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Towards Understanding of Lanta Khola Landslide in Sikkim Himalayas

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ABSTRACT: In the Indian state of Sikkim, the North Sikkim Highway (NSH) has a sector that is prone to landslides. The road transects the geological contact between mica schists of the Lesser Himalayan Sequence (LHS) and quartzofeldspathic gneisses of the Higher Himalayan Crystalline Sequence (HHCS), which is a major Himalayan discontinuity called the Main Central Thrust. The MCT zone is a ductile shear zone characterized by a consistently oriented schistosity and grain-size reduction of the sheared rocks. Site-specific studies at the Lanta Khola slide, located on the contact zone, show that weathering of the contact zone leads to debris production with an increased silt fraction. This zone (called the soggy zone) is water saturated, but is mineralogically identical to the debris in other parts of the slide. Direct shear tests show that the soggy zone debris has lower shear strength, but the increased silt fraction reduces the permeability and is responsible for its higher water content. The resulting increase in pore pressure in this zone makes it increasingly susceptible to failure. Since the zone nucleates at the base of the gneisses of the HHCS, the zone parallels the geological foliation and ‘daylights’ along suitably oriented slopes. Material is extruded laterally from within this zone and subsequently moves downslope. Material removal is responsible for widespread sinking of the NSH road stretch along which the gneiss-schist contact (the MCT zone) is exposed.

1 Introduction

Landslides are major hazards in mountainous regions, as relief and mechanically degraded masses together make slopes vulnerable to frequent failure. Himalayan regions, characterized by extremely steep and rugged slopes, are naturally prone to landsliding. Additional natural and anthropogenic factors, such as high rainfall (e.g. Lama, 2001), and unplanned urbanization (e.g. Schuster, 1996; Ercanoglu and Gokceoglu, 2004), have contributed to make some populated Himalayan domains critically susceptible to landslides. A number of landslide susceptibility zonation studies (after Varnes, 1984) have therefore been conducted in Himalayan regions to identify vulnerable areas within these domains, and probabilistic models have been proposed. These models are largely based on construction and superimposition of thematic maps that supposedly correspond to contributing causative factors, and are interpreted either manually (e.g. Anbalagan, 1992; Pachauri and Pant, 1992; Gupta et al., 1993; Sarkar et al., 1995; Mehrotra et al., 1996; Virdi et al., 1997) or by GIS-based techniques (Gupta and Joshi, 1990; van Westen, 1994; Nagarajan et al., 1998; Gupta, 2003; Kanungo et al., 2006). A prior knowledge of the causative factors is an essential pre-requisite to the applicability of these models, and their validity is subject to the quality of the database that exists on the area.

This study aims at contributing to the generation of such a database in the landslide prone north-east Indian state of Sikkim, along a vital arterial road called the North Sikkim Highway (NSH). The NSH is a connector between the capital Gangtok and the Chinese border, and any major blockage is critical for both the civilian and military population. A number of landslides of varying dimension occur along the NSH, but the largest slides occur most prominently along a specific stretch of the road between the villages of Mangan and Myang. In this study, we utilize geological data to identify the cause for nucleation of landslides within this stretch of the NSH, and document the evolution of a particular slide, called Lanta Khola, within the affected zone before and after the monsoon period. The study demonstrates how regional and local factors contribute to slope instability, and emphasizes the need to ascertain the domains within which probabilistic models can be realistically applied.

2 Geology of the Region

The north-east Indian state of Sikkim (Fig. 1) lies entirely within the Himalayas, and is dominated by two major litho-tectonic units, the Higher Himalayan Crystalline Sequence and the Lesser Himalayan Sequence, that are separated by a major ductile shear zone called the Main Central Thrust (MCT). The Higher Himalayan Crystalline Sequence (HHCS) consists of quartzofeldspathic gneisses of both igneous and sedimentary parentage that suffered high grade amphibolite and granulite facies metamorphism (Neogi et al., 1998; Catlos et al., 2001; Dasgupta et al., 2004). The Lesser Himalayan Crystalline Sequence (LHCS), locally referred to as the Daling Group (Acharyya, 1989), is dominated by garnet-biotite-mica schists and chlorite schists in the upper part, and slates and phyllites in the lower part.

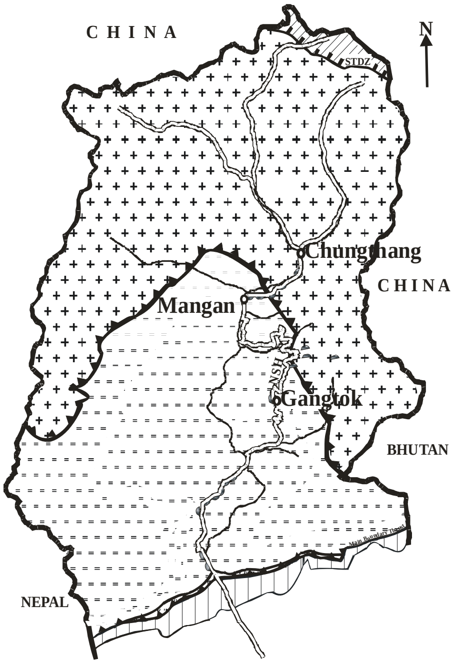


Figure 1. Map of Sikkim.

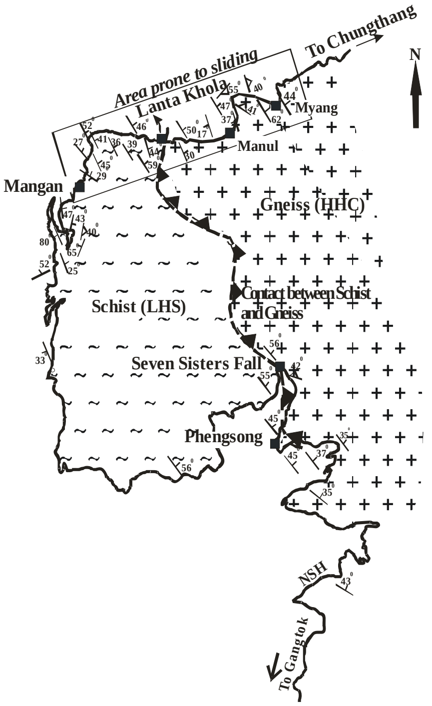


Figure 2. Study Area.

The North Sikkim Highway (NSH) from Gangtok to Chungthang cuts across the Main Central Thrust, from within the LHCS to the HHCS (Fig. 2). The contact between the gneisses and schists intersects the NSH at two locations (Fig. 2): in the vicinity of the Seven Sisters Fall, and in the locality of the Lanta Khola slide. The most prominent sinking/slide zone on the NSH occurs around the latter, while the former is a stable zone with no associated sliding.

Superposition of landslide locations on the geological map of the NSH reveals an almost perfect correlation between the slide-prone zone and the ductile shear zone representing the MCT. A large number of slides occur within this zone, which is characterized by widespread sinking leading to road collapse, and slope failure involving both rock and debris flow. In any particular location, sliding appears to involve an initial phase of rock fall parallel to the MCT foliation and the generation of large boulders. Rock disintegration by mechanical failure and also weathering in the presence of water, leads to the generation of debris which progressively engulfs the diminishing boulder, cobble and pebble fraction. Ultimately, in fully evolved landslides, the larger size fraction is passively enclosed within sand, silt and clay-sized debris material. Following heavy rainfall that typifies the monsoon season, this water charged debris becomes extremely mobile, and represents the main danger to the road in the monsoon aftermath.

We have conducted site-specific studies on one of the major debris flows in the affected zone, referred to as the Lanta Khola slide. The objective was to ascertain, on a preliminary basis, the nature of the slide material, the strength of the debris, and the effect of the monsoon rainfall on the debris zone through a series of geotechnical tests.

3 The Lanta Khola Slide

The Lanta Khola slide is located 72 km from Gangtok on the North Sikkim Highway. Geological mapping indicates that the contact between the HHCS and the LHS passes through the body of the slide itself (Fig. 2). Lanta Khola, is a predominantly debris slide that is prone to mass movement. In 1975, the area developed into a sinking zone (Verma, 1984). The principal causative factor for instability was considered to be the erosion during heavy discharge especially in the monsoon period (Verma, 1984). The heterogeneous, non-cohesive soil and boulders were carried down along the valley bed with such a momentum that after each heavy shower, the road bench along with the culvert was washed away. The old and small subsidence areas along the Lanta Khola road bench have subsequently evolved into one of the largest destabilized zones on NSH, affecting a 200 m long stretch of road bench in 1983. This devastation had been caused by the high velocity surface run off due to the intense and heavy precipitation on the 10th and 11th September 1983 (Verma, 1984). It was reported that on an average, a 10m deep and 150m wide scar extended down to the Tista River along the Lanta Khola. The crown of the scar in 1983 had reached to a height of about 196m above the road level. But since 1999, it has again become severely active after modifying its shape and dimension causing long period of roadblocks during monsoon time. Due to sliding in 2001, the NSH at Lanta Khola was blocked in phases for 54 days.

The width of the Lanta Khola slide is around 50 to 70 meters, but has a longitudinal extent of over 900 meters with an average surface slope (of the debris material) of only around 24° (Fig. 3). The slide has been surveyed several times over a period of 3 years during the course of this study. At present, the crown is located at a height of 1650 m, while the toe occurs close to the Tista River. The sides of the slide are sharp and marked by prominent scarps (Fig. 4a); the height of these side scarps decreases upslope and becomes negligible near the crown. The road bench is located at a height of 1375 m; natural benches are also located at heights of 1495 m and 1610 m. An outcrop of biotite schist (i.e. sheared Lingtse gneiss) underlain by amphibolite is exposed within the debris material near the head of the slide; the lower boundary of the outcrop descends to a height of 1590 m. The outcrop is roughly elliptical in shape. The penetrative fabric within the outcrop has a NW-SE trending, northeasterly dipping attitude consistent with the foliation in the MCT zone. On the northwestern side of the outcrop is a water-saturated debris zone, where the ground is extremely soggy. This 'soggy zone' is about 10 meters wide on the surface, and parallels the trend of the outcrop on the slide slope. Below the soggy zone, the debris material has greater consistency and contains comparatively less water. Importantly, surface run-off is absent within the soggy zone itself, but the lower part of the slide is characterized by a number of anatomising streams.

The debris material above the outcrop zone in the upper part of the slide is largely vegetated (Fig. 4b) suggesting partial stabilization after initial movement, while repeated reactivation of the lower reaches, especially above the road bench, is responsible for the barren nature of the surface in this part of the slide. The abnormally low width to length ratio, and the phases of rapid movement that occur in spite of the low surface slope make the Lanta Khola slide particularly interesting.

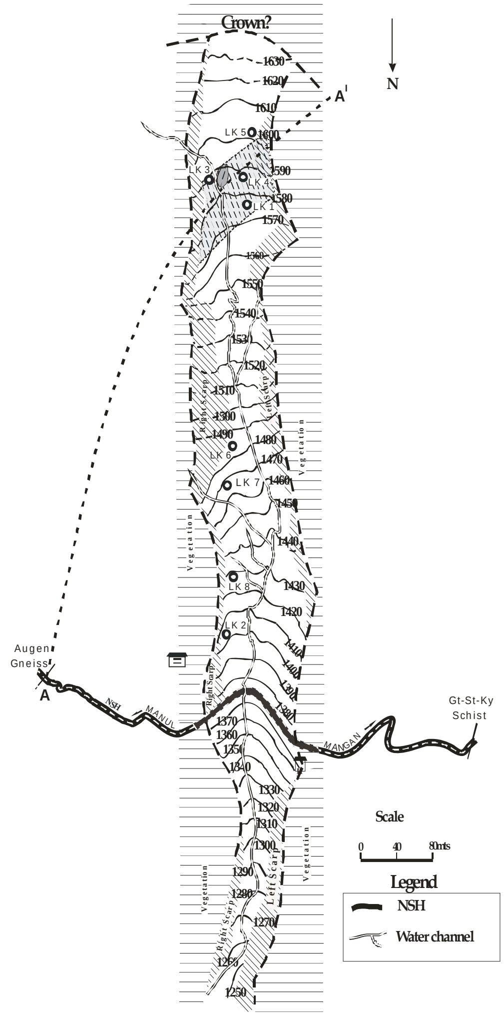
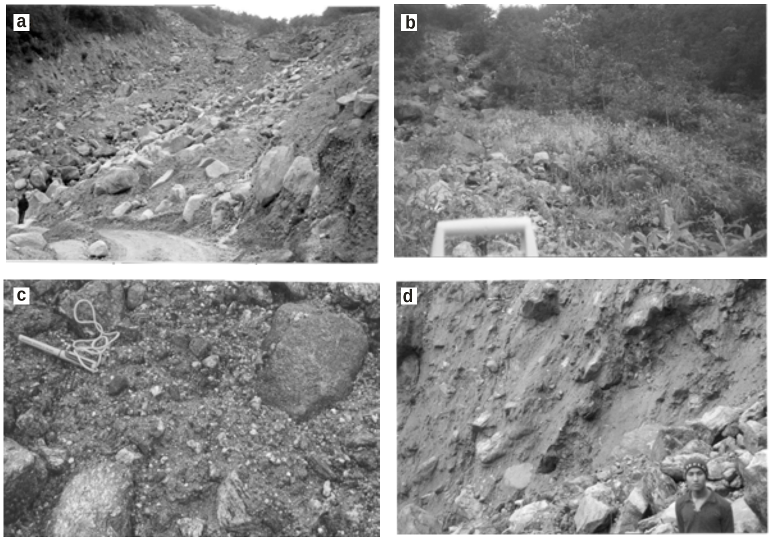


Figure 3. Surveyed Map of the Lanta Khola Slide.



(a) slide just above the road level; (b) slide above rock outcrop; (c) fine debris material from soggy zone; (d) typical debris materials present at Lanta Khola.

Figure 4. Slide Materials at Lanta Khola.

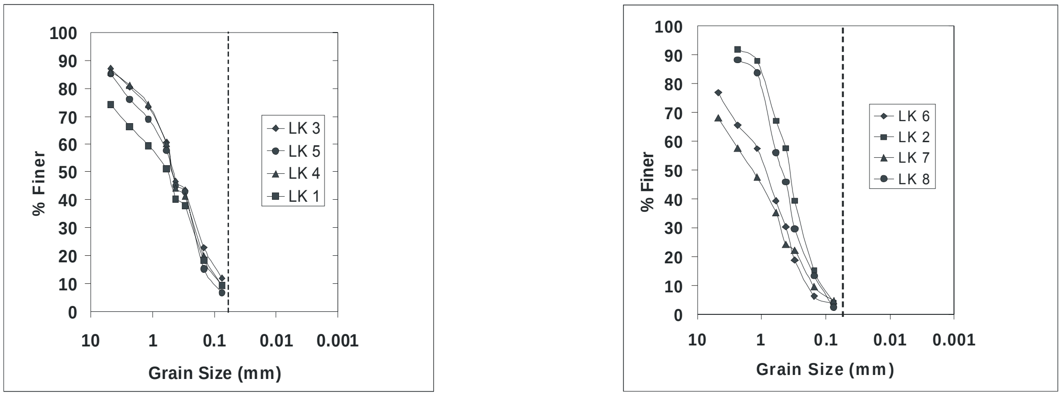
4 The Slide Materials

The slide materials at the Lanta Khola occur in a variety of grain sizes including boulders, cobbles, pebbles and granules, along with slurry/fine masses. The upper part of the slide (Fig. 4b) has a higher proportion of boulders, while pebbles and fines (Fig. 4c) show an increase towards the road bench and the toe. This can be attributed to the removal of fines from the upper part of the slide, and their accumulation in the vicinity of the road bench. Within the most mobile part of the slide boulders, cobbles, pebbles and granules are suspended/embedded within the slurry and fine mass (Fig. 4c); this implies that the movement of the slide is controlled by the strength of the finer matrix, rather than the coarser fraction. Compositionally, the slide material is of three types (Fig. 4d). Most of the boulders are gneissic in nature. The smaller size ranges include fragments of garnet-staurolite-kyanite schist, quartzofeldspathic gneiss and mafics (amphibolites). Garnet-staurolite-kyanite pebbles that occur in the debris along with the gneisses indicate that rocks from both the HHCS and the LHS are present within the landslide. This conforms to the inference from geological mapping that the contact between the HHCS and the LHS passes through the body of the slide at this location. A more precise control on the location of the geological contact between the HHCS and the LHS within the body of the slide has been established through analysis of the debris material. Biotite, quartz and muscovite are constituents common to the Lingtse augen gneiss (of the HHCS) as well as the mica schists of the LHS, and therefore, these components within the debris may have been derived from either or both units. However, kyanite and staurolite are restricted to the metapelites of the LHS and do not occur within the augen gneiss and amphibolite unit immediately overlying the pelitic rocks. The line AA’ on the surveyed map (Fig. 3) discriminates between debris samples that contain, and those that are devoid of, kyanite and / or staurolite. It can be inferred, therefore, that this line demarcates the boundary between LHS and the HHCS within the slide itself, and that the geological contact must pass from below the debris in this zone. Interestingly, the single outcrop of sheared HHCS rocks within the slide lies immediately to the right of the inferred contact, thereby confirming that the contact indeed passes through the Lanta Khola slide, close to the crown.

5 Geotechnical Studies of the Slide Materials

Geotechnical studies have been conducted on the slide materials collected from various levels of the slide, extending from the head to the toe. The samples were analyzed to constrain composition, water content, permeability, particle size and shear strength. Compositionally, all the debris samples contained similar phases derived from the Lingtse augen gneiss, amphibolite and garnet-staurolite-kyanite schist. The water content, however, varied for the different samples. Samples from the lower part of the slide contain about 17% water, while augen-gneiss derived debris contain around 30%. The samples collected from the soggy zone show the highest water content (68%); this includes both the amphibole-dominated debris derived from the HHCS, as well as the kyanite / staurolite bearing sample inferred to be from the LHS unit.

In the lower active part of the slide (above and below the road bench) coarser fragments including boulders are suspended within finer material, indicating that the strength of the slide mass is largely controlled by the finer fraction within the generated debris. A number of geotechnical tests on this fraction of the debris material have been performed to characterize materials and their strength. Initially, eight representative debris samples were collected from within the sliding zone, and grain-size distributions were determined for these samples. Typical particle size curves are shown in Fig. 5. The curves reveal that the sliding material is generally coarse to fine sand and some silt, with a larger fraction comprising cobbles, gravels and boulders. Samples from within the soggy zone show higher silt fraction (> 5%) compared to those from the lower part of the slide. The finer fraction in the samples from the lower part of the slide may be somewhat over-estimated, since gravels and boulders that occur as suspended fraction within the sandy matrix in these samples, could not be collected.

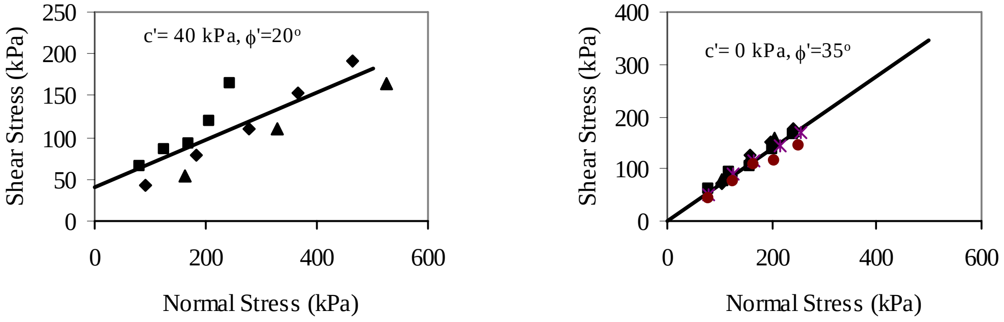


For the Materials from the Lower Portion.

For the Materials from the Soggy Zone.

Figure 5. Grain Size Distribution of the Slide Materials.

In order to determine the shear strength (c, cohesion and ϕ, friction angle) of the sliding materials, direct shear tests were performed on the representative soil samples collected from the Lanta Khola slide. Seven sets of samples were tested during the study. The results of the direct shear tests are shown in Figs. 6**.** As may be seen from the figures, the samples from the soggy zone have an average shear strength of ϕ = 20°, while those from the lower part of the slide have ϕ = 35°. In addition, samples from the soggy zone have small but finite cohesion (40 kPa), while in samples from outside this zone, cohesion is negligible. In general, it is clear that the soggy zone samples have lower shear strength, and a small but finite cohesion.



For the Materials from the Soggy Zone

For the Materials from the Lower Portion

Figure 6. Shear Strength of the Slide Materials.

6 Slope Stability Analyses

The slope stability analyses of a representative cross section of the Lanta khola slide was performed using a computer program UTEXAS2 (Edris & Wright, 1992). The Bishop's method of limit analysis was adopted. The strengths of the slide materials utilized in the analyses are shown in Fig. 6. The results of the stability analyses are shown graphically in Fig. 7. The results of the stability analyses show clearly that the sliding shall initiate in the so called soggy zone located along the gneiss-schist contact.

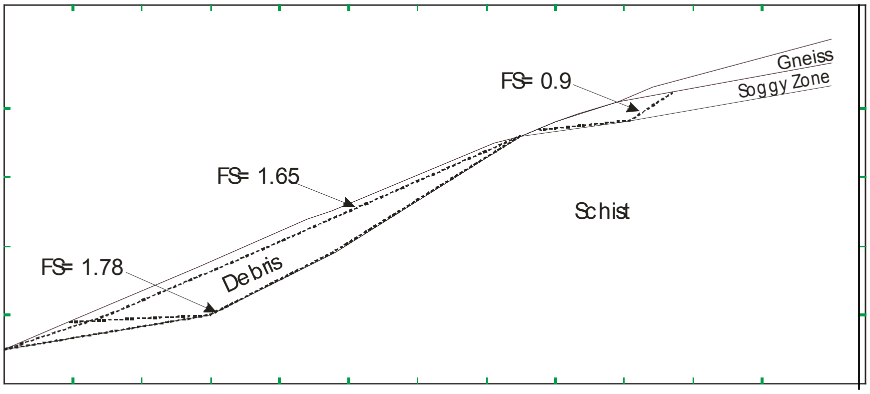


Figure 7. Results of the Slope Stability Analyses.

7 Discussion

7.1 Controls on slide initiation – significance of the soggy zone

Comparison of the survey maps of the Lanta Khola slide prepared between 2002 and 2006 reveals that there has been considerable modification of the main body of the slide, as well as the slide surface, in the period between the surveys. The major changes have involved depletion of material following slide movement, and periodic change in the surface slope. However, in each case, it is observed that slide movement and surface slope modification occurred only from below a height of 1560 metres, the base of the so-called 'soggy zone'. The soggy zone therefore, can be suspected to be involved in slide movement, but the reasons for the differing behaviour of the debris in this zone are not immediately obvious. The only observed physical difference between the soggy zone material and other debris is with respect to particle size; the soggy zone has a larger proportion (9 - 12 %) of silt-sized material. It is possible that the increased fines content leads to a significant decrease in strength, with the collapse potential increasing due to a reduction in intergranular contacts between the coarse grains. This is consistent with the observations in the present study, where the soggy zone material has lower shear strength than the debris in other parts of the slide, with a distinctly lower Φ value (20°). The material in this zone, therefore, is inherently susceptible to failure, and accordingly, has a lower factor of safety.

There are additional factors that affect the strength of debris in the soggy zone. The soggy zone is primarily characterized by its higher water content. This may be attributed to the decrease in grain-size, which leads to a corresponding decrease in the permeability of the material. Permeability tests on the debris samples show a significantly lower permeability for the soggy zone samples. The permeability in soggy zone samples is around 10^{-4} cm/s, while those for the other debris are usually higher by an order of magnitude (10^{-3} cm/s). The lower permeability results in a significant increase in the water content in the soggy zone, which therefore becomes fully saturated. This leads to an increase in the pore pressure within the soggy zone; dissipation of this excess pore pressure in low permeability materials is slow, thereby creating conditions of undrained loading. In this situation, the normal stress that resists movement is unchanged, but the shear stress, that drives movement, is increased, thereby lowering the factor of safety and increasing the likelihood of slope failure (e.g. Wilson et al., 2003). We therefore consider the soggy zone to be of pivotal importance during the process of slide activation.

7.2 Role of the soggy zone during slide movement

As is apparent from this study, the soggy zone is localized along the contact between the augen gneiss (i.e. Lingtse Gneiss) of the HHCS and garnet-staurolite-kyanite bearing mica schists of the LHS. The geological contact is a high strain ductile shear zone characterized by a strong preferred orientation of mica (i.e. muscovite and biotite) and grain-size reduction of the quartz and feldspar. Following weathering and disintegration, therefore, the derived debris also has an increased proportion of finer-grained particles, which, as outlined before, is responsible for the decreased strength and permeability.

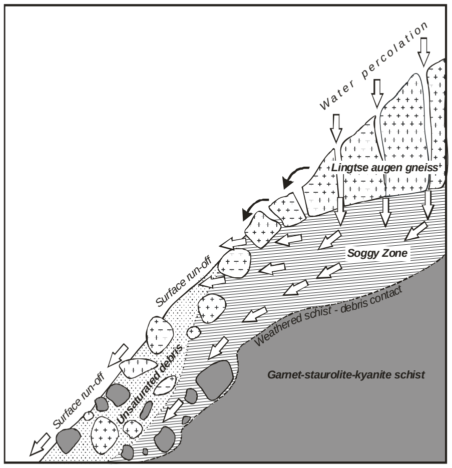


Figure 8. Slide Mechanism.

The manner in which the slide is activated is visualized in the schematic cross-section shown in Fig. 8. The soggy zone is overlain by the Lingtse augen gneiss of the HHCS. This is a crystalline, highly impermeable rock through which water can only percolate through fractures (i.e. joints), or as surface run-off. The water percolates into the debris zone at the contact, which is relatively impermeable and becomes saturated, leading to an increase in pore pressure. This, in turn, causes loss of strength and subsequent failure. Since the soggy zone forms in the ductile shear zone at the interface between the gneiss and the schist, the zone itself would also naturally follow the orientation of the lithocontact. Following the structural trends of the lithologies, this contact ‘daylights’. Where the soggy zone intersects the surface, the bulk of the water is channelled into surface run-off, but a part is in all probability also channelled into the base of the accumulated debris, following a pathway dictated by finer-grained layers along the sheared base of the moving debris.

An implication of the present model is that slide movement at Lanta Khola is dictated by the collapse of the soggy zone, and material from this region is extruded downslope from the point of intersection with the surface. As a consequence, material is consistently removed from within the soggy zone and transported downslope as slide debris. Mass depletion leads to volume reduction within the soggy zone, causing subsidence under the weight of the overlying rock overburden. This causes instability in the overlying Lingtse gneiss unit, and blocks of the gneiss collapse onto, and is ultimately incorporated within, the debris of the slide. It is conceivable that the collapse of these blocks onto the slide may lead to further grain-size reduction in the soggy zone. Most of the slide debris is therefore derived from the soggy zone and underlying mica schists of the LHS, while the boulders and larger fragments are dominantly derived from the Lingtse gneiss unit of the HHCS. This explains the lithological composition of both coarser and finer components of the slide debris.

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