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Typical morphometric and geological characteristics of large-scale landslides in central Nepal

***Manita Timilsina[1], Netra Prakash Bhandary[1], Ranjan Kumar Dahal[1, 2] and Ryuichi Yatabe[1]**

[1]*Department of Civil and Environmental Engineering, Graduate School of Science and Engineering, Ehime University, 3 Bunkyo, Matsuyama 790-8577, Japan*

[2]*Department of Geology, Tri-Chandra Campus, Tribhvuan University, Ghantaghar, Kathmandu, Nepal*

*(*Email: manitatimilsina@gmail.com)*

ABSTRACT

Study of large-scale landslides in Nepal has been largely descriptive and qualitative and limited to site specific cases. This paper describes some preliminary efforts focusing on the understanding of large-scale landslides, their processes and mechanisms that contribute to instability and catastrophic failure in a regional scale. It also reports the use of geographical information system (GIS) database, compiled primarily from aerial photographs and field visits, to describe the physical characteristics of landslides and the statistical correlations between landslide frequency and terrain variables in the Lesser Himalayan Zone of central Nepal. To this end, large-scale landslide database covering a regional area of the Lesser Himalayan Zone is prepared and discussed in terms of their geological and topographical controls with morphometric characteristics.

Keywords: Large-scale landslide, Nepal, Lesser Himalaya, GIS

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INTRODUCTION

In Nepal, landslides occur every year and pose significant hazard to human settlement and infrastructures. On the other hand, landslides help to adjust continuously growing relief and hill-slope created from the tectonic collision between Indian and Eurasian plates maintaining at the threshold level. Therefore, landslides are also regarded as a natural phenomenon of slope modification processes in the Nepal Mountains. According to Shroder and Bishop (1998), Shang et al. (2003), Hasegawa et al. (2009) etc, landslides in Nepal vary from huge whole valley slope creeping to minor slope failures. So, a proper classification system to investigate them individually is very important. Broadly, these landslides can be divided into two categories 1) small-scale landslides (debris flows, debris slides, rock falls, rock slides etc. and 2) large-scale landslides (deep-seated mountain slope creeping). Similarly, landslide related studies are mostly oriented towards the small-scale landslides due to their frequent occurrence and disastrous nature (e.g., Ghimire et al. 2006; Pathak et al. 2007; Petley, et al. 2007; Dahal and Hasegawa 2008; Dahal et al. 2008a; 2008b, 2008c; Poudyal et al. 2010; Regmi et al. 2010; Ghimire 2011; Dahal et al. 2012; Kayastha et al. 2012 etc.) but large-scale landslides have not been well discussed in research.

Large-scale landslides are found in many parts of Nepal but mainly distributed in the Lesser Himalayan Zone. In General, it is a huge slope mass that slide in the past but still persists intact in the topography in active to dormant stages. Such landslides were mainly induced in the geological past (during early upliftment of mountains) and their future occurrences may depend upon future mega-earthquake events but risk of reactivation is always there. The information about large-scale landslides in the scientific literature is very limited. The term "large-scale landslide" originated in Japan symbolizing a huge landslide. However, similar types of landslides in the scientific literatures are termed with different names, for example, large landslides (Dortch et al, 2009), giant landslides (Korup et al. 2007), historical landslides (Van Den Eeckhaut et al. 2007), old deep-seated landslides (Van Den Eeckhaut et al. 2009), deep-seated gravitational slope deformations (DSGSD) (Dramisa and Sorriso-Valvo 1994; Agliardia et al. 2001; Hradecky´ and Pa´nek 2008; Aucelli et al. 2012), etc. Only few studies related to the large-scale landslides have been carried out in Nepal for example Yagi and Nakamura (1995), Yagi (2001), Yatabe et al. (2005), and Hasegawa et al. (2009), which demands further detail study because if left unchecked then they can completely destroy the structure or settlement over time. Therefore, identifying the typical characteristics of large-

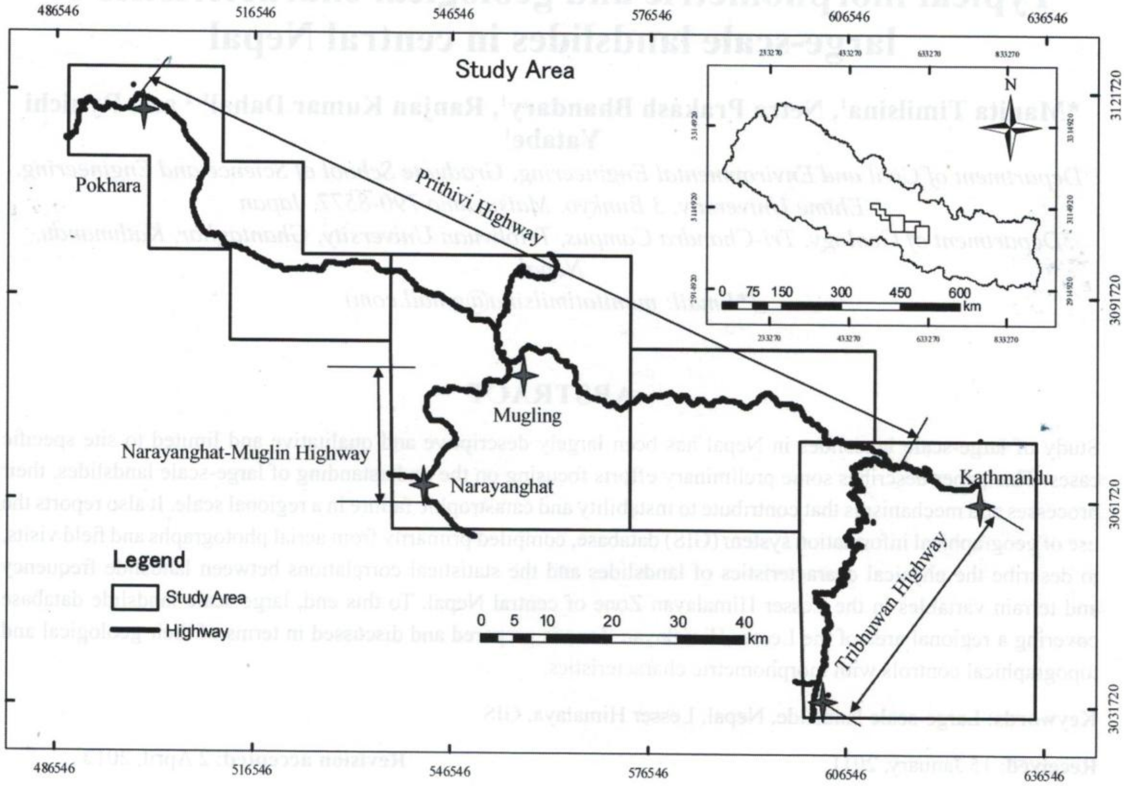

Fig. 1: Location of the study area.

scale landslides is very important.

Thus, the main objective of this study is to determine the typical characteristics of large-scale landslides in the Lesser Himalaya of central Nepal. The typical characteristics mentioned here address the morphometric pattern of large-scale landslides as well as their distribution with topographical and geological parameters. First, a large-scale landslides inventory using aerial photo interpretation and field visits were prepared. Second, the morphometric pattern of the large-scale landslides has been illustrated and finally distribution of large-scale landslides with various topographical and geological parameters has been determined.

STUDY AREA

The study area lies in the Lesser Himalayan Zone of central Nepal (Fig. 1). It covers a total 5,075 km^2 area encompassing the Prithivi Highway, Narayanghat-Mugling Road, Tribhuwan Highway and their peripheral area.

The study area has rocks of the Lesser Himalayan Zone. The Lesser Himalayan Zone comprises of high- to low-grade metamorphic rocks along with a few sedimentary rock sequences and some granitic intrusions (Fig. 2). The area is covered by the rocks of the Nawakot and Kathmandu complexes (Stöcklin, 1980). The Nawakot Complex is mainly composed of the Kuncha Formation, Fagfog Quartzite, Dandagaon Phyllite, Nourpul Formation, Dhading Dolomite, Benighat Slate, Malekhu Limestone and Robang Formation. The Kathmandu Complex consists of Raduwa Formation, Bhainsedobhan Marble, Kalitar Formation, Chisapani Quartzite, Kulikhani Formation, Markhu Formation, Tistung Formation, Sopyang Formation, Chandragiri Limestone, Chitlang Formation and Godawari Limestone. Monotonous, flysh-like alternation of sandy phyllite, phyllitic quartzite and purely argillaceous phyllite are main lithology of the Kuncha Formation and this formation is mainly found around in most of the northern part of study area. The Fagfog Quartzite consists of white, fine- to thick-bedded quartzite. The Dandagaon Phyllite has dark grey quartzitic phyllite and thin bands of quartzite, dolomite and calcareous phyllite. From bottom to top, the Nourpul Formation is made up of some quartzite, laminated phyllite, some dolomite and calcareous phyllite. The Dhading Dolomite consists mainly of grey, medium- to thick-bedded siliceous dolomite. The Benighat Slate is composed of black

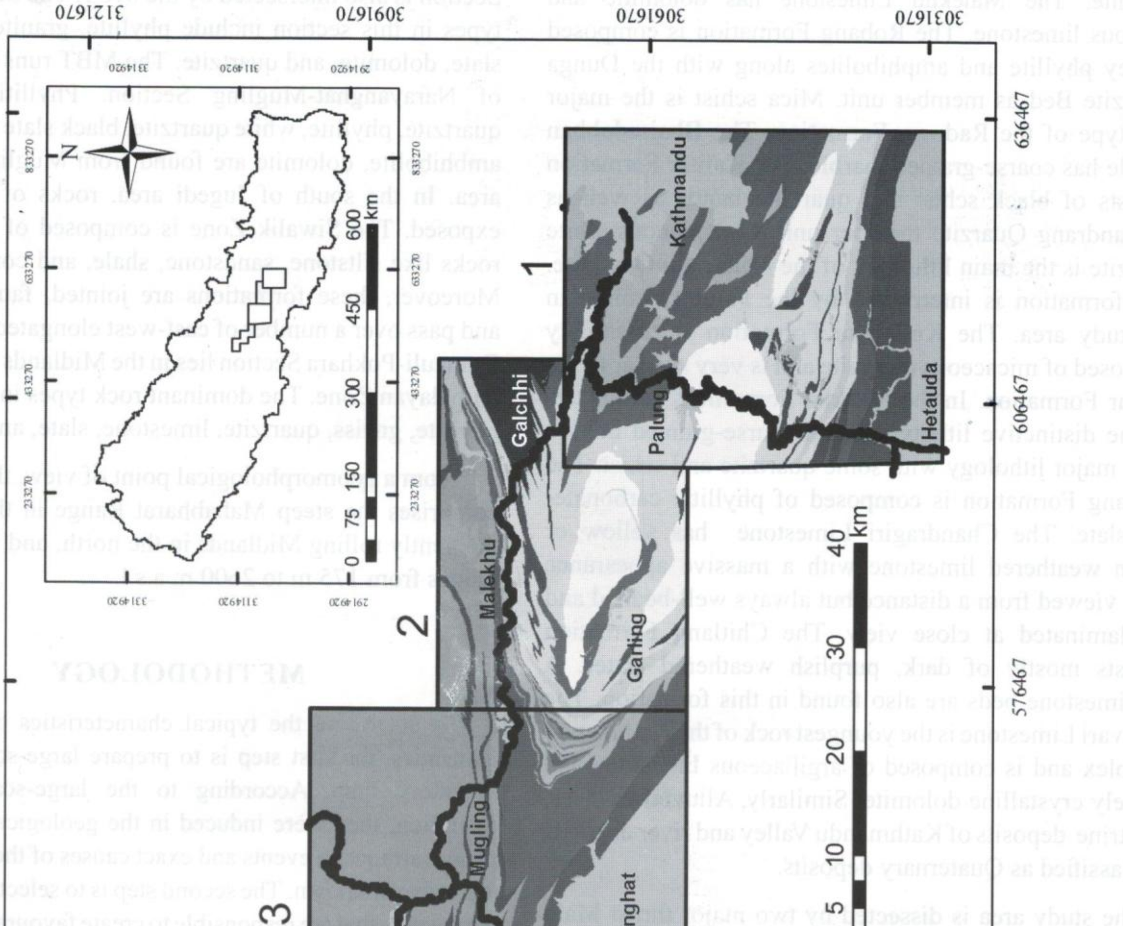

Fig. 2 Rock formation map of the study area.

carbonaceous phyllite and slate with thin bands of silicious dolomite. The Malekhu Limestone has dolomitic and siliceous limestone. The Robang Formation is composed of grey phyllite and amphibolites along with the Dunga Quartzite Bed as member unit. Mica schist is the major rock type of the Raduwa Formation. The Bhaisedobhan Marble has coarse-grained marble. The Kalitar Formation consists of black schist and quartzite bands as well as the Pandrang Quarzite member unit. Conspicuous white quartzite is the main lithology of the Chisapani Quartzite. This formation is interrupted by the Palung Granite in the study area. The Kulikhani Formation is essentially composed of micaceous quartzite and is very similar to the Kalitar Formation. In the Markhu Formation, carbonates are the distinctive lithotypes, and coarse-grained marble is the major lithology with some quartzite and schist. The Sopyang Formation is composed of phyllitic carbonate-rich slate. The Chandragiri Limestone has yellow or brown weathered limestone with a massive appearance when viewed from a distance but always well-bedded and well-laminated at close view. The Chitlang Formation consists mostly of dark, purplish weathered slates. A few limestone beds are also found in this formation. The Godavari Limestone is the youngest rock of the Kathmandu Complex and is composed of argillaceous limestone and coarsely crystalline dolomite. Similarly, Alluvial terraces, lacustrine deposits of Kathmandu Valley and river deposits are classified as Quaternary deposits.

The study area is dissected by two major thrust Main Central Thrust (MCT) and Main Boundary Thrust (MBT). A distinct change in the quality of rock mass can be noticed along the MCT and MBT.

The study area is divided into four sections, namely, 1) Kathmandu-Palung-Hetauda Section, 2) Devighat-Malekhu-Sunaula Bazaar Section, Narayanghat-Mugling Section and Damauli-Pokhara Section for the ease of explanation and data presentation.

GEOLOGY OF THE SELECTED SECTION

The Kathmandu-Hetauda section passes mainly through the Mahabharat Range along with some portion across Siwalik Range. The dominant rock types in this section include metasandstone, siltstones, phyllite, granite, limestone, and quartzite including sandstone, mudstones and conglomerates of Siwalik Group. This highway is intersected by the MBT and MCT separated by a gap of only 4 to 5 km on the north of Hetauda. Such a state of closely passing thrust lines has made the Kathmandu-Hetauda Section comparatively vulnerable to landslides and related slope failure problems. The Galchhi-Malehu-Garling Section is also intersected by the MCT. The dominant rock types in this section include phyllite, granite, limestone, slate, dolomite, and quartzite. The MBT runs on the south of Narayanghat-Mugling Section. Phyllitic quartzite, quartzite, phyllite, white quartzite, black slate and phyllite, ambhibolite, dolomite are found from Mugling to Jugedi area. In the south of Jugedi area, rocks of Siwalik are exposed. The Siwalik Zone is composed of sedimentary rocks like siltstone, sandstone, shale, and conglomerates. Moreover, these formations are jointed, faulted, folded, and pass over a number of east-west elongated local faults. Damauli-Pokhara Section lies in the Midlands of the Lesser Himalayan Zone. The dominant rock types in this area are phyllite, gneiss, quartzite, limestone, slate, and schist.

From a geomorphological point of view, the study area comprises the steep Mahabharat Range in the south and the gently rolling Midlands in the north, and the elevation ranges from 175 m to 2600 m a.s.l.

METHODOLOGY

To determine the typical characteristics of large-scale landslides, the first step is to prepare large-scale landslide inventory map. According to the large-scale landslide definition, they were induced in the geological past due to mega earthquake events and exact causes of these landslides were also unknown. The second step is to select predisposing parameters that are responsible to create favourable condition for the sliding. It is considered and evidenced by many

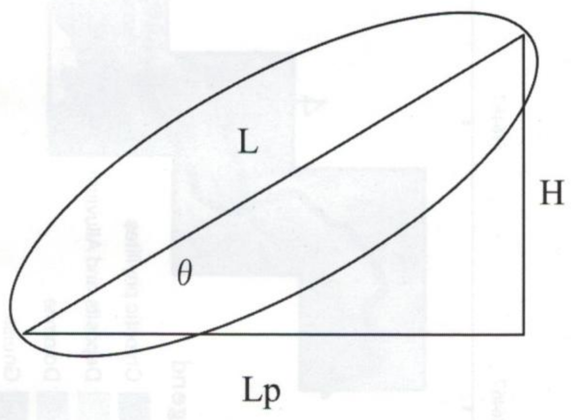

Fig. 3: Interpretation of landslide average slope.

investigations that the primary inducing factors of landslides in Nepal are combination of tectonic activities, climatic factors and geological and geomorphological features.

For the identification of the large-scale landslide, interpretation of aerial photographs is the most suitable approach. Stereoscopic aerial photograph interpretation was used in this study to identify the large-scale landslide. The identified landslides are marked in the aerial photos and then transferred over to the topo-sheet of that area. The next step was digitizing the landslides marked on the topo-sheets. In order to do so, a polygon shape file for the landslide is prepared and opened in ArcGIS 9.3 environment along with the digital contour data of that area. The landslide shape file was edited and each landslide location was drawn over the digital contour map using the editor tool to create new features. The landslide polygon is entered so the shape and size should not alter. The next step was to determine the average slope of landslide. The average slope of landslide is calculated using the formula given in Eq. 1. The graphical illustration of the average slope of landslide is given in Fig. 3.

$$\theta = \tan^{-1}\left(\frac{H}{Lp}\right) \qquad \text{............ (Eq. 1)}$$

where θ is the average slope angle of landslide. H is the elevation difference between highest and lowest point on the landslide. Lp is the horizontal length of landslide. Similarly, inclined length of landslide is calculated using the horizontal length and average slope of landslide. Breadth of landslide is also recorded. Thus, in this way, a large-scale landslide database including their length, breadth, area and average slope was created.

In the study area, 14 different geological units were found but some of them are very small in areal extent and have less abundant landslide distribution. Therefore, to find the geological control on landslides, various geological units are merged on the basis of similarity in lithology and a broader rock domain was made with nine lithological domains. Geological map prepared by Stöcklin and Bhattarai (1977) and Jnawali and Tuladhar (1996) were used in this study.

Similarly, to determine the influence of geological structures in large-scale landslides, landslide distribution was compared with the anticlinal and synclinal structures of the study area. A sub-area covering Damauli-Pokhara section was selected to interpret the influence of folding structures on landslide distribution. The orientation of fold structures in Damauli-Pokhara section was mapped with the help of anticlinal and synclinal axis given in the geological map. Finally, the landslide distribution in dip slope and counter dip slope was compared. Next, the orientation and inclination of landslides were compared with the attitude of rock domain. For this, dip and strike information of rock domain available in the geological map is extracted. Similarly, orientation and inclination of landslide is derived from the database of landslide. Based on the attitude of rock domain and orientation and inclination of landslides, rose diagram, stereo plot and density plot of rock domain and landslide were prepared and compared.

ANALYSIS AND RESULTS

Large-scale inventory mapping

As illustrated in the methodology, large-scale landslides were identified and their morphometric characteristics were also calculated. Fig. 4 shows the inventory map of large-scale landslide. A total of 2222 large-scale landslides were found in the whole study area which is equivalent to a density of one landslide every 2 km^2. The landslides mapped area range from 4931 m^2 to 771801 m^2 with an average area of 88251 m^2. The average length varies of 200 m to 400 m and an average breadth of 100 m to 300 m.

Physical features of large-scale landslides

In this section, the frequency-size analysis for the identified landslides has been carried out. It provides general information of what size of landslides do occur in central Nepal. Fig. 5 shows the landslide length versus frequency graph which indicates that about 50 % of the landslides lie within a 200 m to 400 m range of length. Similarly, the frequency of landslide decreases as the length increases, but the reason behind the gradual decrease is unknown. Many researchers (e.g., Satrk and Hovius 2001; Guzzetti et al. 2002; Van Den Eeckhaut et al. 2007 etc.,) have investigated and found out that landslide size distribution generally exhibit a power law scaling for limited scale range for different parts of world. Petley et al. (2007) also highlighted that landslide in Nepal exhibit power law scaling but for smaller order of magnitude size. Therefore, the gradual decreasing trend of frequency on the right side of the curve might be the effect of power law scaling, but in this study, the power law frequency-size analysis was not carried out. Fig. 6 shows landslide breadth versus frequency graph. About 70% of the landslides breadth is 100 m to 300 m. Fig. 6 also indicates the decreasing trend

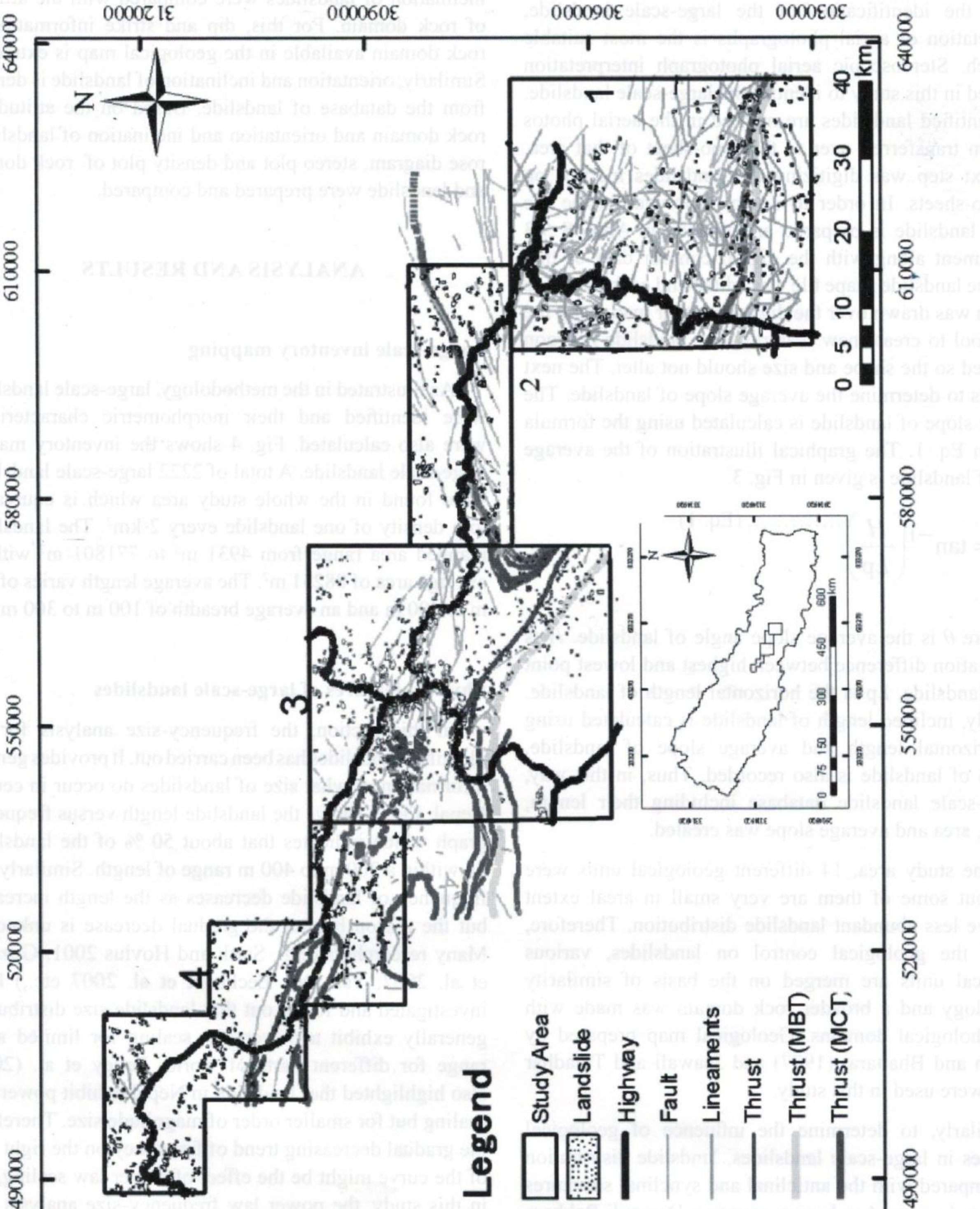

Fig. 4: Large-scale landslide inventory map of the study area

of frequency with the increase in breadth. Fig. 7 shows landslide area versus frequency graph which also indicate a clear decreasing trend with the increase in area. The average size of the landslide that occur in Nepal is about 4 ha to 12 ha (1 ha=10000 m^2). Fig. 8 shows the relation between the landslide length and breadth. In average the landslide breadth is half of the landslide length and it also shows a linear increment.

Relation between large-scale landslide and topographical parameters

In this study, average slope is calculated in order to explore the relation between the topography and large-scale landslide. The average slope defines the large-scale landslide rather than the pixel–based slope in GIS environment. In general, the steeper slopes might have higher potential to undergo failure than the flatter slopes. Similarly, steep river bank slopes are also much more prone to failure than the slopes away from the rivers. However, very steep slopes in this context of slow moving large-scale landslides are insignificant because the rate of displacement on a relatively steep slope must be quicker, which in turn exceeds the range of creep movement and the landslide may move abruptly. The average slope analysis (Fig. 9) indicates that the about 70% of the landslide posses slope angle of 20 to 40 degrees. Additionally, large-scale landslides are mainly distributed along the river and highway corridors.

Similarly, Figs. 10, 11 and 12 show the scatter plot to express the relation between the landslide slope and the physical dimensions such as length breadth and area of landslide. However, it is quite difficult to show an exact trend or relation between these factors but the general trend of decrease in the landslide dimension with the increase in landslide slope was noticed. In Fig.10, a curvilinear decrease in landslide length with the increase in landslide slope has been observed which also indicates the power law effect of landslide frequency and size. The data conclude that landslides of moderate size are more frequent.

Relation between large-scale landslide and geology

In case of large-scale landslides in the central Nepal, rock types are one of the important causative factors. The rock mass is highly fractured along the major thrusts the MBT and MCT. In the study area, phyllite, quartzite, slate, limestone, conglomerates, schist, dolomite are the dominant rock types. Most landslides are distributed in phyllite and slate domain as shown in Fig.13. Previous studies such as Yagi and Nakamura (1995), Yatabe et al. (2005), Dahal (2006), have also indicated that low-grade metamorphic rock such as phyllite and slate, and combination of phyllite and quartzite are found to be more prone to landslides. Slate and foliated phyllite are highly weathered and possess little resistance to shear stress which enhance the large-scale landslides processes. Higher distribution of landslides is found in the phyllite rock accommodating 42% of total landslides. In general, closer the tectonic structure or weak plane, higher the probability of landslides distribution. A clear indication of major thrust fault effect in the occurrence of landslides are seen as 47 % of the landslides lie at a distance of 500 m as shown in Fig. 14. However, such effect of thrust-fault may disappear when analyzed in local scale.

Relation between large-scale landslide and geological structures

Anticlinal and synclinal structures were compared with landslide morphometric feature (landslide orientation and landslide inclination). Fig. 15 shows the anticlinal and synclinal structure map of the Damauli-Pokhara section. Four cross-sections were prepared with the underlying synformal and antiformal structures and landslide locations as shown in Figs. 16, 17, 18 and 19. The synformal and antiformal structures are interpreted from the geological map (Jnawali and Tuladhar 1996). The four cross-sections indicate that landslides are distributed on both dip and counter dip slope but slightly higher distribution in dip slope.

In order to investigate the influence of folding structure more precisely, attitude of rock domains and orientation and inclination of landslides are compared. For this, the most abundant type of rock domain, phyllite and quartzite zone domain were selected and attitude were referred from the geological map. In case of landslide, average slope is considered as the landslide inclination and length direction as dipping direction. Similarly, breadth of the landslides is used to describe orientation of landslides. This orientation is strike direction of imaginary landslide plane. After calculating the orientation and inclination of landslide and attitude of foliation of phyllite and quartzite domain; rose diagram, stereo plot, and density plot were prepared and compared. The rose diagram (Fig. 20), stereo plot (Fig. 21), and density plot (Fig. 21) of landslide and phyllite and quartzite zone shows some similarities. It indicates that orientation of landslides is influenced by the orientation of rock mass.

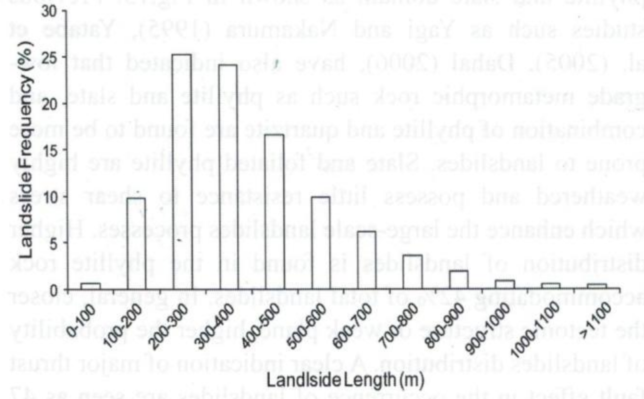

Fig. 5: Frequency of landslide versus landslide length. Frequency of landslide decrease with increament in landslide length.

Fig. 6: Frequency of landslide versus landslide breadth. Frequency of landslide decrease with increament in landslide breadth.

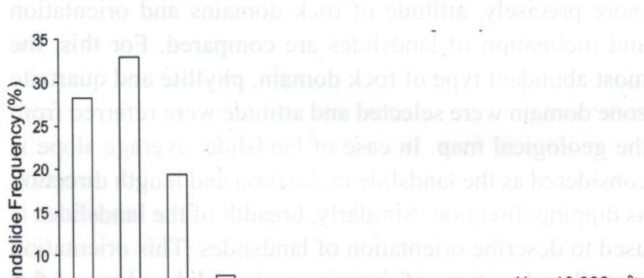

Fig. 7: Frequency of landslide versus landslide area. Frequency of landslide decrease with increament in landslide area.

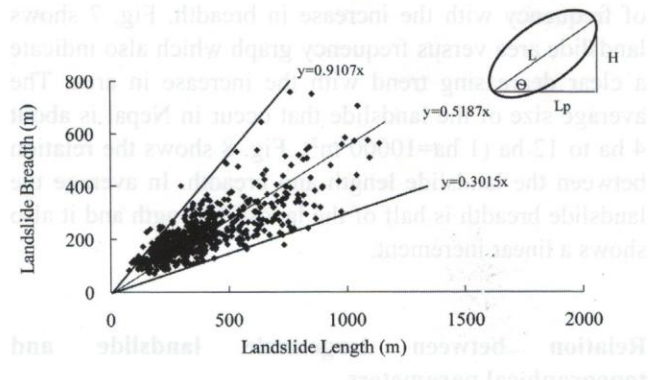

Fig. 8: Distribution of landslide length versus landslide breadth indicating most of the landslides length is twice their breadth.

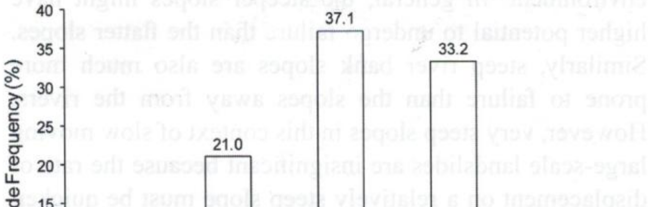

Fig. 9: Landslide frequency versus average slope of landslide, 70% of landslides lie in 20 to 40 degrees slope.

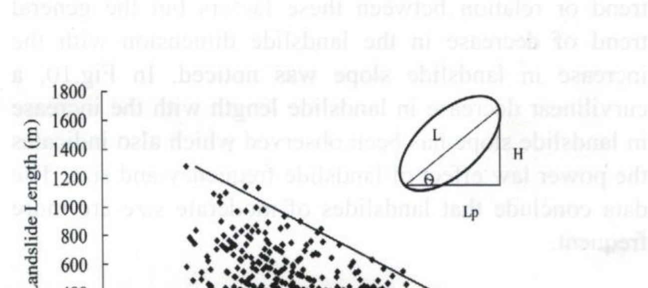

Fig. 10: Relationship between landslide length and average slope of landslide.

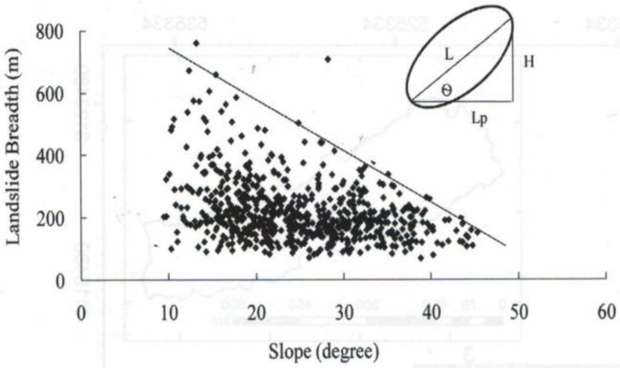

Fig. 11: Relationship between landslide breadth and average slope of landslide.

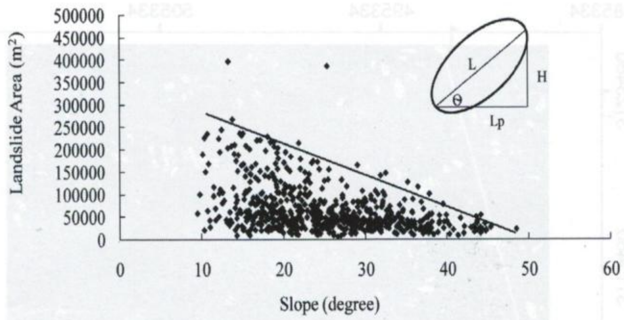

Fig. 12: Relationship between landslide area and average slope of landslide.

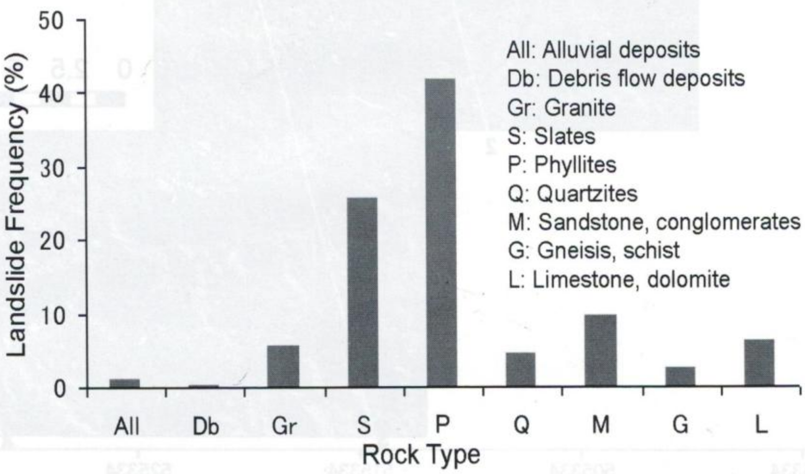

Fig. 13: Distribution of landslide in different rock types. Large-scale landslides are highly concentrated in phyllite and slate domain.

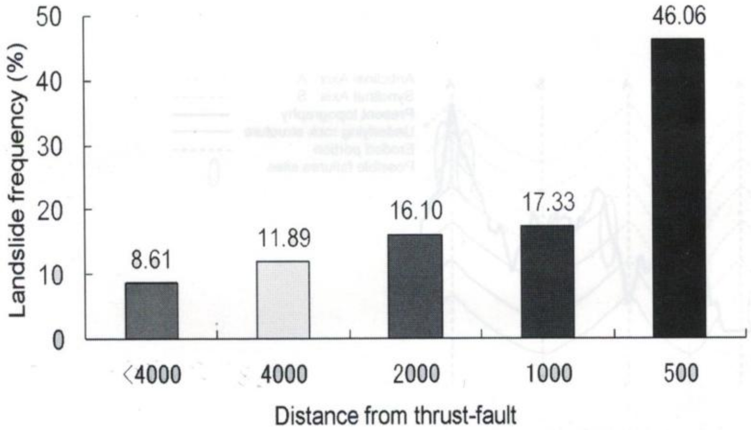

Fig. 14: Distribution of landslides with the proximity of thrust-faults.

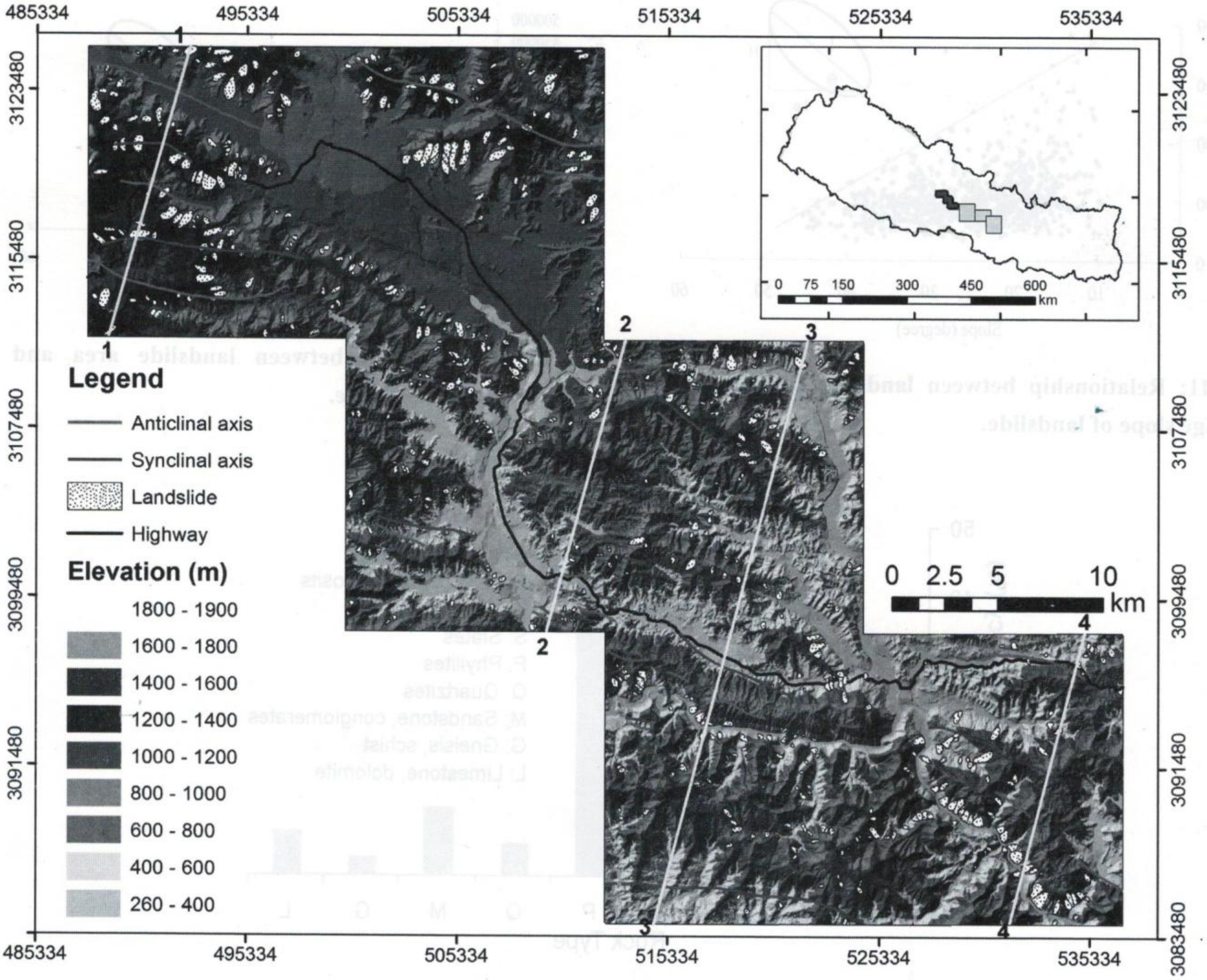

Fig. 15: Anticlinal and synclinal structure map of Damauli-Pokhara Section showing landslide distribution and four cross-sections.

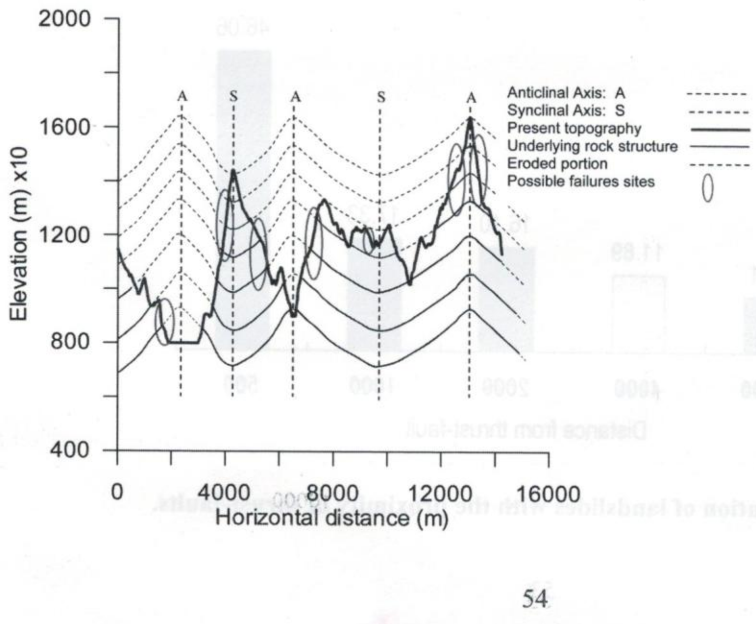

Fig. 16: Cross-section along 1-1.

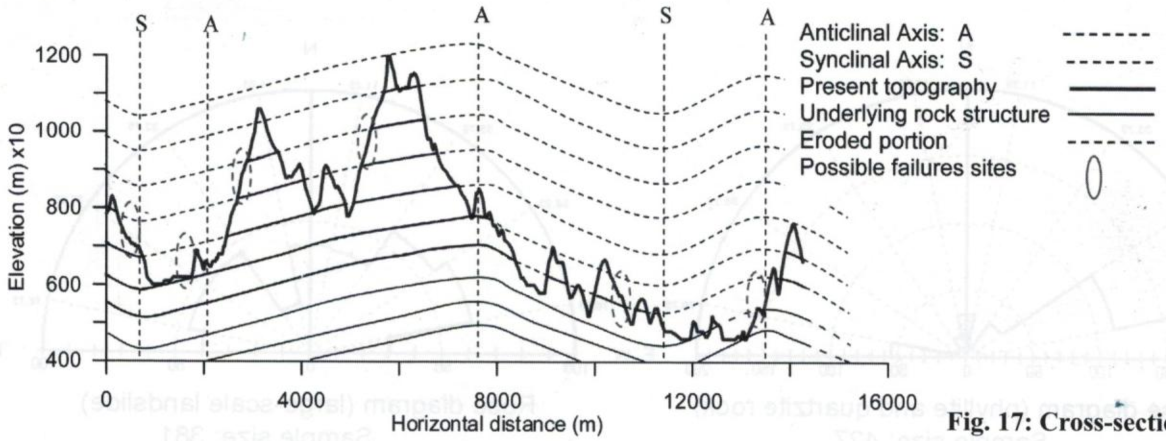

Fig. 17: Cross-section along 2-2.

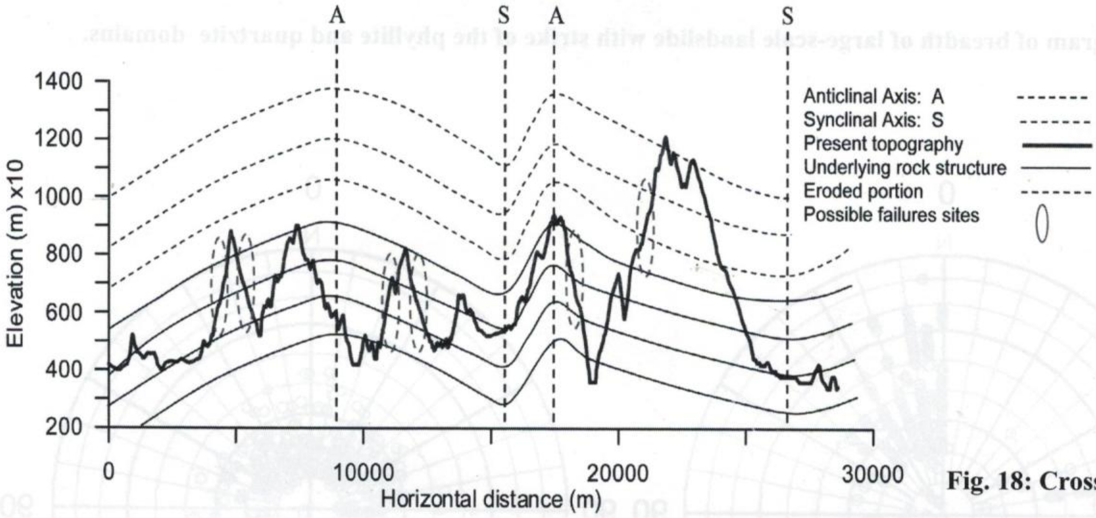

Fig. 18: Cross-section along 3-3.

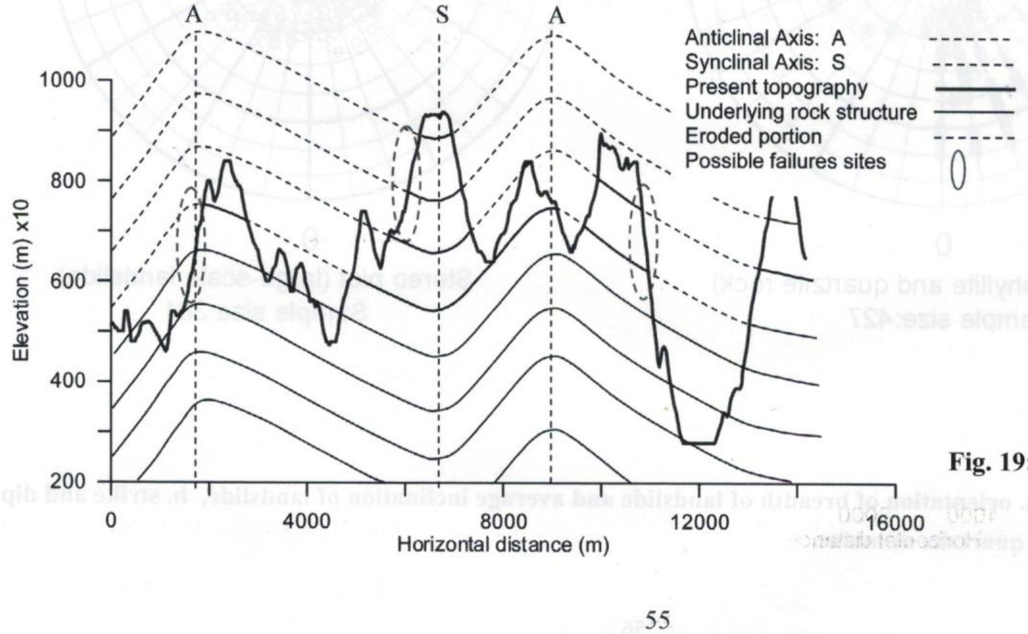

Fig. 19:Cross-section along 4-4

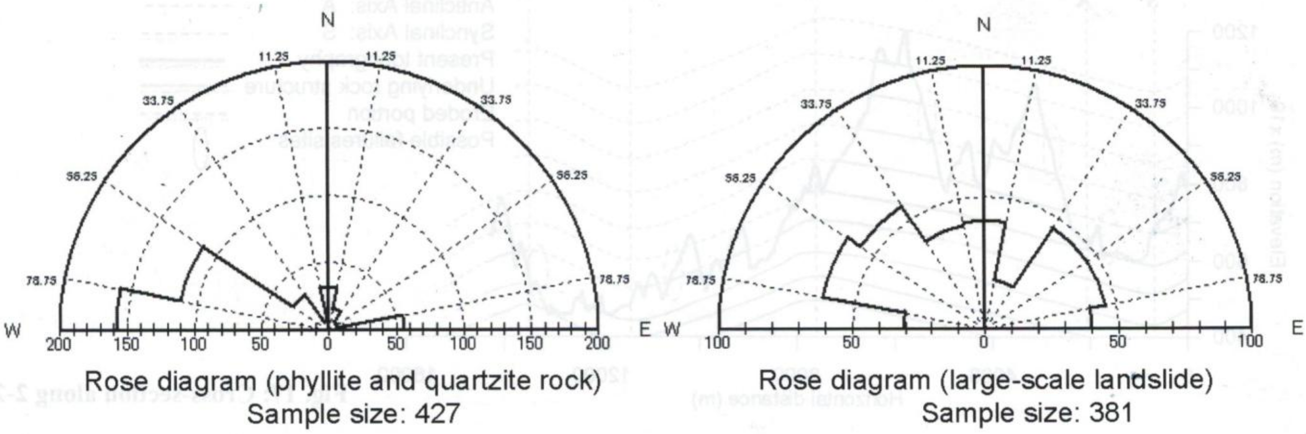

Fig. 20: Rose diagram of breadth of large-scale landslide with strike of the phyllite and quartzite domains.

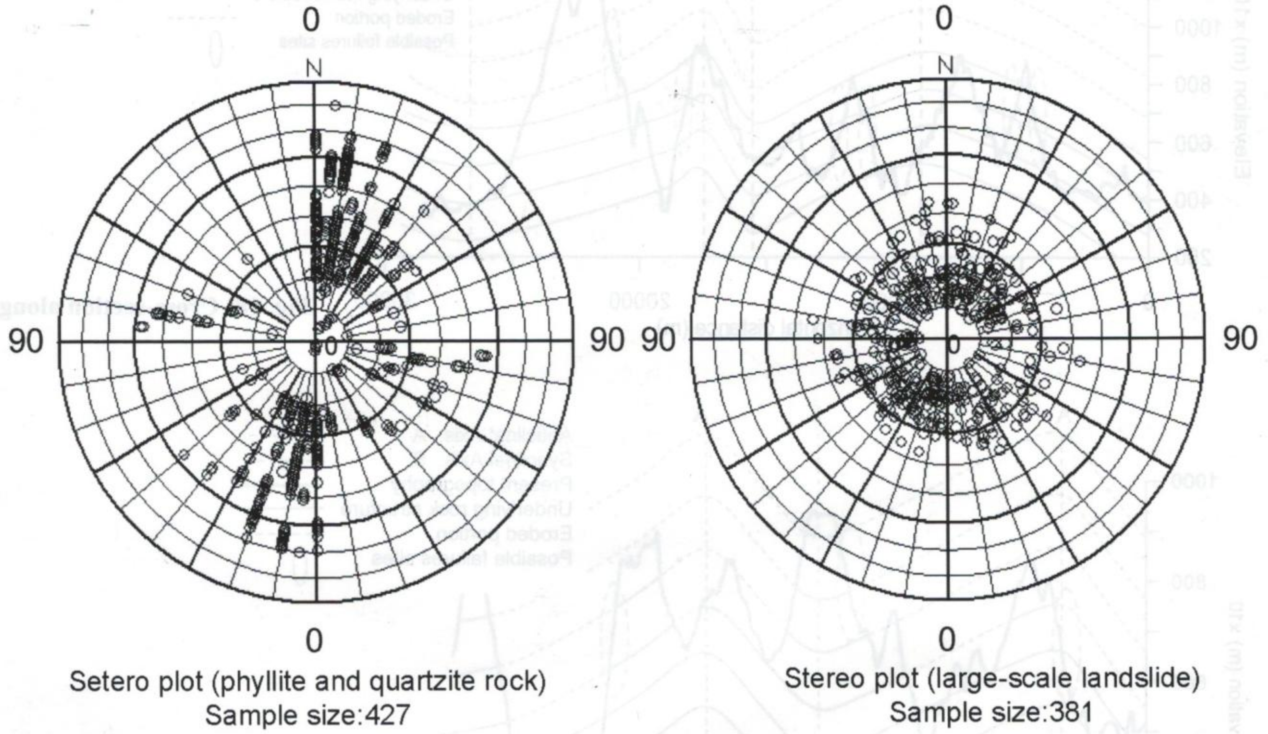

Fig. 21: Stereo plot of a. orientation of breadth of landslide and average inclination of landslide, b. strike and dip of foliation in phyllite and quartzite domains.

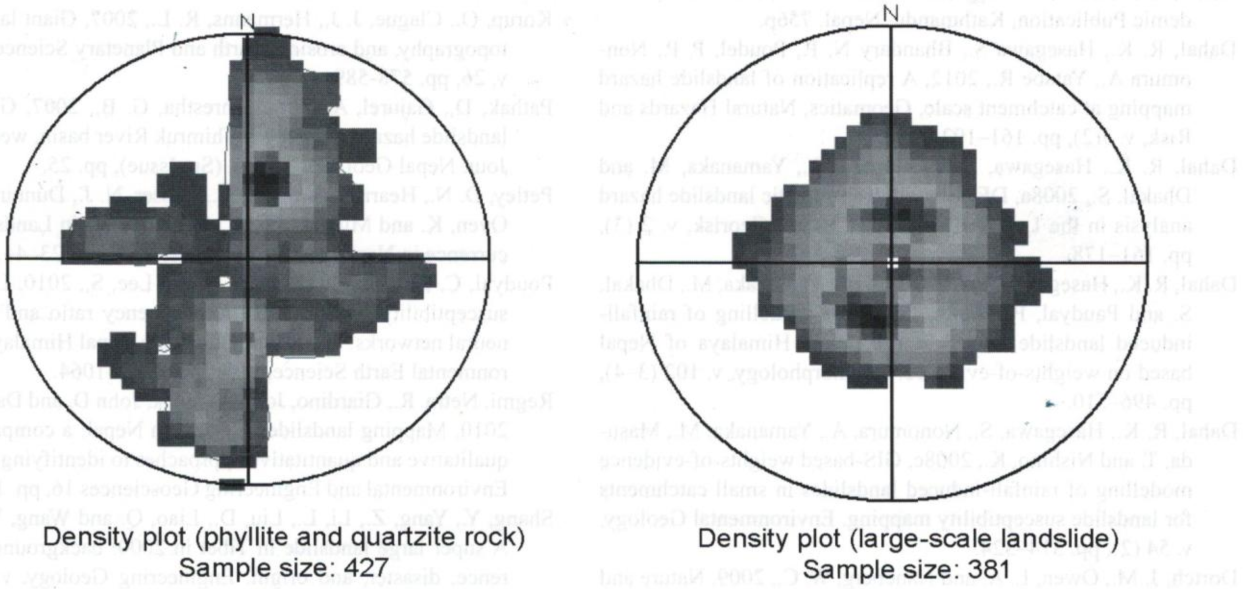

Fig. 22: (a) Density plot of orientation of breadth of landslides and average inclination of landslide. (b) Strike and dip of foliation in phyllite and quartzite domains.

CONCLUSIONS

In this study, morphometric features of large-scale landslides were compared with the geological features. A large-scale landslide inventory is prepared covering three major highways from Kathmandu to Pokhara. Most of the large-scale landslides in central Nepal have an average area of 4 ha to12 ha. The average length of large-scale landslides varies from 200 m to 400 m. Similarly, the average breadth varies from 100 m to 300 m. The relationship between average length and average breadth shows that length is nearly twice the breadth of the landslides. This confirms that large-scale landslides are elongated in nature. The frequency of landslide occurrences decreases with the increment in morphometric features (length, breadth, and slope) of landslide. More than 70% of the landslides lie in the slope range of 20-40 degrees. They are highly concentrated (nearly 50%) within a distance of 500 m from the thrust-fault. About 70 % of the landslides were found to be in the phyllite and slate domains. Orientation and inclination of landslide is similar with the strike and dip of foliation plane of the underlying rock mass. This indicates attitude of foliation of rock mass controls the morphometry of large-scale landslides. Moreover, distribution of landslides is higher in dip slopes than counter dip slopes.

Finally, it is concluded that attitude of foliation, lithology and geological structures have controlled the distribution of large-scale landslides in central Nepal. Therefore, a comprehensive study is necessary between attitude of foliation, lithology and geological structures to illustrate the spatial distribution of large-scale landslide and to establish the empirical relationship between them.

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