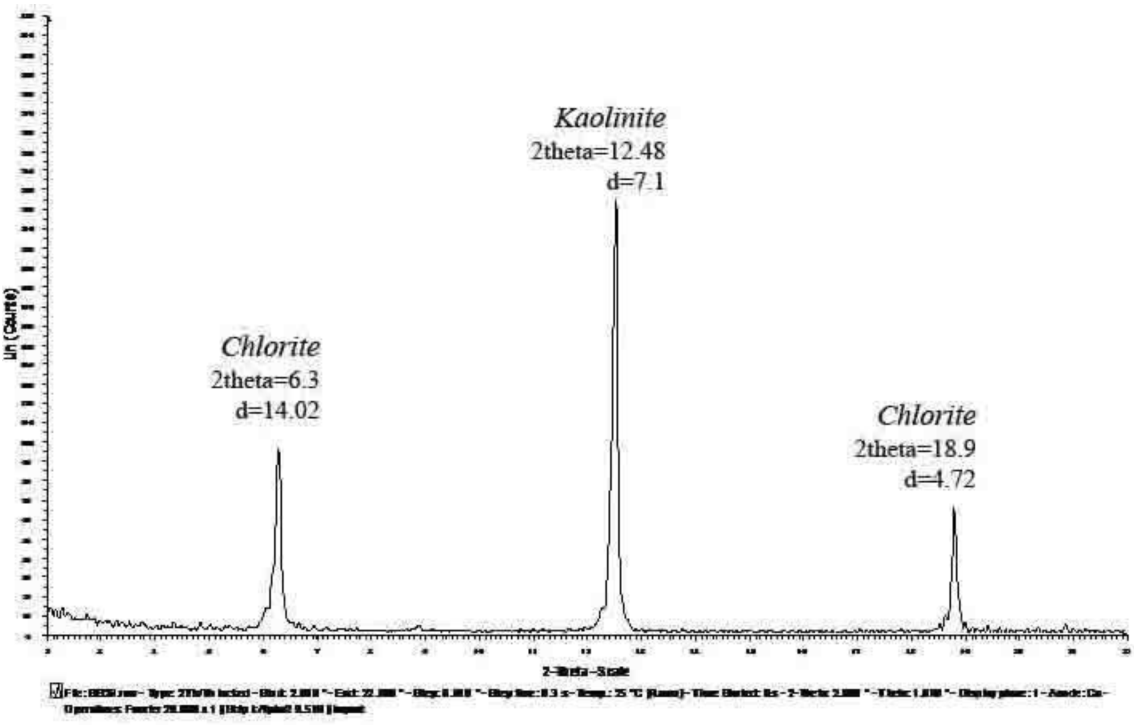


Figure 33: X-ray diffractogram of sample from Kerabari Khola Landslide (Sample No. BS 26)

The landslide in Kerabari Khola is active because of a highly weathered and deformed phyllites and slate in the basal part and heavily jointed amphibolites in the upper part. The slide is active only during monsoon period. Landslides in this area the reason of slaby and jointed rocks, it has 3-4 sets of joint and weak geology i.e. interbaded hard and soft rocks. As the amphibolites is heavily fractures and jointed, the valley walls are prone to rock failure. Generally there are not sufficient role of clay minerals as shown in Figure BS 26 (lack of Illite) and landslide activity is largely due to jointed rock mass.

Gaighat Khola (Ch: 18+450)

The soil sample of the Gaighat Khola in the X-Ray analysis shown the presence of Chlorite peak at 2theta = 6.3, Illite at 2theta = 8.8, Kaolinite at 2theta = 12.4, Illite at 2theta = 17.8 and Chlorite at 2theta = 18.9 (Figure 34). The bed rock is quartzite but it is completely weathered into powder form and the color is ash grey as shown in the photograph (Figure 21).

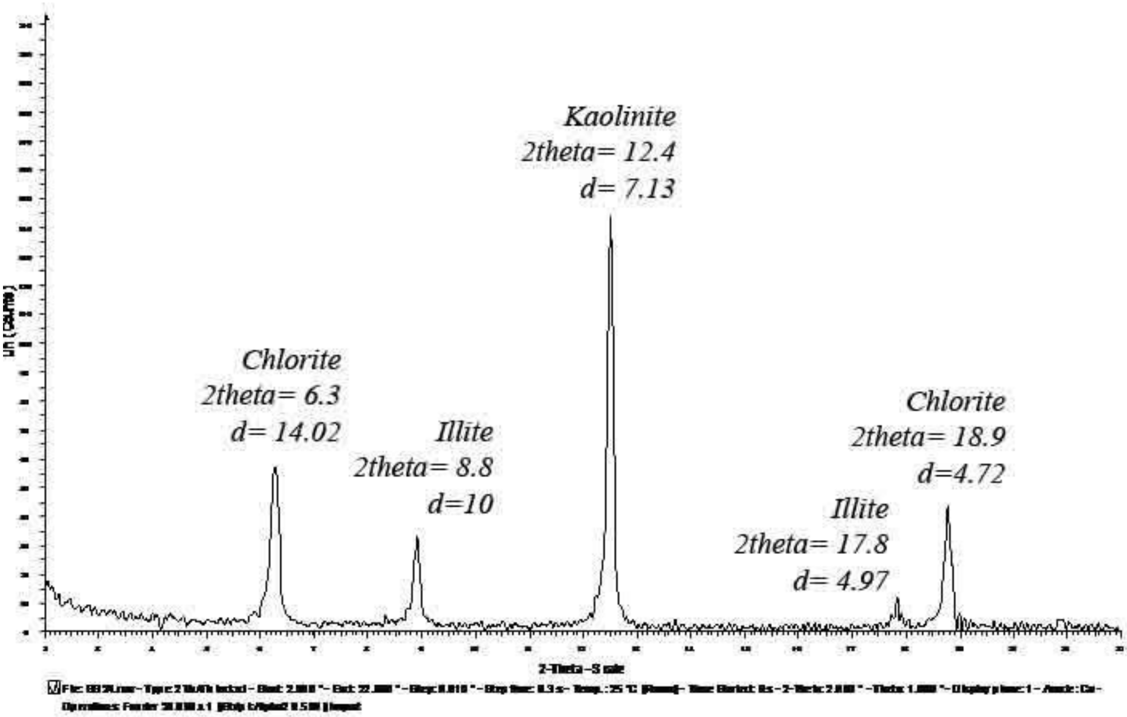


Figure 34: X-ray diffractogram of sample from Gaighat Khola Landslide (Sample No. BS 24)

The Landslide of Gaighat Khola area is one of the most active landslides in the area. The Simaltal Thrust Fault (STF) runs across the landslide (Figure 11), and the rock (Quartzite) is highly jointed and fractured. The landslide is ever expanding and threatening life and property. The formidable activity of the landslide is interpreted as the influence of Illite content in the soil.

The Siwalik Area

Das Khola Valley

The colluvial sample from Das Khola Landslide (Figure 22), in X-Ray analysis is Shawn in Figure 35. The result indicates that there were not any clay minerals in the studied sample. All the peak value is not identified.

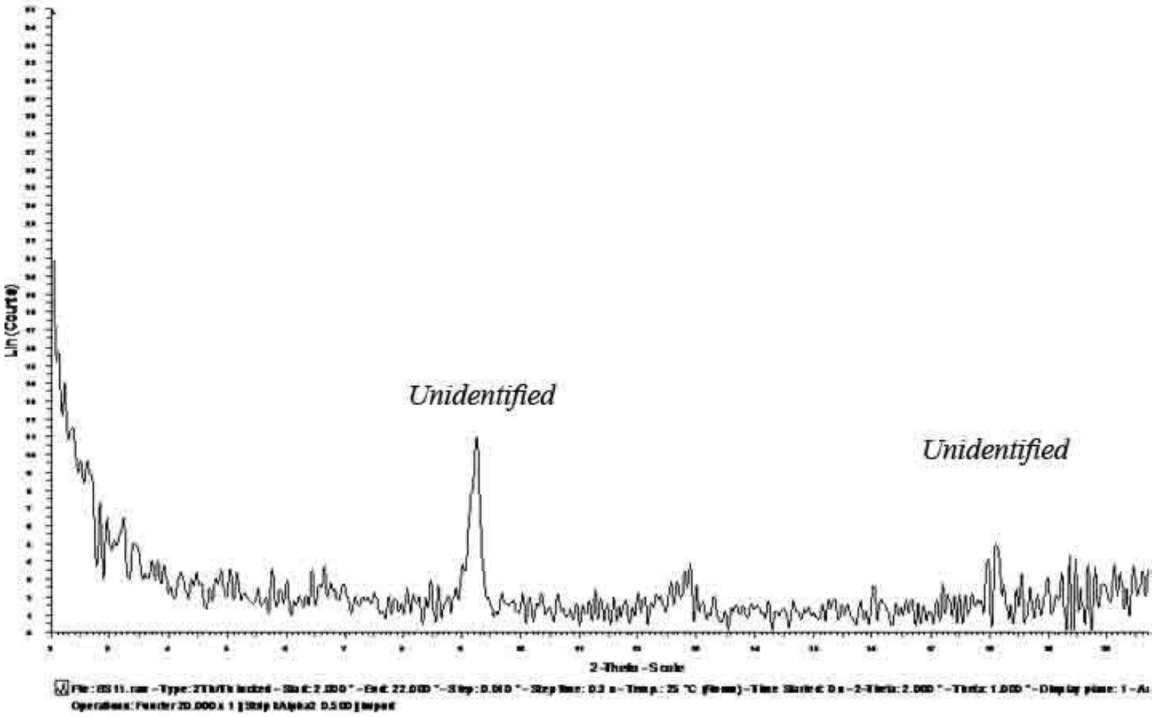


Figure 35: X-ray diffractogram of sample from Das Khola Landslide (Sample No. BS 11)

Das Khola Valley lies in the Mahabharat Range. Within the MBT zone and north of it, there are thick Quarternary loose sediments. Large slides were observed in this area. The major role of occurrence of slide is the presence of the MBT (Figure 11). The above result shows that there is lack of clay minerals in studied sample. Colluvial sample also suggested that there is absence of clay particles.

The X-ray result of the fault gauges BS 12 at Das Khola in the MBT zone (Figure 23) displays the presence of Illite at 2theta = 8.8, Chlorite at 2theta = 12.6 and again Illite at 2theta = 17.7.

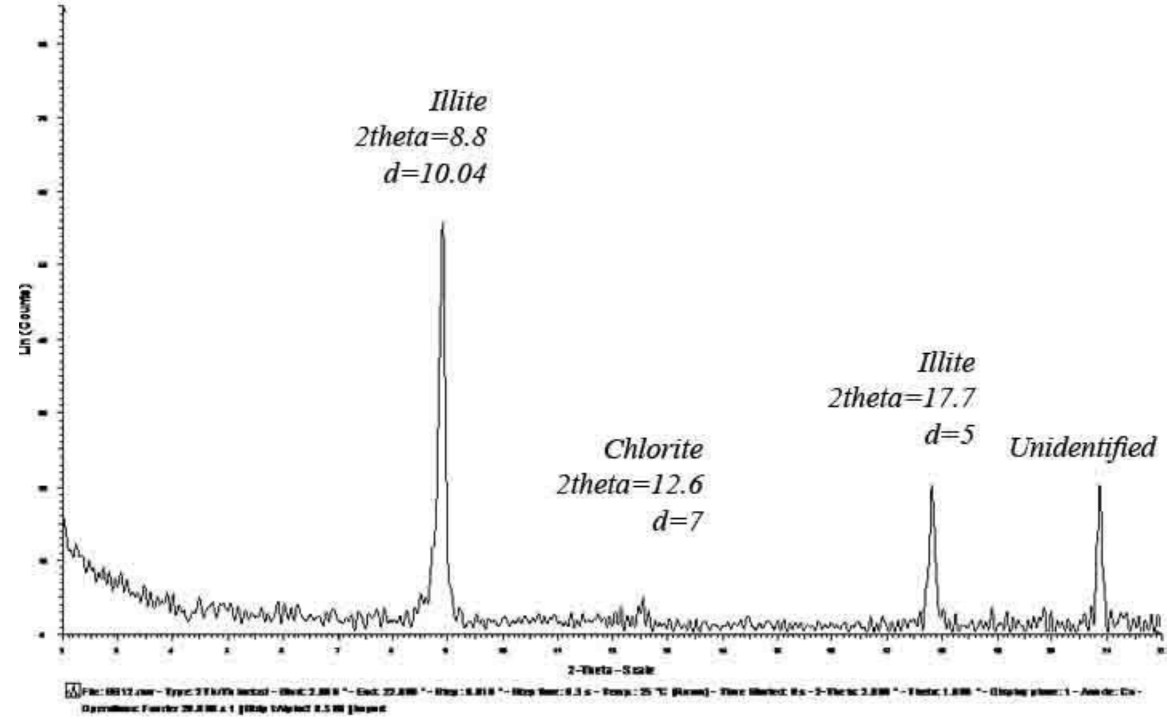


Figure 36: X-ray diffractogram of sample from fault gauge in Das Khola valley (Sample No. BS 12)

The studied sample of fault gauge shows that there is presence of Illite and Chlorite. Though there was no landslide at the sampling site as it was stream bed, the presence of Illite in the sample clearly indicates that fault and thrust zones are not only susceptible to landslide because of tectonic activity but susceptible due to the presence of clay mineral content. This is the first finding that fault gauge contains clay minerals.

Landslide Distribution

All the landslides mentioned above and some other smaller landslides in the study area were mapped and represented as landslide distribution map in Figure 11. The landslide distribution map shows that the landslides are concentrated in the region where the major thrust MBT and some other local thrust faults Simaltal Thrust Fault (STF), Kamalpur Thrust Fault (KTF), and Virkuna Thrust Fault (VTF) pass. The landslide distribution is therefore structurally control, but the activities are influenced by clay mineral content.

Rock and earth falls, topple and debris avalanche are the major classes of landslides occurred in the study area. There are two major tectonic zones observed in the study area, namely, Sub-Himalaya (Siwaliks) and Lesser Himalaya, which is separated by the Main Boundary Thrust (MBT). The Lesser Himalaya is more landslides prone in comparison to the Siwalik area. There are big landslide occurs due to the presence of MBT, and other local thrust fault like: KTF, STF, and VTF. Therefore large slide occur in The MBT zone. In the previous studies of Mugling-Narayanghat are the only reason of landslide is attributed geology and tectonics. There are other factors in the occurrence of landslide in the study area such as: intense monsoon rainstorms, prolonged periods of sustained rainfall, seismic shaking, slope undercutting, and debris flow occurrence.

Medium to Coarse sand and gravel as listed in Annex I, almost present in the study area, and it indicates that the porosity and permeability is high. Therefore different grain size originally fallen into water alternates with different clays like Kaolinite and Illite. The covering soil has high expandable clay mineral content, too. These rocks swell due to saturation with water and slides may occur on their surfaces. The swelling of clay minerals plays an important role in the occurrence of landslide.

Therefore, the above result shows that the presence of Illite is the main cause of occurrence of landslides in Sindhure Khola, Kamere Khola, Bangesal area, Dumre Khola, Virkuna Gaira and Gaighat Khola. Soils containing Illite reduces shear strength and it has higher swelling potentials. These properties make the Illite containing soil more prone to landslide occurrence than those composed of kaolinite and chlorite.

CHAPTER - 6
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The study concludes that the Mugling-Narayanghat Road section is prone to landslide due to its geology, geological structures, geomorphology, climate and human activity and their combination(s). Moreover, the present study also reveals that the landslide activity is largely controlled by the presence of high swelling clay mineral illite along with the low swelling clay minerals chlorite and kaolinite.

The covering soil on landslide porn area has high expandable clay mineral content, too. These rocks swell due to saturation with water and slides may occur on their surfaces. The swelling of clay minerals plays an important role in the damaging changes of the surface. The clay soils within the Nourpul Formation with dominance of Illite play an important role in causing landslides. The X-Ray analysis of sample shows that the samples are composed of illite clay mineral which appears to be the dominant material in the soil environment. As population pressure increases, not only the stability of the slopes will be reduced, but people will also be forced to cultivate even more unstable slopes. As a consequence, the risk of damage by slope failure will increase. In addition, the fact that Virkuna Gaira area is an inherently unstable area turns the search for solutions to the landslide problem into a true challenge. The instability can be partly reduced by tempering the human impact. The excavation or terracing of slopes and the construction of structures concentrating water into vulnerable zones should be avoided. Total reforestation with deep-rooted trees would reduce the landslide risk in the region but is not realistic given the high agricultural activity. Nevertheless, planting tree grows in risk zones could locally enhance stability. These measures can never completely impede the occurrence of landslides and it seems that the search for solutions will only come to results by doing the conscious agricultural activity.

Adverse human activities have also contributed to the creation of landslides, these include excavation works, irregular agricultural activity, embankments, and in particular drainage works. Water is one of the most predominant factors which cause landslides which usually occur during periods of high precipitation. So, in natural slope areas, it is important to construct drainage systems for collecting water so that movement on the slopes can be reduced. Landslides occur frequently in the Mugling-Narayanghat section. This is due to high intensity of rainfall, high inclination that contributes to rapid erosion and weathering of the rock mass causing reduction in the stability of natural slopes. The sliding of the overlying clay soil is associated with the saturation of clay pores and deep subsurface flows that generate pore water pressure in the materials that form the slopes. Loss of life and damage to property will reduce if these mitigation measures are taken at the right time.

Recommendations

- The study only used untreated XRD analysis due to the lack of laboratory facilities in Tribhuvan University. It needs further works like Ethylene glycol test and Heat test for the best results.

- This is the preliminary study on clay mineral analysis and needs further research works for the best findings.

- Several mitigation measures like Drainage Management, use of retaining Structures have been suggested in this study.

- Before the infrastructural development works such highway, tunnel, dam etc necessary to study the geological structure as well as the clay minerals content in the soils.

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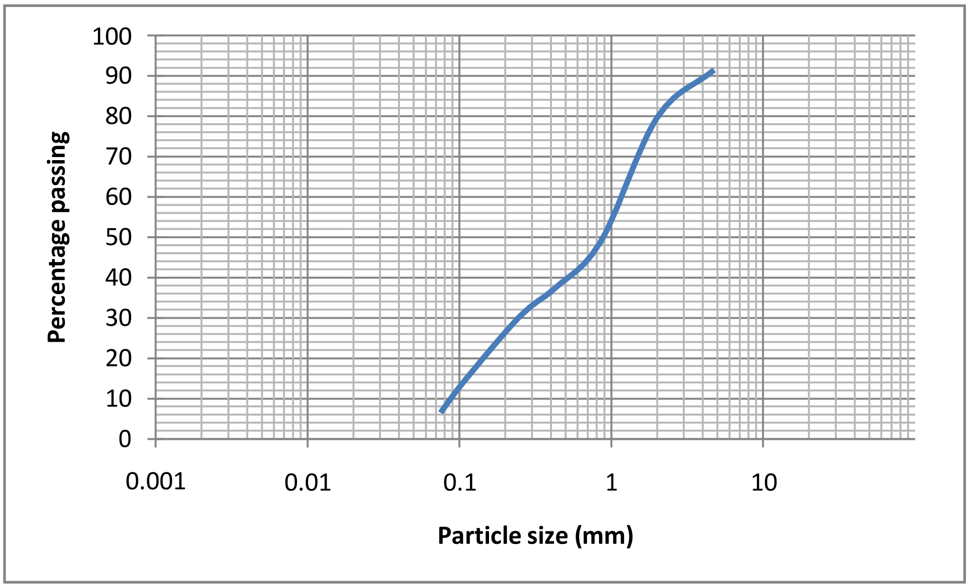
ANNEXES

Particle Size Distribution Curve

Sample No. : BS 1



Maximum size of the smallest 10% of the sample (D_{10}) = 0.09

Maximum size of the smallest 30% of the sample (D_{30}) = 0.25

Maximum size of the smallest 60% of the sample (D_{60}) =1.18

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 13.11

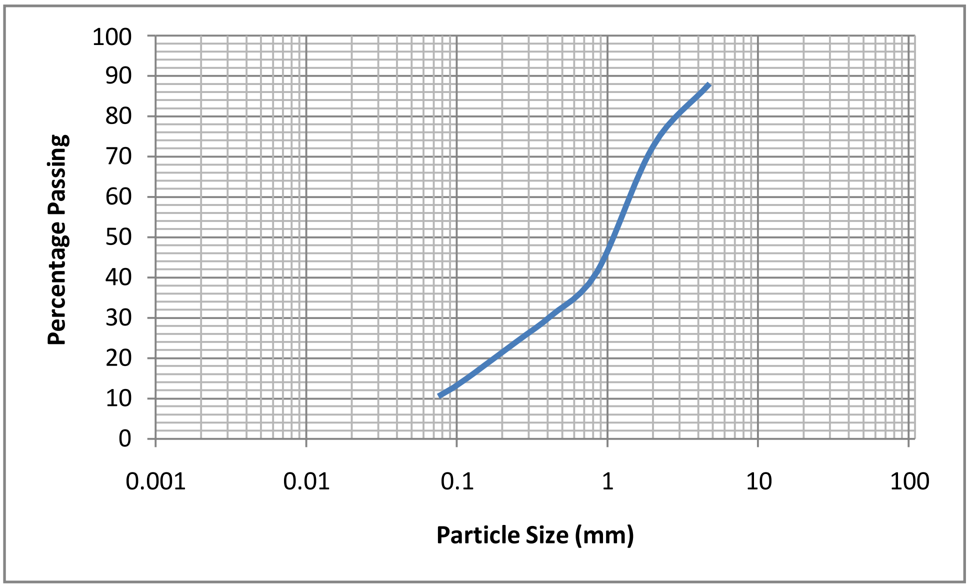
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 0.59

Discussion:

Classification of Soil: **Medium to Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 5



Maximum size of the smallest 10% of the sample (D_{10}) = 0.10

Maximum size of the smallest 30% of the sample (D_{30}) = 0.425

Maximum size of the smallest 60% of the sample (D_{60}) =1.60

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 16

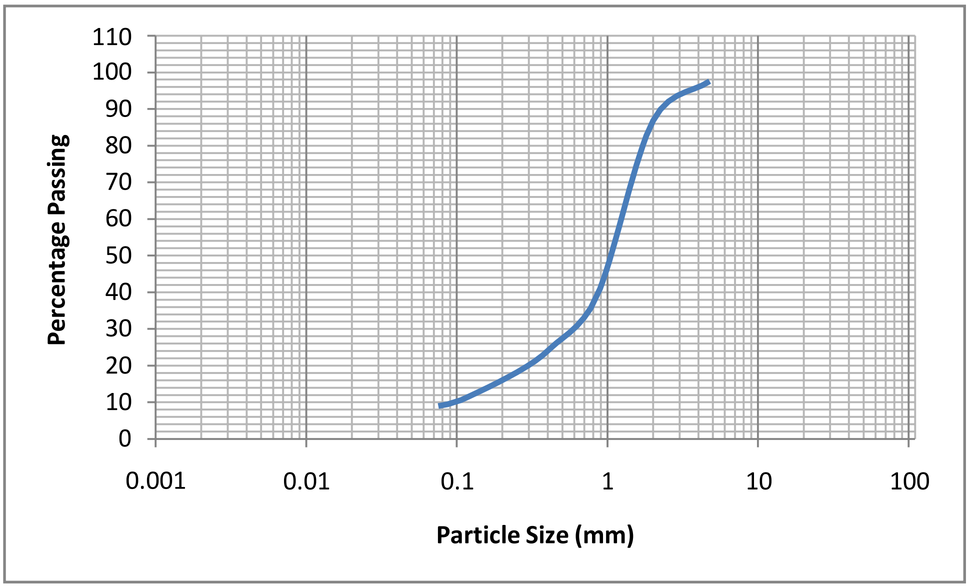
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.13

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 9



Maximum size of the smallest 10% of the sample (D_{10}) = 0.1

Maximum size of the smallest 30% of the sample (D_{30}) = 0.500

Maximum size of the smallest 60% of the sample (D_{60}) =1.30

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 11.8

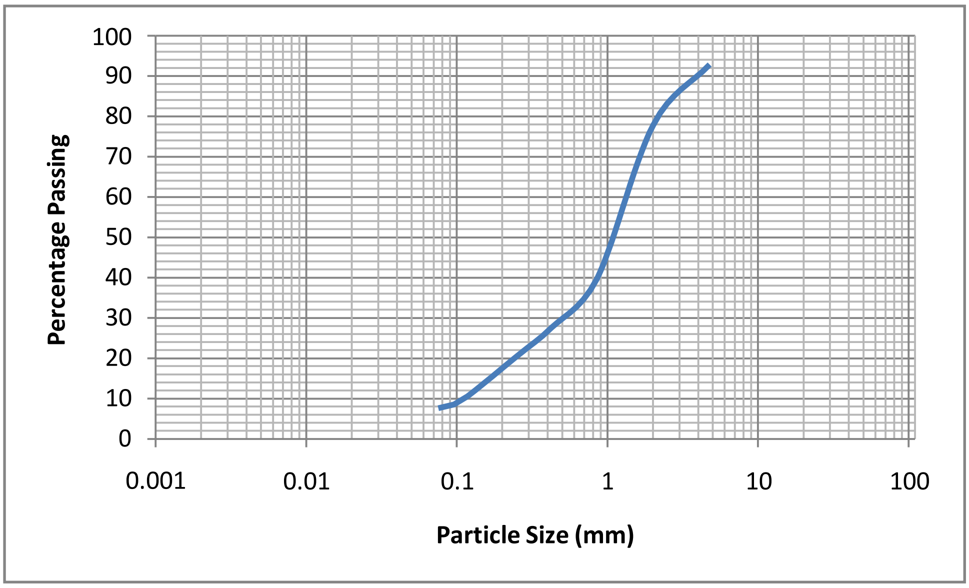
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.92

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 11



Maximum size of the smallest 10% of the sample (D_{10}) = 0.108

Maximum size of the smallest 30% of the sample (D_{30}) = 0.600

Maximum size of the smallest 60% of the sample (D_{60}) =1.30

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 12.04

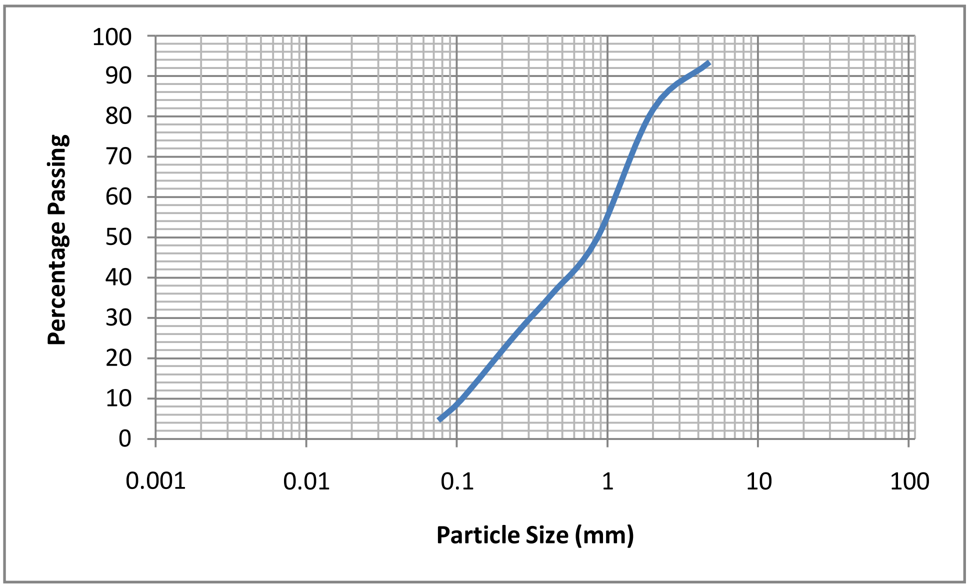
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 2.56

Discussion:

Classification of Soil: **Fine Gravel**

Particle Size Distribution Curve

Sample No. : BS 12



Maximum size of the smallest 10% of the sample (D_{10}) = 0.106

Maximum size of the smallest 30% of the sample (D_{30}) = 0.320

Maximum size of the smallest 60% of the sample (D_{60}) =1.18

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 11.13

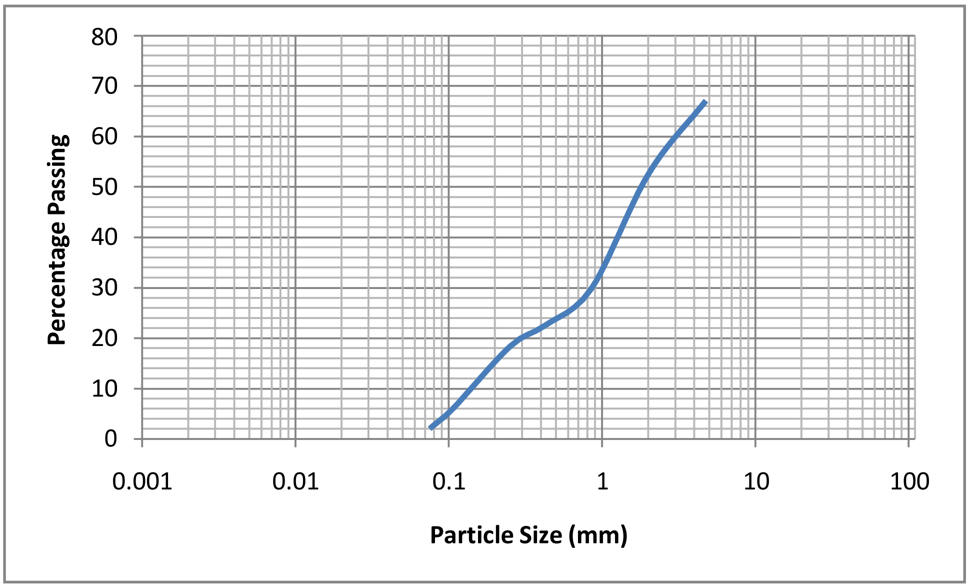
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 0.82

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 15



Maximum size of the smallest 10% of the sample (D_{10}) = 0.105

Maximum size of the smallest 30% of the sample (D_{30}) = 0.850

Maximum size of the smallest 60% of the sample (D_{60}) =3.35

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 22.33

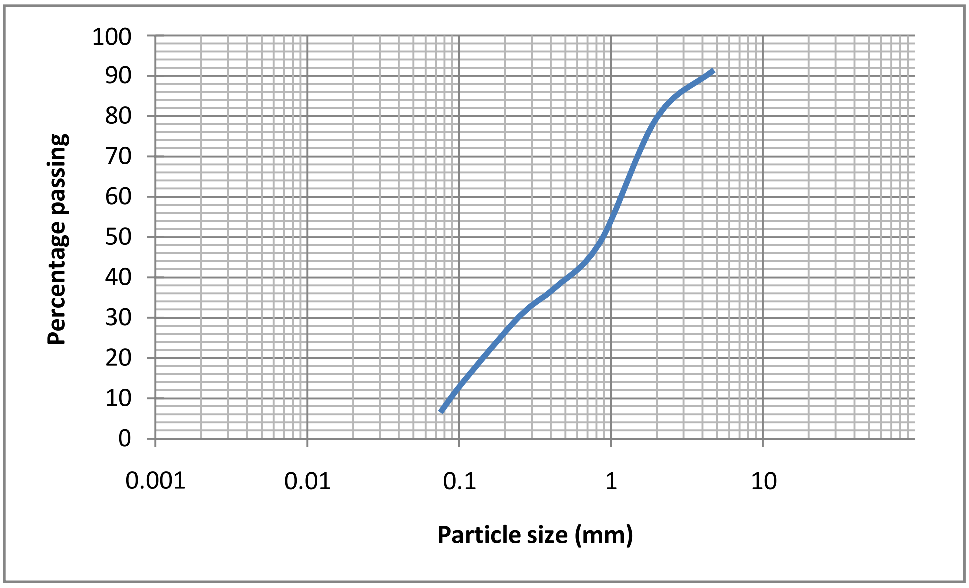
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.44

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 16



Maximum size of the smallest 10% of the sample (D_{10}) = 0.150

Maximum size of the smallest 30% of the sample (D_{30}) = 0.600

Maximum size of the smallest 60% of the sample (D_{60}) =1.70

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 11.33

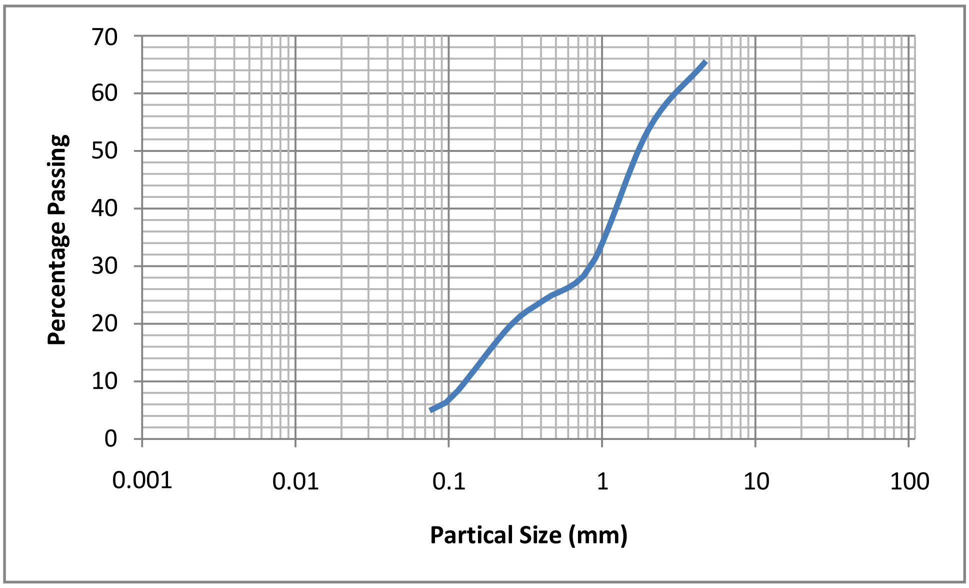
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.41

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 17



Maximum size of the smallest 10% of the sample (D_{10}) = 0.150

Maximum size of the smallest 30% of the sample (D_{30}) = 0.800

Maximum size of the smallest 60% of the sample (D_{60}) =3.35

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 22.33

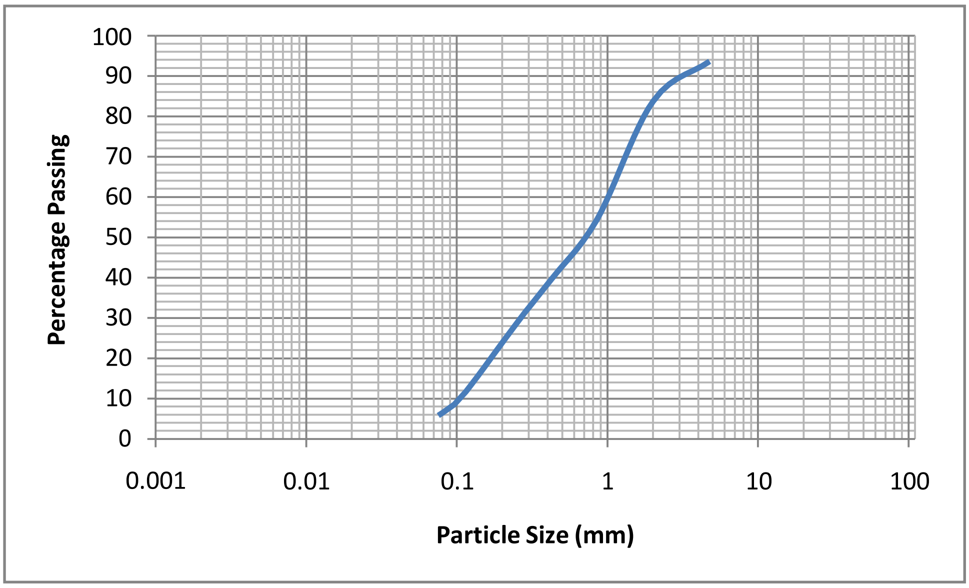
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.27

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 24



Maximum size of the smallest 10% of the sample (D_{10}) = 0.100

Maximum size of the smallest 30% of the sample (D_{30}) = 0.250

Maximum size of the smallest 60% of the sample (D_{60}) =1.18

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 11.8

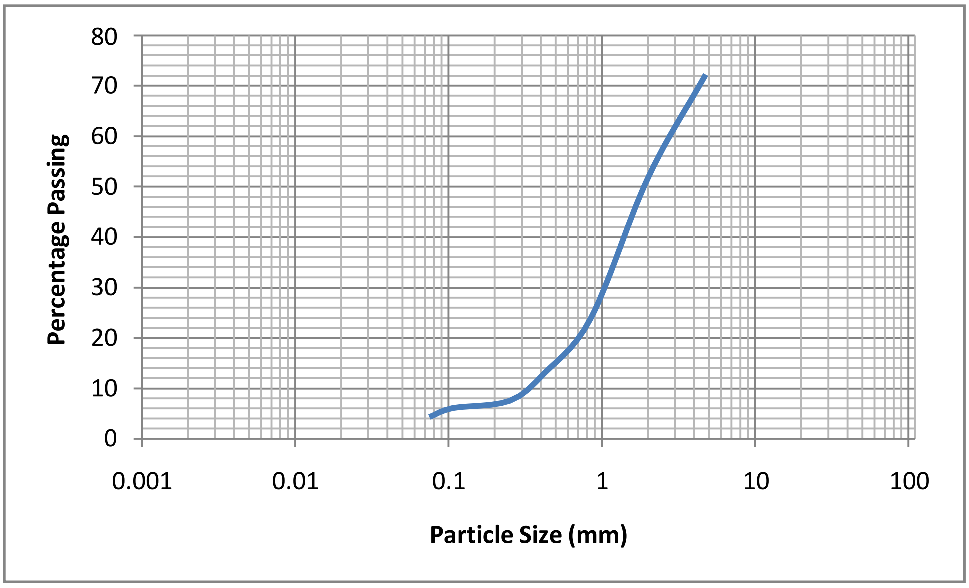
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 0.53

Discussion:

Classification of Soil: **Medium Sand**

Particle Size Distribution Curve

Sample No. : BS 26



Maximum size of the smallest 10% of the sample (D_{10}) = 0.380

Maximum size of the smallest 30% of the sample (D_{30}) = 1.18

Maximum size of the smallest 60% of the sample (D_{60}) =3.35

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 8.82

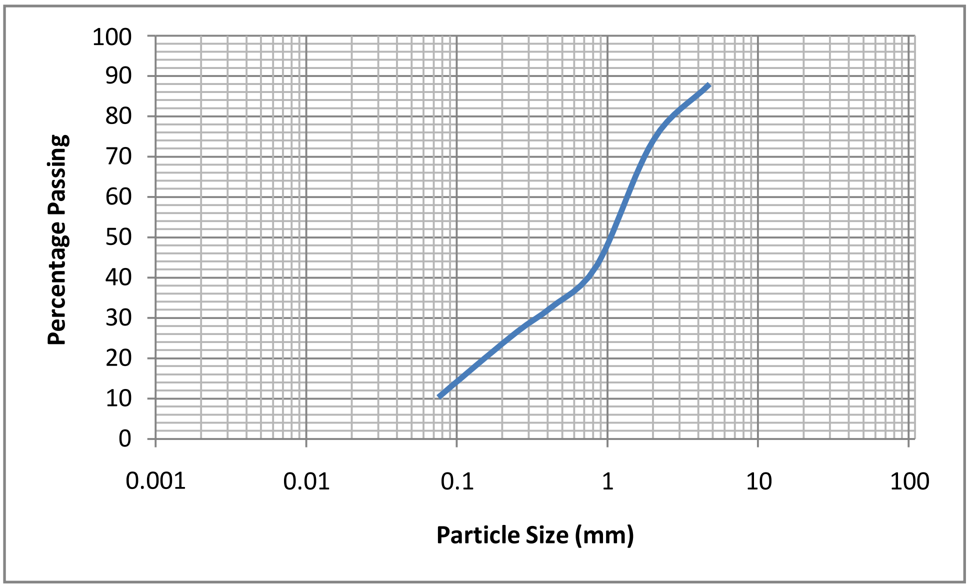
Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 1.09

Discussion:

Classification of Soil: **Coarse Sand**

Particle Size Distribution Curve

Sample No. : BS 27



Maximum size of the smallest 10% of the sample (D_{10}) = 0.07

Maximum size of the smallest 30% of the sample (D_{30}) = 0.35

Maximum size of the smallest 60% of the sample (D_{60}) =1.80

Uniformity coefficient (Cu) = $\frac{D60}{D_{10}}$ = 25.71

Coefficient of Gradation (Cc) = $\frac{(D_{30})^2}{D_{60} \times D_{10}}$ = 0.97

Discussion:

Classification of Soil: **Coarse Sand**