Journal of Nepal Geological Society, 2023, Vol. 65 (Sp. Issue), pp. 183–194
https://doi.org/10.3126/jngs.v65i01.57777

Spatial variability of slope movements in central and western Nepal Himalaya: Evaluating large-scale landslides to cut-slopes

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ABSTRACT

Spatial variability of slope movements is common in the Himalayan terrain of central and western Nepal Himalaya due to the intricate topography, differential geo-environment, and frequent rainstorms. The process of mass movements in the Himalaya have been described in the past by many researchers. The spatial variability of slope movement phenomena is scale dependent and is affected by causative and triggering processes. The limited researchers delivered output to understand the scale-dependent spatial variability resulting from the causative and triggering mechanism of slope movement phenomena. This study has presented a rigorous scientific examination of the spatial variability of slope movements, focusing on large-scale landslides to cut slopes across the central and western regions of the Nepal Himalaya. To achieve this, a multidisciplinary approach was employed, encompassing geospatial analysis, remote sensing, and field investigations. High-resolution satellite imagery was utilized to identify and map slope movement features, while digital terrain analysis techniques aided in quantifying their characteristics. This approach quantitatively analyzed slope movement distribution, frequency, and characteristics in terms of various geo-environmental settings. The findings reveal diverse patterns of slope movements influenced by complex interactions between geological factors, geomorphology, triggering factors, and anthropogenic activities. Geological and geomorphological heterogeneity play roles differently in the spatial distribution of slope movements. Moreover, rainfall distribution and peak ground acceleration act similarly for the scale dependency phenomena of slope movement. The spatial variation concerning the causative and triggering variables signify the scale-dependency nature of slope movement processes. This study has provided insights into the scale dependency and spatially variable nature of slope movement events due to variations in causative and triggering mechanisms in the Nepal Himalaya.

Keywords: Spatial variability, large-scale landslides, cut-slopes, Nepal Himalaya

Received: 20 April 2023 **Accepted:** 07 July 2023

INTRODUCTION

A number of mass movements (landslides, slope failures, cut-slope failures, etc.) occur every year in central and western parts of Nepal Himalaya due to the intricate geological characteristics and variable topography. The area has undergone a high degree of tectonic deformation caused by complex geological structures and the presence of variable and fragile rock formations. The uneven distribution of slope movement events is intensified by frequent seismic activity that are coupling with substantial and prolonged monsoonal rainfall during specific periods (Dahal et al., 2008, 2010; Regmi et al., 2012, 2013; Devkota et al., 2010; Thapa, 2011; Pathak, 2016; Nepal et al., 2019; Phuyal et al., 2022).

The slope movements are a prevalent phenomenon in the Himalayan region and exhibit a range of scales, spanning from minor slope failures to extensive mountain collapses. The studies by Shroder and Bishop (1998) and Shang et al. (2003) emphasize the scale-dependent variability. Classification of slope movements takes into account of various factors such as the materials involved, the scale of the landslide, and the type of movement. This categorization framework has been established by researchers like Varnes (1978), Cruden and Varnes (1996), and Hungr et al. (2014). Slope movement events, which encompass both landslides and cut-slope occurrences are differentiated based on their dimensions, extent, and underlying failure mechanisms. Cut-slopes typically emerge due to human activities and span a range of meters to hundreds of meters, while natural landslides vary significantly in scale, ranging from meters to kilometers. The causal agents for medium- and large-scale landslides are predominantly of natural origin, whereas both natural and human-induced factors can contribute to smaller slide events. Small slides and cut-slope incidents typically have the concise deformation histories and are often triggered by a single initiating factor. Contrastingly, medium to large-scale landslides are characterized by prolonged histories of deformation, shaped by the interplay of multiple triggering mechanisms. The complex nature of failure processes in large-scale landslide occurrences is a consequence of the interrelationship between causative and triggering factors.

Evidence of extensive and catastrophic slope movements has profoundly shaped much of the Himalayan landscape (Fort, 1987; de Terra and Paterson, 1939; Burbank, 1982; Heuberger et al., 1984; Weidinger and Schramm, 1995; Weidinger et al., 1996; Ibetsberger, 1996; Spray, 1997). The spatial distribution of these slope movements exhibits a distinctive dependence on scale, influenced by the varying strength characteristics of the rock mass, an assertion articulated by Goodman (1980). Especially, the presence of discontinuities spread within the spatial domain cause a reduction in the strength of the rock mass as the spatial scale increases (Schmidt and Montgomery, 1995). This has significant implications as the strength of rock masses at the scale of mountains considers a critical role, comparable to the influences of tectonic and climatic processes, in shaping the geomorphological evolution. Thus, the assessment of the processes of spatial variability of the slope movement and scale dependencies in the Himalaya is crucial to evaluate the phenomena.

SETTING OF THE AREA

The Nepal Himalaya displays diverse geomorphological and geological attributes due to its location within the Himalaya. Geographically, the area lies in Terai, Dun Valley, Siwalik Hills, Mahabharat Range, Midlands, Fore Himalaya, Great Himalaya, and Inner Himalaya (Dhital, 2015), and encompasses elevations from 55 m to 8153 m above sea level. The area comprises mountains, hills, and numerous river valleys having major rivers which include Trishuli, Marshyangdi, Kali Gandaki, Indrawati, Sunkoshi, Bhotekoshi, and Tamakoshi. Prithvi Highway, Pasang Lhamu Highway, BP Highway, Araniko Highway, Mahendra Highway are the major roadway to connect the area. The climate varies with elevation, ranging from subtropical in the lowlands to alpine in the high mountain regions. Monsoons from June to September bring substantial rain via the southwest monsoon, affecting regions differently due to topography. Rainfall diminishes with elevation rise to the north (Chalise and Khanal, 2001).

The geological and structural complexities of the central and western Nepal Himalaya are categorized into various tectonic divisions: Terai, Sub-Himalaya, Lesser Himalaya, Higher Himalaya, and Tethys Himalaya. The chronological arrangement of rock sequences is shown in Figure 1, with various thrusts demarcating these formations. The Main Frontal Thrust (MFT) demarcates the interface between Quaternary sediments in the Terai region and the Sub-Himalayan rock strata (Neogene) (Dhital, 2015). The Sub-Himalayan rocks, spanning the Middle Miocene to Early Pleistocene, comprise mainly sandstone, mudstone, and conglomerate. The Sub-Himalayan rocks are separated from Lesser Himalayan rocks (Paleoproterozoic to Neoproterozoic) by the Main Boundary Thrust (MBT) (Dhital, 2015). The boundary between Lesser Himalayan and Higher Himalayan rocks (Proterozoic to Cambrian) is delineated by the Main Central Thrust (MCT). The South Tibetan Detachment System (STDS) separates Palaeozoic to Mesozoic Tethys Sedimentary Zone from Higher Himalayan rocks. Regional tectonic features including

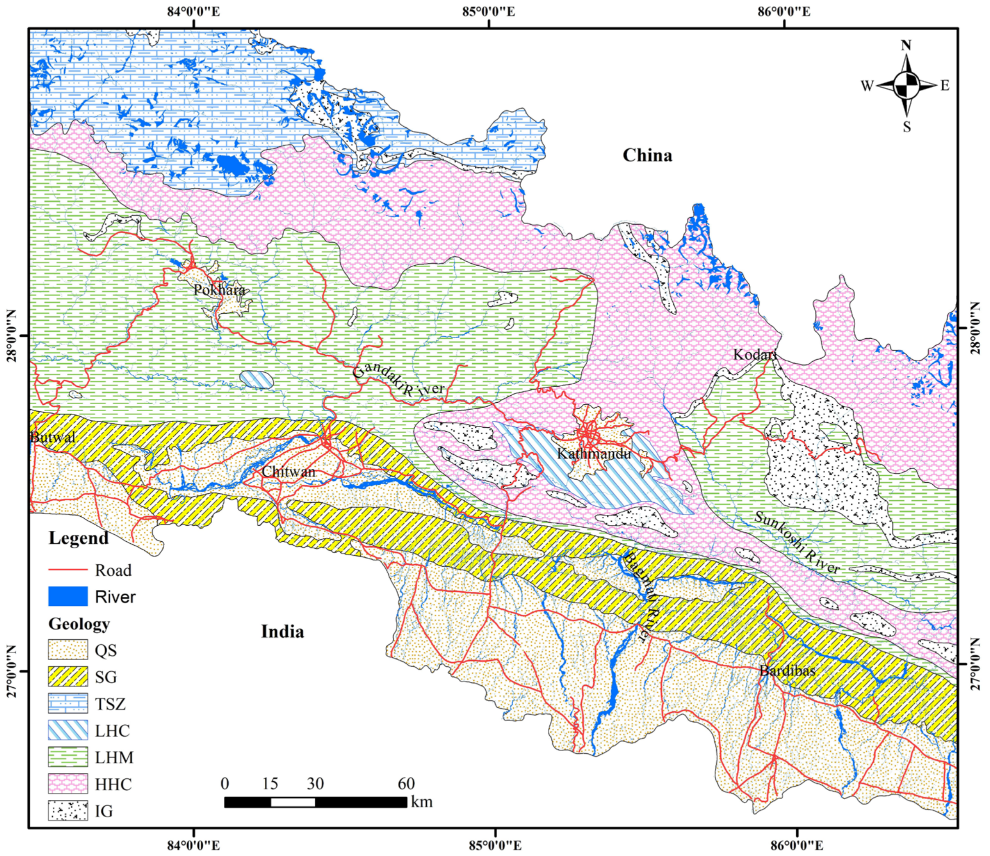


Fig. 1: Location map showing the geological characteristics of the study area (after Dhital, 2015). IG; igneous rock (Paleoproterozoic–Miocene), HHC: Higher Himalayan Crystalline (Proterozoic–Cambrian), LHM: Lesser Himalayan Meta-sedimentary (Paleo–Neoproterozoic), LHC: Lesser Himalaya Crystalline (Paleo–Neoproterozoic), TSZ: Tethys Sedimentary Zone (Paleo–Mesozoic), SG: Siwalik Group (Neogene), QS: Quaternary Sediments.

the Midland Antiform, Great Mahabharat Synclinorium, Okhaladhunga Window, and Kathmandu Nappe, have experienced substantial deformation within the rock strata (Dhital, 2015). The intense deformation caused by these structures could potentially serve as a significant factor in scale varying spatial distribution of the slope movements in the area.

ANALYTICAL APPROACH

Methodology of the analytical approach included several steps: database acquisition, derivation of landslide characteristics based on controlling parameters, and assessment of the spatial variability of slope movement occurrences (Fig. 2). A collection of landslide data was extracted by the interpretation of satellite images, analysis of geological and geomorphic parameters. Furthermore, the study was complemented by field surveys to verify the database and inventory map of landslides and cut-slopes. A total of 10153 landslides and 67 cut-slopes were documented from the study area and utilized the size-based categorization criteria from studies such as Bruckl (2001), Chung et al. (2018), and Lin et al. (2013) for the classification of slope movements into small, medium, and large-scale categories.

Database preparation

A landslide inventory database is the vital information for landslide distribution and activity defined by Cruden and Varnes (1996) and WP/WLI (1993). A landslide inventory map is useful to establish the relationships between landslides and influencing factors as well as it is a prerequisite to evaluating landslide susceptibility (Chen et al., 2017). The landslides from the database are categorized into cut-slopes, small-slides, medium-landslides, and large-scale landslides (Zerathe et al., 2014; Chung et al., 2018; Lin et al., 2013; Wen and Chen, 2007; Zhou and Cheng, 2015) shown in Figure 3. A geomorphological database is based on the topographical characteristics of the area, derived from the survey department of Nepal. Slope angle, slope aspect, slope curvature, and elevation are used to evaluate the spatial variability of the slope movement events. The appropriate class division and method of the geomorphological parameters are presented in Table 1. Another prime factor for the study of landslides is the geology of the area and its associated geological database (Dhital, 2015). Integrating information on land cover with landslide data can provide insights into the relationship between land use and landslide occurrences. Analyzing land cover patterns and changes over time in landslide-prone areas can help identify areas at higher risk. The land cover database of ICIMOD (2021) of Nepal of 2019 AD was used. Rainfall and peak ground acceleration (PGA) are two critical factors that can trigger landslides and influence the spatial variability. The significance of these factors with the data sources and factor classes is shown in Table 1.

RESULT AND DISCUSSION

Occurrence of slope movements

An effective classification of influencing factors contributes to enhancing the dependability of evaluation of landslide distribution. During the assessment of the spatial variations of landslides, eight conditioning factors were taken into account, guided by the geological context and the dispersion pattern of landslides: slope angle, slope aspect, slope curvature, elevation, lithology, land cover, rainfall, and peak ground acceleration (PGA).

A slope angle is an important factor when evaluating the slope movement process. Slope angles are classified manually into seven classes; <15°, 15–25°, 25–35°, 35–45°, 45–55°, 55–65° and >65°. These classes occupy 22.56%, 23.03%, 26.93%, 18.79%, 7.19%, 1.37%, and 0.13% of the analysis area respectively shown in Figure 4a. Similarly, the slope aspect is another factor that plays a role in landslide occurrence due to variations in soil moisture, evaporation, and erosion. Slope aspect is divided into nine classes; flat, north, northeast, east, southeast, south, southwest, west, and northwest covering 0.72%, 11.92%, 11.92%, 11.75%, 12.43%, 13.94%, 13.38%, 12.43% and 11.50% of the analysis area respectively (Fig. 4b). The curvature map in the analysis area is sub-classified into three classes; concave, flat and convex that covers 35.23%, 32.34%, and 32.43% area respectively (Fig. 4c). Elevation is considered a vital factor that influences the occurrence and distribution of landslides, degree of weathering and human activities (Hong et al., 2016). In the analysis area, the elevation range is classified into five classes: <500 m, 500–1500 m, 1500–2500 m, 2500–3500 m, and >3500 m. These classes occupy 17.69%, 51.57%, 20.60%, 6.87%, and 3.27% of the analysis area respectively shown in Figure 4d.

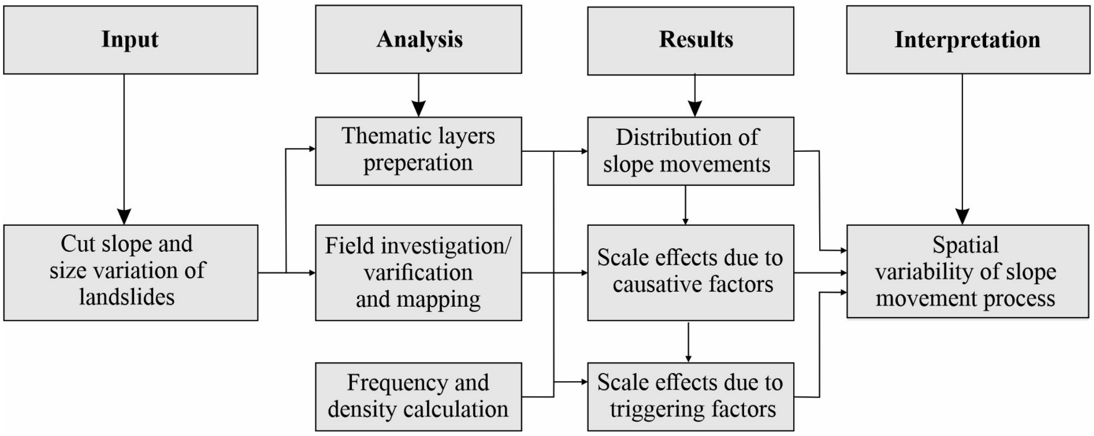


Fig. 2: Methodology of the analytical workflow.

Table 1: Data sources of controlling variable for the spatial distribution of the landslides.

Variables	Significance	Class	Methods	Data source
Slope angle	Slope gradient, an important factor for mass movement (García-Rodríguez et al., 2008; Corominas et al., 2014). Landslide occurrence increases with increasing slope angle (Kamp et al., 2008; Demir et al., 2013)	7	Manual break	Survey Department of Nepal
Slope aspect	Related to the weather condition, weathering and land cover, soil moisture, evaporation and erosion thereby affect the occurrence of landslides (García-Rodríguez et al., 2008; Kamp et al. 2008; Corominas et al., 2014; Ilia and Tsangaratos, 2016)	9	Categorical factor	Survey Department of Nepal
Slope curvature	Curvature, a topographic factor, crucially important for landslides (Hasegawa et al. 2009; Corominas et al., 2014)	3	Manual break	Survey Department of Nepal
Elevation	A vital factor that influences the occurrence and distribution of landslides, degree of weathering, and human activities (Corominas et al., 2014; Owen et al., 2008; Hong et al., 2016)	5	Manual break	Survey Department of Nepal
Geology	The slope materials are base for the landslide generation depends upon the lithological character (Dai and Lee, 2002; Corominas et al., 2014; Pellicani et al., 2014; Yalcin et al., 2011).)	6	Categorical factor	Dhital (2015)
Land cover	Land cover defines the land anchoring capacity (Meusburger and Alewell, 2008) and is a highly important conditioning factor for landslide occurrences (Montgomery et al., 2000; García-Rodríguez et al., 2008; Corominas et al., 2014)	11	Categorical factor	ICIMOD (2021)
Rainfall	Annual rainfall is important triggering factor of landslides (Chalise and Khanal, 2001)	6	Manual break	OCHA (2015)
PGA	Peak ground acceleration gives the earthquake generated additional driving force on the slope which favors the landslides (Duncan et al., 2014; Corominas et al., 2014; Budimir et al., 2015; Keefer, 2002; Delgado et al., 2011; Xu et al., 2012)	5	Manual break	USGS (2015)

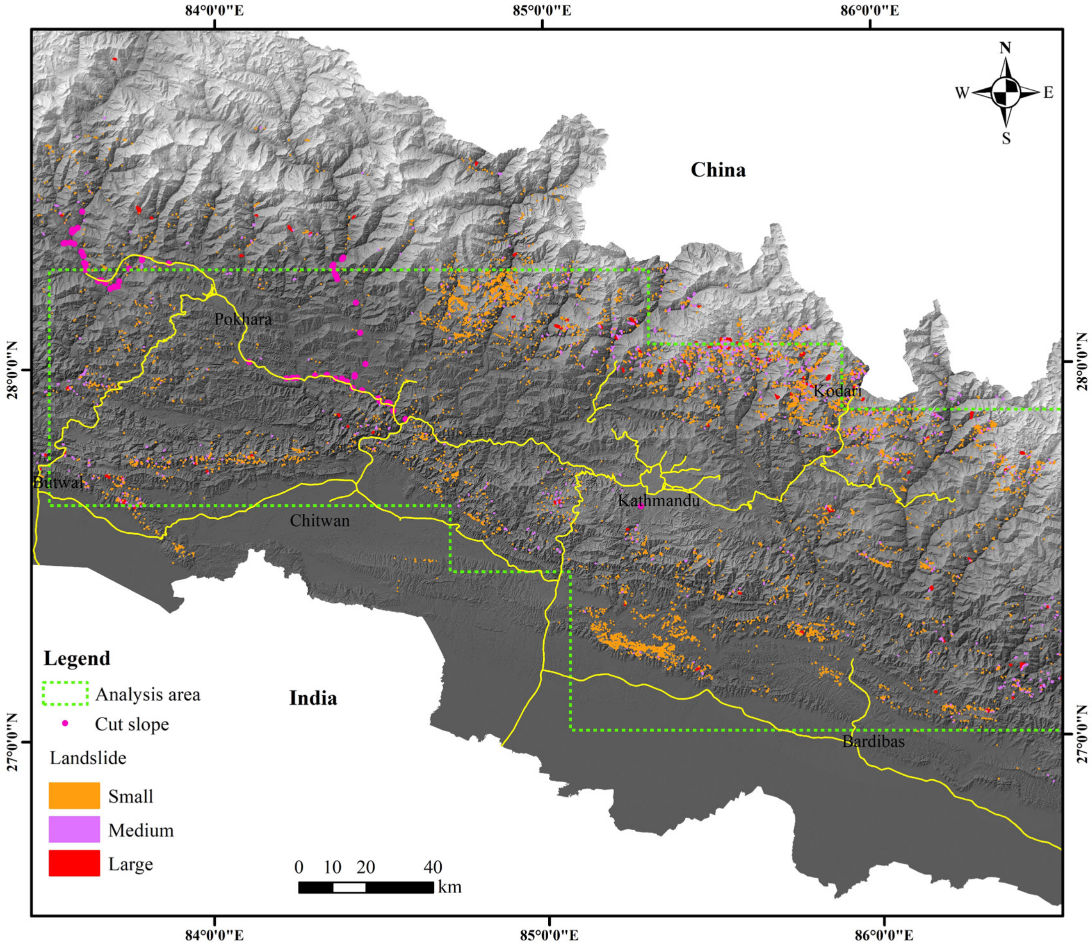


Fig. 3: Landslide distribution of the study area. Large, medium, and small landslides were categorized based on Zerathe et al. (2014), Chung et al. (2018), Lin et al. (2013), Wen and Chen (2007), Zhou and Cheng (2015), Phuyal et al. (2022).

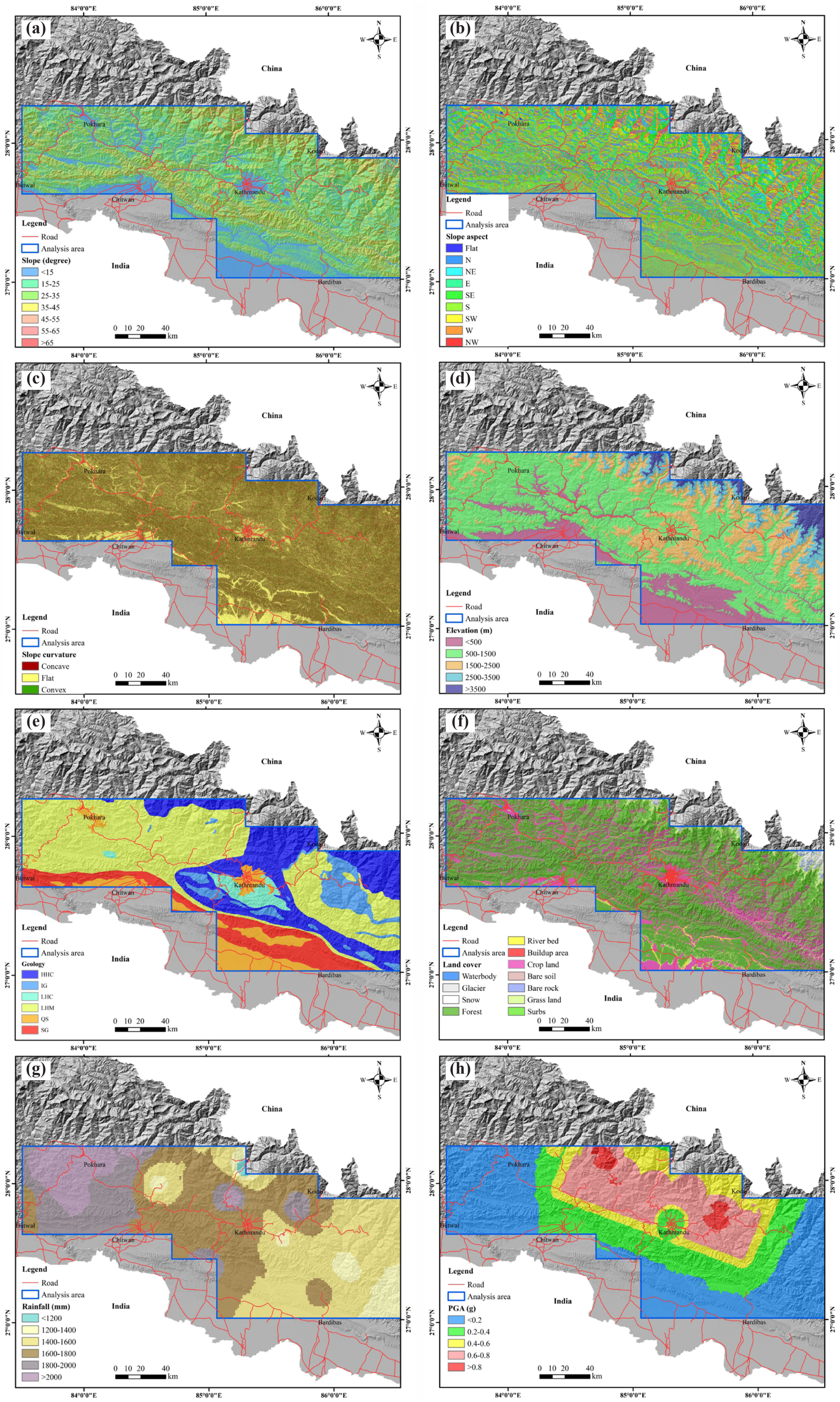


Fig. 4: Causative and triggering factors of slope movements; (a) slope angle, (b) slope aspect, (c) slope curvature, (d) elevation, (e) Geology, (f) land cover, (g) rainfall, (h) peak ground acceleration (PGA).

Lithology plays an important role in the formation and evolution of landslides, as it forms the material based for landslide generation (Yalcin et al., 2011). Different rock and soil masses differ in physio-mechanical properties that lie over the slope that controls the landslide events (Pellicani et al., 2014). The lithological category in the area is divided into six classes; Quaternary sediments, Siwalik Group, Lesser Himalaya Crystalline, Lesser Himalaya Meta-sediments, Higher Himalaya Crystalline, and Igneous rock occupying 9.36%, 11.42%, 3.06%, 45.60%, 23.15% and 7.40% of the area respectively (Fig. 4e). Land cover pattern also play significant role to control the landslides. The land cover map of the study area is categorized as water body, glacier, snow, forest, riverbed, built-up area, cropland, bare soil, bare rock, grassland, and shrubs. These categories occupy 0.45%, 0.28%, 0.39%, 62.54%, 1.15%, 1.01%, 25.84%, 0.00%, 0.48%, 4.62%, and 3.24% of the analysis area respectively and is shown in Figure 4f. Annual rainfall is significant triggering factor of landslides (Chalise and Khanal, 2001). Based on the distribution pattern of rainfall data, the analysis area is classified into six classes; <1200 mm, 1200–1400 mm, 1400–1600 mm, 1600–1800 mm, 1800–2000 mm, and >2000 mm covering 0.30%, 6.78%, 33.92%, 32.97%, 15.75%, and 10.27% area respectively (Fig. 4g). Similarly another triggering factor is PGA and is classified into five classes; <0.2 g, 0.2–0.4 g, 0.4–0.6 g, 0.6–0.8 g and >0.8 g. These PGA range classes occupy 42.41%, 22.40%, 12.70%, 20.20%, and 2.30% of the area respectively as shown in Figure 4h.

Scale-dependent on slope-movements

Scale dependency of slope movement process is highly controlled by the causative and triggering mechanisms that define the characteristics, behavior, and impact of landslides vary depending on the spatial and temporal scales (Shroder and Bishop, 1998). Landslides can occur over a wide range of sizes, from small, localized movements of soil to large, catastrophic events that involve massive volumes of rock and debris (Shroder and Bishop, 1998; Hewitt, 1972, 1988, 1989). The ways to evaluate the scale dependency of the slope movements lie in their size and volume, triggering factors, speed and velocity, and deformation behavior. Landslides can vary significantly in terms of their size and volume. Small-scale landslides might only affect a small portion of a hillside or road, while large-scale landslides can cover vast areas and result in significant environmental and infrastructural damage. The minimum, maximum, and average size of the cut-slopes from the studied location are found as 6, 6000, and 692 m^2 respectively. The average length of cut-slope is 22.5 m with a width of 26 m, presented in Table 2 and Figure 5. Similarly, the average size of the landslide from central and western Nepal is 6273 m^2 with maximum and minimum sizes are ~1 to 1,020,250 m^2. After categorization of the landslide based on their sizes, the average size of smaller slides, medium and large-scale landslides is found as 367 m^2, 8,346 m^{2,} and 222,349 m^2 (Fig. 5, Table 2).

The triggering factors in the area can accelerate the results of scale dependency on the landslide process. Small-scale landslides might be triggered by relatively minor factors such as rainfall and ground shaking, while large-scale landslides might require a long temporal frame with more substantial triggers such as heavy rainfall and/or earthquakes. The speed at which landslides occur can differ based on their scale. Small-scale landslides might move slowly and gradually, whereas large-scale landslides can exhibit rapid movement, sometimes reaching speeds of several meters per second. The deformation behavior of landslides, including the way they move and the mechanisms behind their movement can vary with the scales of events. Microscopic-scale landslides might involve particle-level interactions, while larger-scale landslides might exhibit more complex behavior involving sliding, rolling, and fluidization of materials. The speed of a landslide usually depends on the deformation behavior controlled by

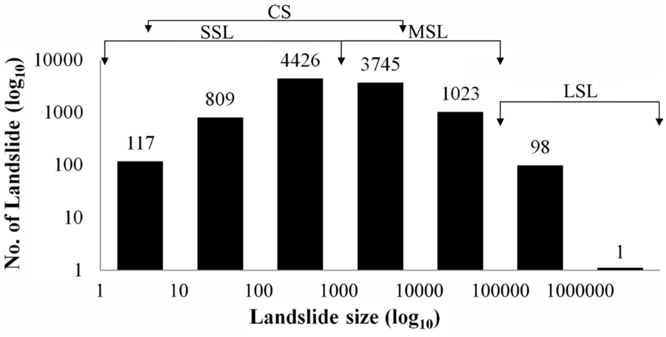


Fig. 5: Landslide size distribution and number of events in central and western Nepal Himalaya.

Table 2: Descriptive statistics analysis of landslides and cut-slopes with controlling factors.

Factors	Statistical values			
	Min	Max	Mean	Std. dev.
Cut slope area	6	6000	691.8507463	1018.273498
Cut slope length	6	100	22.46268657	19.35108513
Cut slope width	1	100	25.92537313	17.0430057
Landslide area	0	1020250	6273	28790
Small landslide area	0	998	367	269
Medium landslide area	1000	99368	8347	12913
Large landslide area	100299	1020250	222349	168809
Slope angle	0	82.76	25.99	13.83
Slope aspect	1	359.91	178.09	102.51
Slope curvature	-170.75	201.25	-0.72	3.62
Elevation	91	6939	1288.86	930.53

geomorphological factors. The slope angle ranges from 0 to 83 degrees in the study with an average value of 23 degrees. The range of slope aspect is 1 to 360 and the average is 178 azimuths. The slope curvature range is from -170 to 201 while the elevation range is 91 m to 6939 m in the study area (Table 2).

The geometry and extent of the cut-slope are controlled by the varying nature of mechanical properties of rock and slope mass (Wilson et al., 2003; Timilsina et al., 2012; Zerathe et al., 2014; Chung et al., 2017; Ghobadi et al., 2017; Kuo et al., 2018). The cut-slope on high strength slope mass can go from gentle to steep slopes while a slope having low strength mass can be stable with a low slope gradient (Fig. 6). Cut-slopes at the road section of Maldhunga–Kushma road in the conglomerate (Fig. 6a) shows that overall height of slope without benching are still stable. While cut-slopes from Dumre Bazar and Bhansar of Tanahun were cut in the residual soil (Fig. 6b,c) with low height and proper benching. Similarly, the cut-slope from Kushma–Dimuwa section in the red soil shows a height of <10 m with proper toe support (Fig. 6d,e). It clearly shows the lithology of the area is highly influenced by the size and extent of cut-slopes.

The significant impact of causative factors and triggering factors play a key role in the initiation and propagation of medium to large-scale landslides in the Himalaya. These types of landslides are mostly initiated at the ridge and body of the slope depending on structural controls and geology of the local area (Fig. 7). The discontinuities play an important role in the rock mass while weathering process is significant in soil-rich slopes. Geomorphological parameters such as slope angle,

Fig. 6: Cut slope at road section from central and western Nepal (a) conglomerate at Maldhunga–Kushma road, (b) slope with benching on residual soil at Dumre Bazar, Tanahun, (c) residual soil at Bhansar, Tanahun, (d) near Kushma Bazar, (e) red soil cut slope at Kushma–Dimuwa section.

slope aspect, and curvature define the shape and thickness of landslides. Landslides generally occur in areas with steep slopes where the soil cover is thin and often accelerated by seismic events and rock mass conditions (Fig. 7a,c). On the other hand, in regions characterized by moderately steep terrain with thicker soil cover, landslides are primarily induced by a combination of seismic activity and heavy rainfall (Fig. 4b,d).

Groundwater fluctuations play a crucial role in the occurrence of medium to large-scale landslides. The significant scale dependency, influenced by a variety of controlling factors, is particularly prominent in medium-sized landslides characterized by notable substantial spatial variation.

The spatial variability of large-scale landslides is temporal scale dependent due to less distribution and long deformation history in the Himalaya. The long deformation process is favored by the complex geological environment and structural characteristics (Huang and Li, 2008, 2009; Xu et al, 2011; Zhoa et al., 2019). Geological and structural control is thus important in the initiation and occurrence of large-scale landslides. This type of slope movement mostly occurs at the crown of hill-slope with a steeper to gentle head scarp defined by the orientation of the geological stratum (Fig. 8a,b,c). The Jure Landslide in Sindhupalchok, Dutti Landslide in Kavre and Gyapche Landslide in Ramechhap are examples of these types of landslides. The thickness is either due to thick strata of soil or favorable environment of rock mass distribution (Fig. 8b,c,d). Large-scale landslides if occurred in the river valley, they often exhibit a width surpassing their length and tend to be relatively shallower in nature (Fig. 8e). The Bhanjayang Landslide in Syangja illustrates as an example of a large-scale landslide that occurred in the river valley, characterized by considerable extent compared to its height. The study shows that the scale dependency of large-scale landslides is usually controlled by geological discontinuities along with the complex effect of triggering factors.

Causative and triggering mechanisms

The spatial variability of the landslides in the Himalayan terrain is significantly influenced by geological, geomorphological, and triggering factors. To evaluate this, the frequency and density of slope movement events from central and western Nepal Himalaya are calculated from different sub-classes of controlling factors. The frequency of cut-slope is high at slopes <15°, and comparatively lower in slope range from 55° to 65°. Relative density is also higher where more cut-slopes are observed and slopes >55° has lower density. The frequency distribution of small slides and medium slides is higher at slope class 35° to 45° and lesser at extremely less or high slope angle class. While the relative density of smaller and medium landslides falling in the gentle class (<15°) is low and steeper

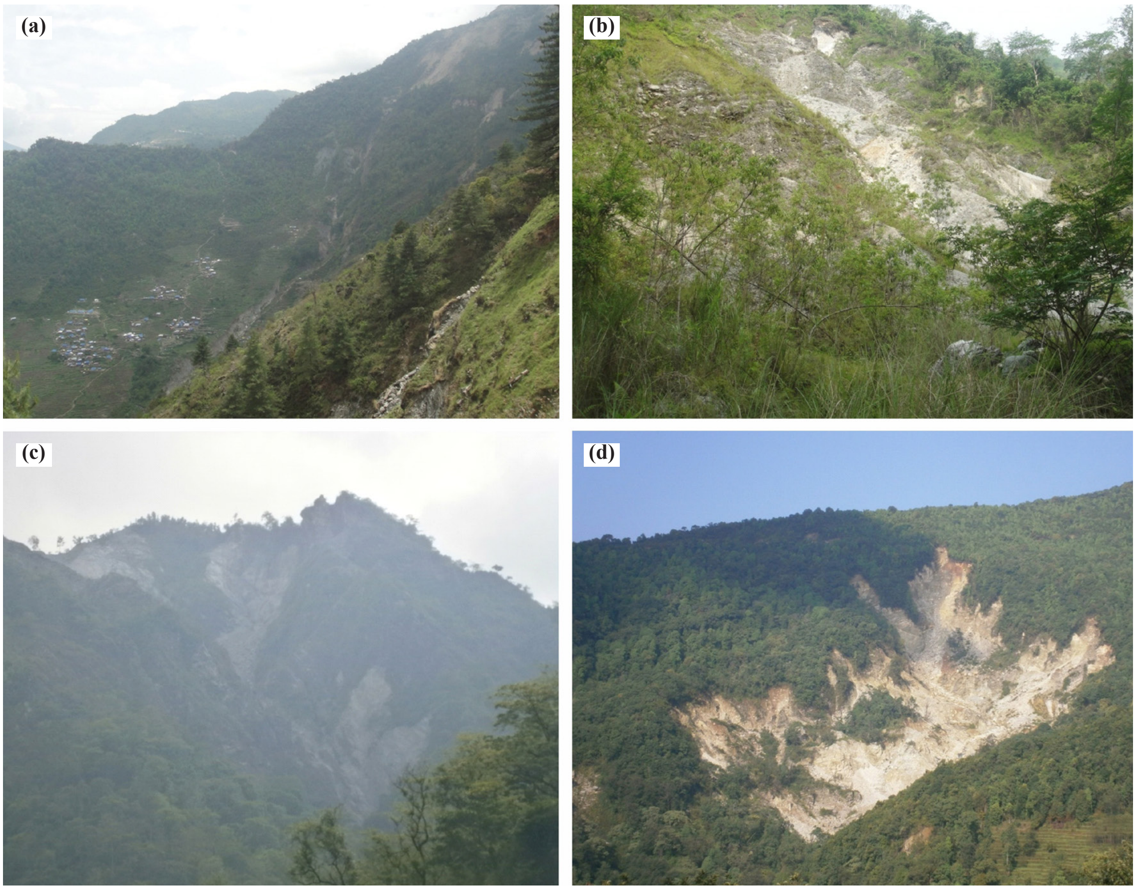


Fig. 7: Mostly medium sized landslides from central and western Nepal (a) Khanigaun landslide of Dharche, Gorkha, (b) from view the toe of the slide at Dharmpani, Tanahun, (c) reoccurring slide at Ghumaune near the confluence of Trishuli and Seti rivers, (d) affected area of Bhakadjung landslide, Kaski.

class (>65°) is high. Similarly, frequency distribution of large-scale landslides is high in slope class interval of 25° to 45° and relative density increases when the slope angle becomes steeper (Fig. 9a). The frequency distribution of cut-slope, small, medium, and large-scale landslides is higher at N–S and SE–S–SW directions and relative density is higher at same class of slope aspect respectively (Fig. 9b). Concave slope class has high frequency of cut-slopes and landslides but relative density shows similar distribution in concave and convex class shown in Figure 9c. Frequency distribution of cut-slopes and landslides is higher in 500 to 1500 m class which contradicts the relative density showing higher with increasing value of elevation class (Fig. 9d).

The cut-slopes and small slides have high frequency in the Lesser Himalaya Meta-sedimentary succession while medium and large-scale landslide has high distribution in Higher Himalaya Crystalline succession. The relative density is higher in Higher Himalaya Crystalline succession followed by igneous rock and the Siwalik Group shown in Figure 9d. The frequency distribution of cut-slopes and landslides is higher in forest and cropland having a higher relative density of landslides in grassland (Fig. 9f). Rainfall pattern shows 1600 to 1800 mm class has higher landslide frequency however the cut-slope shows a high frequency distribution in >2000 mm rainfall class. The relative density of landslides is higher at low rainfall and higher at high rainfall (Fig. 9g). The frequency distribution and relative density of cut-slopes, and landslides show higher at <0.2 g, 0.4–0.6 g, and 0.4–0.6 g PGA class respectively shown in Figure 9h.

The evaluation of scale dependency and spatial variability with major controlling factors of slope movement events illustrates not all factors contribute correspondingly. Slope angle, geology, land cover, and rainfall patterns assisted oppositely for scale dependency of the spatial distribution of slope movements from large-scale landslides to cut-slopes. Scale dependency is partially significant due to contributing effect of slope aspect and elevation factors. While the slope curvature and PGA factors show similar kinds of spatial variability of large-scale landslides to cut-slopes.

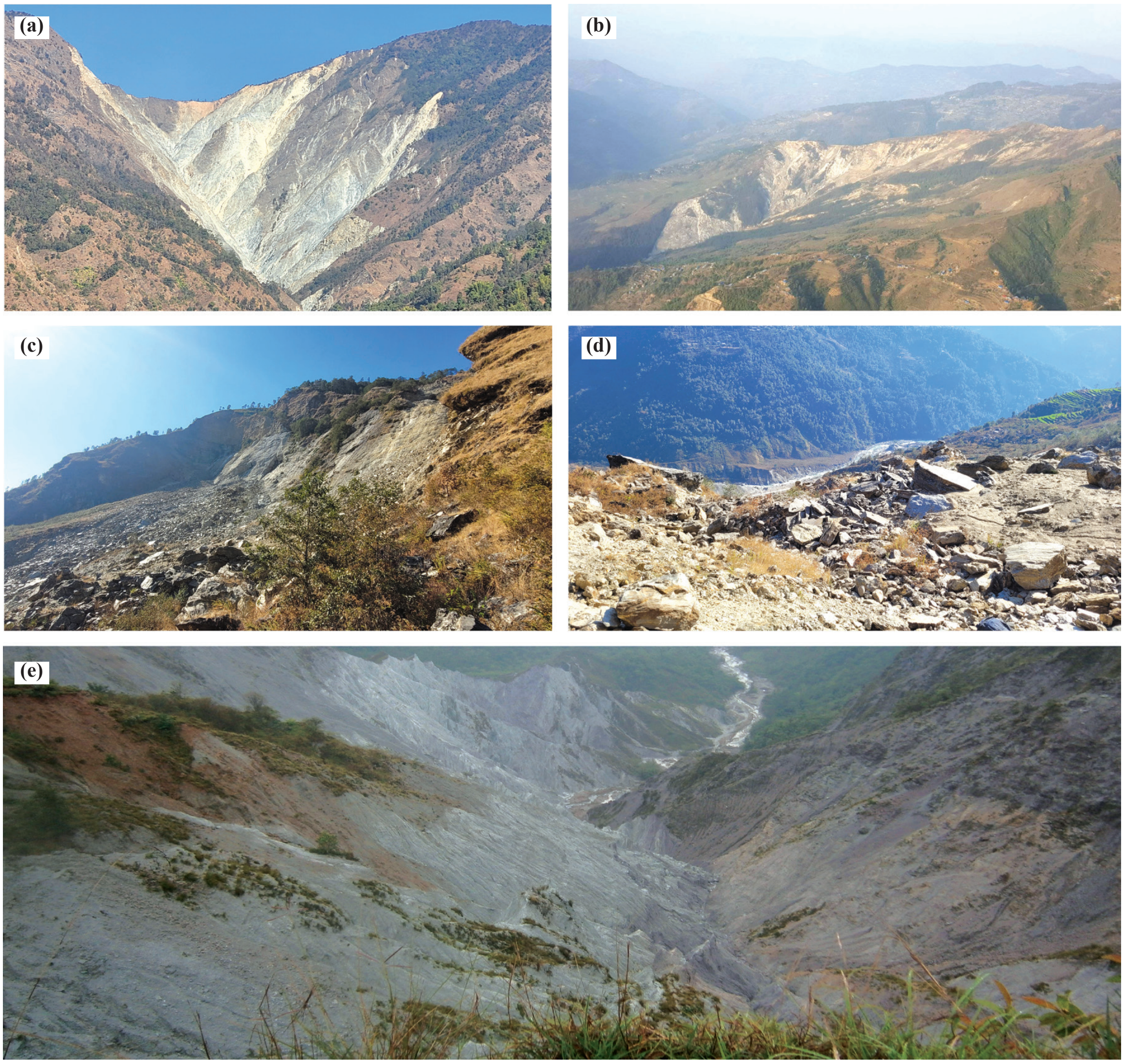
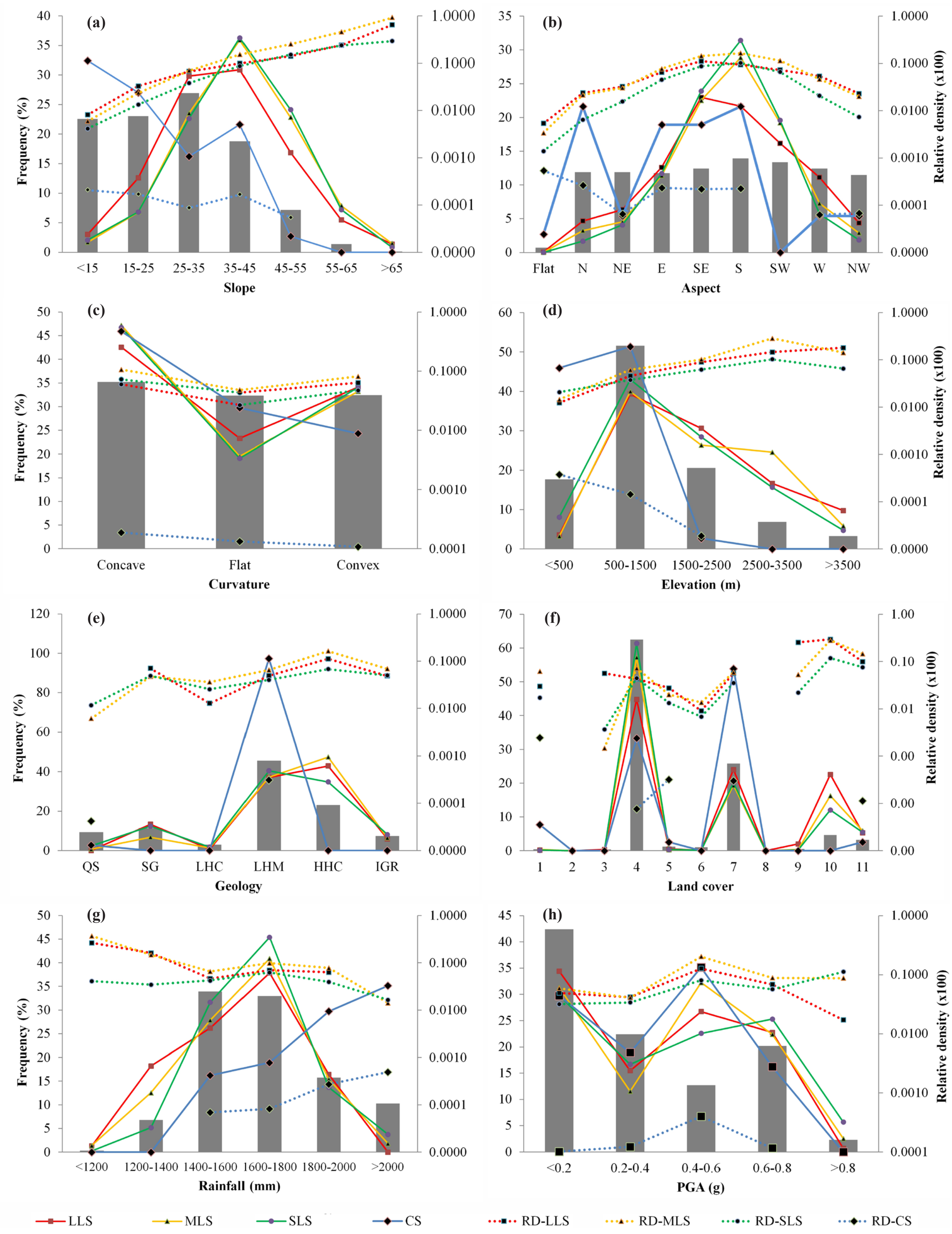


Fig. 8: Large-scale landslides from central and western Nepal (a) Gyapche Landslide near Manthali, Ramechhap, (b) aerial view of Dutti Landslide, Kavre, (c) head scarp and rock debris deposition at main body of Jure Landslide, Sindhupalchok, (d) huge rock boulders at main body section of Jure Landslide, (e) view of the overall area of Bhanjayang Landslide, Birgha-Archale of Syangja.



Note: Land cover classes; 1 – water body, 2 – glacier, 3 – snow, 4 – forest, 5 – riverbed, 6 – built-up area, 7 – cropland, 8 – bare soil, 9 – bare rock, 10 – grassland, 11 – shrubs.

Fig. 9: Frequency distribution and density plot of cut-slopes, small slides, medium and large-scale landslides with controlling factors (a) slope angle, (b) slope aspect, (c) slope curvature, (d) elevation, (e) geology, (f) land cover, (g) rainfall, (h) PGA.

CONCLUSION

This study has investigated the understanding on spatial variability of slope movements in the central and western Nepal Himalaya. The spatial variations of slope movements (landslides, cut-slopes) were evaluated in terms of eight conditioning factors. These factors include slope angle, slope aspect, slope curvature, elevation, lithology, land cover, rainfall, and peak ground acceleration (PGA). An evaluation of scale dependency in the spatial distribution of slope movements was extracted based on these contributing factors which indicated that the slope movement process is strongly influenced by the causative and trigger mechanisms for defining the characteristics of spatial variation. Small-scale landslides and cut-slope failures often occur due to basic change in equilibrium conditions whereas large-scale landslides may require a longer duration of cumulative effect of geo-hydrological conditions together with substantial effect of triggering factors such as heavy rainfall and/or earthquakes. The assessment of scale dependency and spatial variability with major controlling factors of slope movements have illustrated that each factor contribute individually or coupling influence of these factors. The geomorphological, geological, land cover, and rainstorms can contribute significant influence in the spatial localization of slope movements which are ranging from large-scale landslides to cut-slopes in the central and western Nepal Himalaya.

REFERENCES

Bruckl, E., 2001, Cause-effect models of large landslides. Natural hazards, v. 23(2), pp. 291–314.

Budimir, M. E. A., Atkinson, P. M., and Lewis, H. G., 2015, A systematic review of landslide probability mapping using logistic regression. Landslides, v. 12(3), pp. 419–436.

Burbank, D. W., 1982, The chronologic and stratigraphic evolution of the Kashimir and Peshwar intermontaine basins, northwest Himalaya. Dartmouth College, Hanover, NH, unpublished PhD dissertation.

Chalise, S. R. and Khanal, N. R., 2001, Rainfall and related natural disasters in Nepal. In: Tianchi, Li., Chalise, S. R., and Upreti, B. N. (eds.), Landslide hazards, mitigation to the Hindukush-Himalayas, ICIMOD, Kathmandu, pp. 63–70.

Chen, Z., Liang, S., Ke, Y., Yang, Z., and Zhao, H., 2017, Landslide susceptibility assessment using evidential belief function, certainty factor and frequency ratio model at Baxie River Basin, NW China. Geocarto International, v. 34(4), pp. 1–20.

Chung, M., Chen, C., Lee, C., Huang, W., and Tan, C. 2018, Failure impact assessment for large-scale landslides located near human settlement: Case study in southern Taiwan. Sustainability, v. 10, pp. 1491.

Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., and Pitilakis, K., 2014, Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and Environment, v. 73(2), pp. 209–263.

Cruden, D. M. and Varnes, D. J., 1996, Landslide types and processes. In: Turner A. T., Schuster R. L. (Eds.) Landslides investigation and mitigation. Transportation Research Board Special Report no. 247. National Academy Press, Washington, DC, pp. 36–75.

Dahal, R. K., Hasegawa, S., Nonomura, A., Yamanaka, M., Masuda, T., and Nishino, K., 2008, GIS-based weights of evidence modelling of rainfall-induced landslides in small catchments for landslide susceptibility mapping. Environmental Geology, v. 54(2), pp. 314–324.

Dahal, R. K., Hasegawa, S., Yamanaka, M., Bhandary, N. P., and Yatabe, R., 2010, Statistical and deterministic landslide hazard assessment in the Himalayas of Nepal. IAEG conference, pp. 1053–1060.

Dai, F. C. and Lee, C. F., 2002, Landslide characteristics and slope instability modeling using GIS, Lantau Island, Hong Kong. Geomorphology, v. 42(3), pp. 213–228.

de Terra, H. and Paterson, T. T., 1939, *Studies on the Ice Age in India*. Carnegie Institute, Washington, DC, 354 p.

Delgado, J., Garrido, J., López-Casado, C., Martino, S., and Peláez, J. A., 2011, On far field occurrence of seismically induced landslides. Engineering Geology, v. 123(3), pp. 204–213.

Demir, G., Aytekin, M., Akgün, A., İkizler, S. B., and Tatar, O., 2013, A comparison of landslide susceptibility mapping of the eastern part of the North Anatolian Fault Zone (Turkey) by likelihood frequency ratio and analytic hierarchy process methods. Natural Hazards, v. 65(3), pp. 1481–1506.

Devkota, K. C., Kim, G. W., Pradhan, A. M., Lee, J. H., and Kwon, H. J., 2010, Landslide Hazard Analysis in the Lesser Himalaya, Central Nepal. Proceedings of the Korean Society of Engineering Geology, pp. 8–9.

Dhital, M. R., 2015, *Geology of the Nepal Himalaya: Regional Perspective of the Classic Collided Orogen.* Springer International Publishing, Switzerland. In: Lesser Himalaya of Koshi Region, pp. 163–164.

Duncan, J. M., Wright, S. G., and Brandon, T. L., 2014, Soil strength and slope stability. Wiley, Hoboken.

Fort, M., 1987, Sporadic morphogenesis in a continental subduction setting: an example from the Annapurna Range, Nepal Himalaya. Z. Geomorphol., Neue Folge, v. 63, pp. 9–36.

García-Rodríguez, M. J., Malpica, J. A., and Benito, B., Díaz, M., 2008, Susceptibility assessment of earthquake-triggered landslides in El Salvador using logistic regression. Geomorphology, v. 95(3), pp. 172–191.

Ghobadi, M. H., Firuzi, M., and Noorzad, A., 2017, A large-scale landslide and related mechanism: a case study in the Qazvin-Rasht freeway, Iran. Environmental Earth Sciences, v. 76, pp. 478.

Goodman, R. E., 1980, *Introduction to Rock Mechanics*. Wiley, New York, 478 p.

Hasegawa, S., Dahal, R. K., Nishimura, T., Nonomura, A., Yamanaka, M., 2009, DEM based analysis of earthquake-induced shallow landslide susceptibility. Geotechnical and Geological Engineering, v. 27(3), pp. 419–430.

Heuberger, H., Masch, L., Preuss, E., and Schrocker, A., 1984, Quaternary landslides and rock fusion in central Nepal and in the Tyrolean Alps. Mountain Res. Dev., v. 4, pp. 345–362.

Hewitt, K., 1972, The mountain environment and geomorphic process. In: Slaymaker, H. O. and McPherson, H. J., (eds.), Mountain Geomorphology: Geomorphological Processes in the Canadian Cordillera. B. C. Geographical Ser. No. 14, Tantulus Res., Vancouver, pp. 17–34.

Hewitt, K., 1988, Catastrophic landslide deposits in the Karakoram Himalaya. Science, v. 242, pp. 64–77.

Hewitt, K., 1989, The altitudinal organization of Karakoram geomorphic processes and depositional environments. Z. Geomorphology, v. 76, pp. 9–32.

Hong, H., Pourghasemi, H. R., and Pourtaghi, Z. S., 2016, Landslide susceptibility assessment in Lianhua County (China): a comparison between a random forest data mining technique and bivariate and multivariate statistical models. Geomorphology, v. 259, pp. 105–118.

Huang, R. Q. and Li, W. L., 2008, Research on development and distribution rules of geohazards induced by Wenchuan earthquake on 12th May, 2008. Chinese Journal of Rock Mechanics and Engineering, v. 27(12), pp. 2585–2592. (In Chinese)

Huang, R. Q. and Li, W. L., 2009, Fault effect analysis of geo-hazard triggered by Wenchuan earthquake. Journal of Engineering Geology, v. 17(1), pp. 19–28. (In Chinese)

Hungr. O., leroueil, S., and Picarelli, L., 2014, The Varnes classification of landslide types, an update. Landslides. DOI: 10.1007/s10346-013-0436-y

Ibetsberger, H. J., 1996, The Tsergo Ri landslide: an uncommon area of high morphological activity in the Langthang valley, Nepal. Tectonophysics, v. 260, pp. 85–94.

ICIMOD, 2021, Land cover of Nepal 2019. Kathmandu, Nepal: ICIMOD. http://apps. geoportal.icimod. org/ ArcGIS/ rest/ services/ Nepal/ Landcover2 010/MapServer/0. Assessed 15 May 2023

Ilia, I. and Tsangaratos, P., 2016, Applying weight of evidence method and sensitivity analysis to produce a landslide susceptibility map. Landslides, v. 13, pp. 379–397.

Kamp, U., Growley, B. J., Khattak, G. A., and Owen, L. A., 2008, GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. Geomorphology, v. 101(4), pp. 631–642.

Keefer, D. K., 2002, Investigating landslides caused by earthquakes–a historical review. Surveys in Geophysics, v. 23(6), pp. 473–510.

Kuo, H. L., Lin, G. W., Chen, C. W., Saito, H., Lin, C. W., Chen, H., and Chao, W. A., 2018, Evaluating critical rainfall conditions for large-scale landslides by detecting event times from seismic records. Natural Hazards and Earth System Sciences, v. 18, pp. 2877–2891.

Li, L., Xu, C., Yao, X., Shao, B., Ouyang, J., Zhang, Z., and Huang, Y., 2022, Large-scale landslides around the reservoir area of Baihetan hydropower station in Southwest China: Analysis of the spatial distribution. Natural Hazards Research, v. 2, pp. 218–229.

Lin, M., Chen, T., Lin, C., Ho, D., Cheng, K., Yin, H., and Chen, M., 2013, Detecting large-scale landslides using lidar data and aerial photos in the Namasha-Liuoguey area, Taiwan. Remote Sensing, v. 6, pp. 42–63.

Meusburger, K. and Alewell, C., 2008, Impacts of anthropogenic and environmental factors on the occurrence of shallow landslides in an alpine catchment (Urseren Valley, Switzerland). Natural Hazard, v. 8, pp. 509–520.

Montgomery, D. R., Schmidt, K. M., Greenberg, H. M., and Dietrich, W. E., 2000, Forest clearing and regional landsliding. Geology, v. 28(4), pp. 311–314.

Nepal, N., Chen, J., Chen, H., Wang, X., and Sharma T. P., 2019, Assessment of landslide susceptibility along the Araniko Highway in Poiqu/Bhote Koshi/Sun Koshi Watershed, Nepal Himalaya. Progress in Disaster Science, v. 3, pp. 1–10.

OCHA, 2015, Nepal total annual rainfall distribution, 2015. https://data.humdata.org/dataset/nepal-historical-annual-and-monthly-rainfall-distribution-for-monsoon-months?. Assessed 10 April 2023.

Owen, L. A., Kamp, U., Khattak, G. A., Harp, E. L., Keefer, D. K., and Bauer, M. A., 2008, Landslides triggered by the 8 October 2005 Kashmir earthquake. Geomorphology, v. 94(1), pp. 1–9.

Pathak, D., 2016, Knowledge based landslide susceptibility mapping in the Himalayas. Geoenvironmental Disasters, v. 3(1), pp. 8.

Pellicani, R., Van Westen, C. J., and Spilotro, G., 2014, Assessing landslide exposure in areas with limited landslide information. Landslides, v. 11, pp. 463–480.

Phuyal, B., Thapa, P. B., and Devkota, K. C., 2022, Characterization of large-scale landslides and their susceptibility evaluation in central Nepal Himalaya. Journal of Nepal Geological Society, v. 63, pp. 109–122.

Regmi, A. D., Devkota, K. C., Yoshida, K., Pradhan, B., Pourghasemi, H. R., Kumamoto, T., and Akgun, A., 2013, Application of frequency ratio, statistical index, and weights of evidence models and their comparison in landslide susceptibility mapping in Central Nepal Himalaya. Arabian Journal of Geosciences, v. 7(2), pp. 725–742.

Regmi, A. D., Kohki, Y., Dhital, M. R., and Devkota, K. C., 2012, Effect of rock weathering, clay mineralogy, and geological structures in the formation of large landslide, a case study from Dumre Besei landslide, Lesser Himalaya, Nepal. Landslides, v. 9(2), pp. 1–13.

Schmidt, K. M. and Montgomery, D. R., 1995, Limits to relief. Science, v. 270, pp. 617–620.

Shang, Y., Yang, Z., Li, L., Liu, D., Liao, Q., and Wang, Y., 2003, A super large landslide in Tibet in 2000: background, occurrence, disaster, and origin. Engineering Geology, v. 54, pp. 225–243.

Shroder, J. F. and Bishop, M. P., 1998, Mass movement in the Himalaya: new insights and research directions. Geomorphology, v. 26, pp. 13–35.

Spray, J.G., 1997, Superfaults. Geology, v. 25, pp. 579–582.

Thapa, P. B., 2011, Landslide susceptibility modelling in the central Nepal Lesser Himalaya. Jour. of Appl. Reg. Geol. (ZDGG), v. 162(4), pp. 405–420.

Timilsina, M., Bhandary, N. P., Dahal, R. K., and Yatabe, R., 2012, Typical morphometric and geological characteristics of largescale landslides in central Nepal. Jour. Nepal Geol. Soc., v. 44, pp. 45–58.

USGS, 2015, United States Geological Survey's Shake map of M7.8–36 km E of Khudi. Nepal. https:// earth quake. usgs. gov/ earth quakes/ event page/us200 02926/ shake map/ pga. Assessed 11 April 2023

Varnes, D. J., 1978, Slope movement types and processes. In: Schuster, R. L. and Krizek, R. J. (eds.), Special Report 176: Landslides: Analysis and Control. Transportation and Road Research Board, National Academy of Science, Washington D. C., pp. 11–33.

Weidinger, J. T. and Schramm, J. M., 1995, A short note on the Tsergo Ri landslide, Langtang Himal, Nepal. Jour. Nepal Geol. Soc., v. 11 (Sp. Issue), pp. 281–287.

Weidinger, J. T., Schramm, J. M., and Surenian, R., 1996, On preparatory causal factors, initiating the prehistoric Tsergo Ri land-slide Langtang Himal, Nepal. Tectonophysics, v. 260, pp. 95–107.

Wen, B. and Chen, H., 2007, Mineral compositions and elements concentrations as indicators for the role of groundwater in the development of landslide slip zones: a case study of large-scale landslides in the Three Gorges Area in China. Earth Science Frontiers, v. 14(6), pp. 98–106.

Wilson, A. J., Petley, D. N., and Murphy, W., 2003, Down-slope variation in geotechnical parameters and pore fluid control on a large-scale Alpine landslide. Geomorphology, v. 54, pp. 49–62.

WP/WLI, 1993, A suggested method for describing the activity of a landslide. Bulletin of the International Association of Engineering Geology, v. 47, pp. 53–57.

Xu, C. and Xu, X., 2012, Comment on "Spatial distribution analysis of landslides triggered by 2008.5. 12 Wenchuan Earthquake, China. In: Qi, S., Xu, Q., Lan, H., Zhang, B., and Liu, J. (eds.), Engineering Geology, v. 133, pp. 40–42.

Xu, Q., Zhang, S., and Li, W., 2011, Spatial distribution of large-scale landslides induced by the 5.12 wenchuan earthquake. Journal of Mountain Sciences, v. 8, pp. 246–260.

Yalcin, A., Reis, S., Aydinoglu, A. C., and Yomralioglu, T., 2011, A GIS-based comparative study of frequency ratio, analytical hierarchy process, bivariate statistics and logistics regression methods for landslide susceptibility mapping in Trabzon, NE Turkey. Catena, v. 85, pp. 274–287.

Zerathe, S., Lebourg, T., Braucher, R., and Bourles, D., 2014, Mid-Holocene cluster of large-scale landslides revealed in the Southwestern Alps by 36CI dating. Insight on an Alpine-scale landslide activity. Quaternary Science Reviews, v. 90, pp. 106–127.

Zhao, B., Wang, Y., Luo, Y., Liang, R., Li, J., and Xie, L., 2019, Large landslides at the northeastern margin of the Bayan Har Block, Tibetan Plateau, China. Royal Society open science, v. 6(180844). DOI: 10.1098/rsos.180844

Zhou, X. P. and Cheng, H., 2015, The long-term stability analysis of 3D creeping slopes using the displacement-based rigorous limit equilibrium method. Engineering Geology, v. 195, pp. 292–300.