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Mechanism of activation of the Lanta Khola landslide in Sikkim Himalayas

Abstract The Lanta Khola is a major landslide on the North Sikkim Highway in the Indian state of Sikkim. The abnormally low width-to-length ratio and slope instability in spite of the gentle surface slope (24°) make this slide unique. Geological, geophysical, and geotechnical studies reveal that a major Himalayan discontinuity daylights within the slide. At the contact, the schist is weathered to fine sand and silt with lower shear strength and permeability. The overlying gneiss is less weathered and exposed at the contact. Surface runoff enters the contact zone through crevices in the overlying gneiss, and debris material is extruded laterally from within this zone rendering instability, with blocks collapsing and eventually rolling down the slope after cloud bursts. Numerical modeling of the slide confirms this mechanism of instability. Diversion of runoff, plugging of crevices, and construction of pipe piles and horizontal drains are suggested as remedial measures.

Keywords Landslides · Sikkim Himalayas · Geology · Site investigation · Numerical analysis

Introduction

In Himalayan regions, characterized by extremely steep and rugged slopes, landslides are a major hazard. Very few site-specific studies have been conducted on landslides in these regions because of the very difficult terrain, though a number of landslide susceptibility zonation studies have been carried out to identify the vulnerable areas. These studies mostly include 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) or by geographic information system-based techniques (Gupta and Joshi 1990; Nagarajan et al. 1998; Kanungo et al. 2006). Some of the factors identified to be responsible for landsliding in the Himalayas are steep slopes, toe erosion by rivers, heavy rainfall, loss of vegetation, mining, and unplanned urbanization.

At the Lanta Khola landslide, located on a vital arterial road called the North Sikkim Highway (NSH) in Sikkim, India, the above causes are either absent or clearly do not contribute to sliding. The Lanta Khola landslide has a gentle surface slope. Since the nearest stream/river is located at a significant distance from the main slide body, toe erosion can be ruled out. The slide area is not densely populated, with the towns on either side being more than 2 km away; anthropogenic control is therefore unlikely. Though the middle portion of the slide, on which the road is located, is barren due to continuous movement of debris materials, the sides, the crown, and the toe of the slide are very densely vegetated. There is, however, some correlation between the amount of rainfall and slide movement (Sengupta et al. 2009); the area receives very high rainfall, and slide activity is characteristically triggered in the monsoon season, usually only after cloud bursts.

Several preventive measures (Fig. 1) had been adopted at different times in the past since the activation of the slide. These included construction of gabion walls, benches along the slide, surface chutes to drain the surface runoff, etc. However, none of these preventive measures survived for more than one monsoon season.

In view of this record, a comprehensive study was recently undertaken to find out the cause for the activation of this landslide and to monitor the landslide. The study includes geological, geotechnical, and geophysical investigations. This paper presents these field and laboratory studies, and the conclusions are derived from these studies.

The Lanta Khola slide

The Lanta Khola slide (Figs. 2 and 3) is located 71.2 km from Gangtok on the NSH in Sikkim, India. It is a predominantly debris slide that is prone to mass movement. In 1966, the area developed into a sinking zone (Verma 1984). The subsidence area along the Lanta Khola road bench has subsequently evolved into one of the largest destabilized zones on the NSH. Following heavy rainfall on 10th and 11th September 1983, heterogeneous, noncohesive soil and boulders were carried down along the valley bed with such a momentum that a 200-m-long stretch of road bench along with the culvert was washed away, forming a 10-m-deep and 150-m-wide scar along the Lanta Khola. The crown of the scar was then located 196 m above the road level. After remaining dormant for a few years, the slide has again become severely active since 1998, causing periodic roadblocks during every monsoon season.

At present, the width of the Lanta Khola slide is around 70 m (though the actual area affected is over 1 km) but has a longitudinal extent of over 900 m with an average surface slope (of the debris materials) of only around 24° (Fig. 4). The crown is located at an elevation of 1,650 m, about 275 m above the road bench. The sides of the slide are sharp and marked by prominent scarps (Fig. 2); the height of these side scarps decreases upslope and becomes negligible near the crown. The road bench is located at a height of 1,375 m; natural benches are also located at heights of 1,495 and 1,610 m. An outcrop of gneiss underlain by amphibolite is exposed within the debris material near the head of the slide; the lower boundary of the outcrop descends to an elevation of 1,590 m. On the northwestern side of the outcrop is a water-saturated debris zone, where the ground is extremely wet. This wet zone is about 25 m wide on the surface and referred to as the “contact zone” in this study. Below the contact zone, the debris material has greater consistency and contains comparatively less water. Importantly, surface runoff is absent within the contact zone itself, but the lower part of the slide is characterized by a number of anastomosing

Fig. 1 Preventive measures adopted at Lanta Khola

streams. The debris material above the outcrop in the upper part of the slide is sparsely vegetated 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 (Fig. 2). The two sides, the stable ground above the crown and the toe of the slide, are very densely vegetated with shrubs and tall trees. 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.

The geological study of the region

The northeast Indian state of Sikkim lies entirely within the Himalayas and is dominated by two major lithotectonic units, the Higher Himalayan Crystalline Sequence (HHCS) and the Lesser Himalayan Sequence (LHS) that are separated by a major ductile shear zone called the Main Central Thrust (MCT; Figs. 3 and 5). The HHCS consists of quartzofeldspathic gneisses of both igneous and sedimentary origin (Fig. 6a) that suffered high-grade metamorphism (Neogi et al. 1998; Catlos et al. 2001). The LHS is dominated by garnet–biotite–mica schists and chlorite schists (Fig. 6b) in the upper part and slates and phyllites in the lower part.

A comprehensive geological study was undertaken during the course of this investigation along the NSH from Gangtok to Chungthang (Fig. 3) and on the Lanta Khola slide itself. The study included identification of rock type, measurement of strike and dip of the rock foliations using a clinometer, and positioning by a handheld GPS (Global Positioning System). Table 1 compares the published strike and dip of the MCT zone (Acharyya 1989) with those for the rock foliations at the Seven Sisters Fall, Mangan sinking zone, Myang slide, Rang Rang slide, Manul, and Lanta Khola. The location of these places is shown in Fig. 3. At the Lanta Khola, the strikes and dip of the rock foliations at elevation 1,590 m

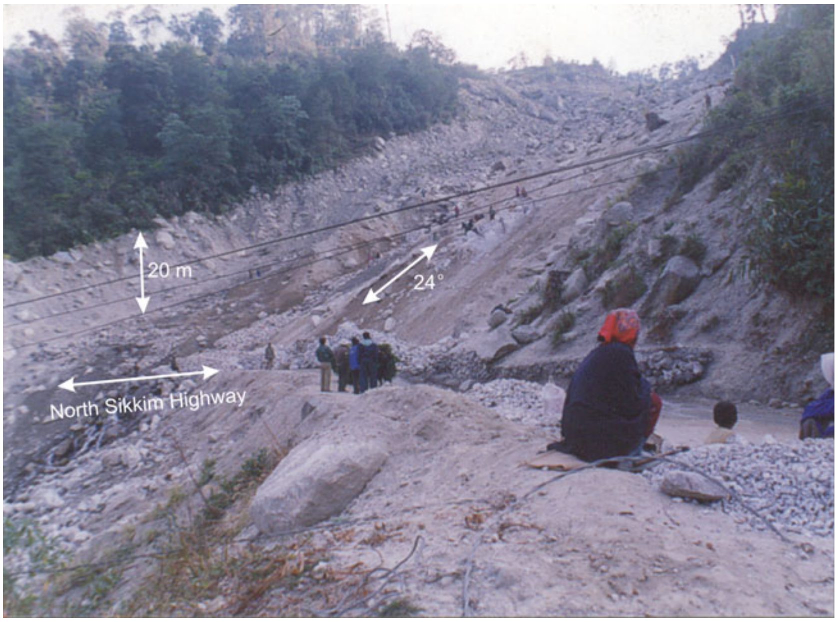


Fig. 2 The Lanta Khola landslide

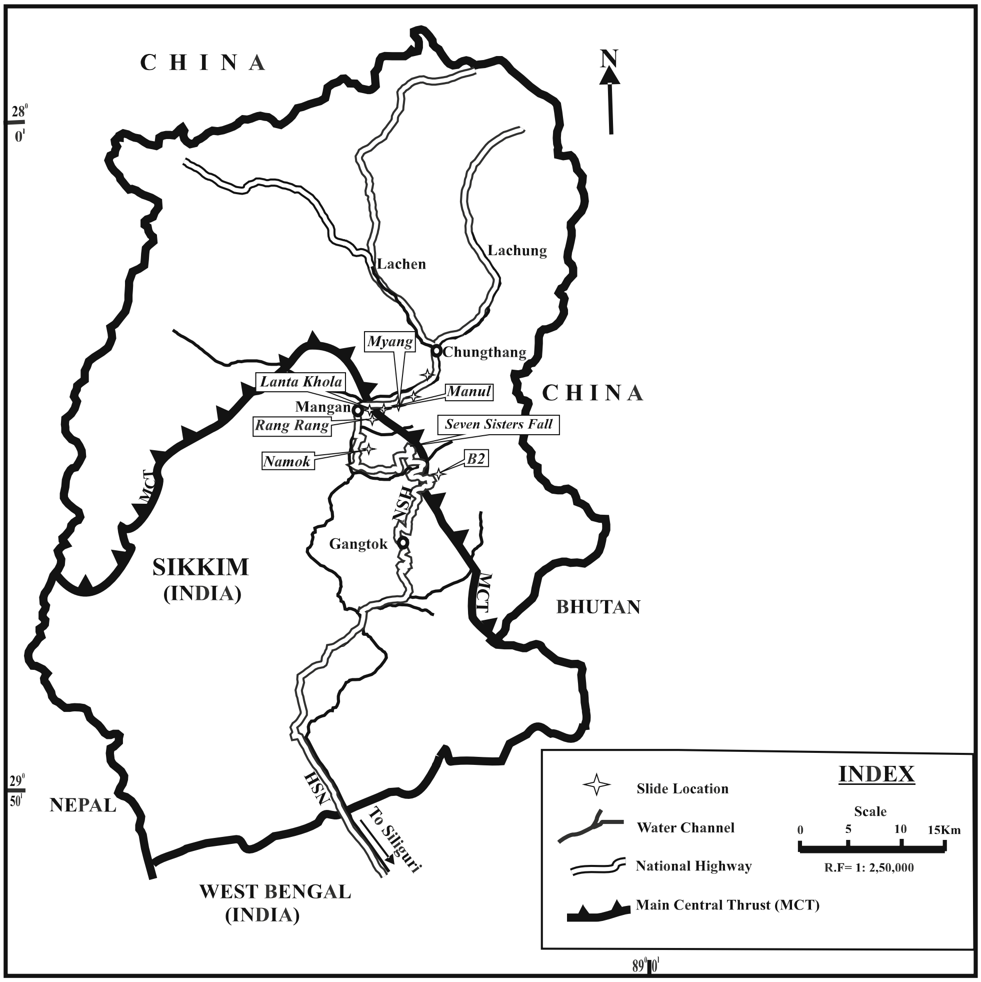


Fig. 3 The location of the slide

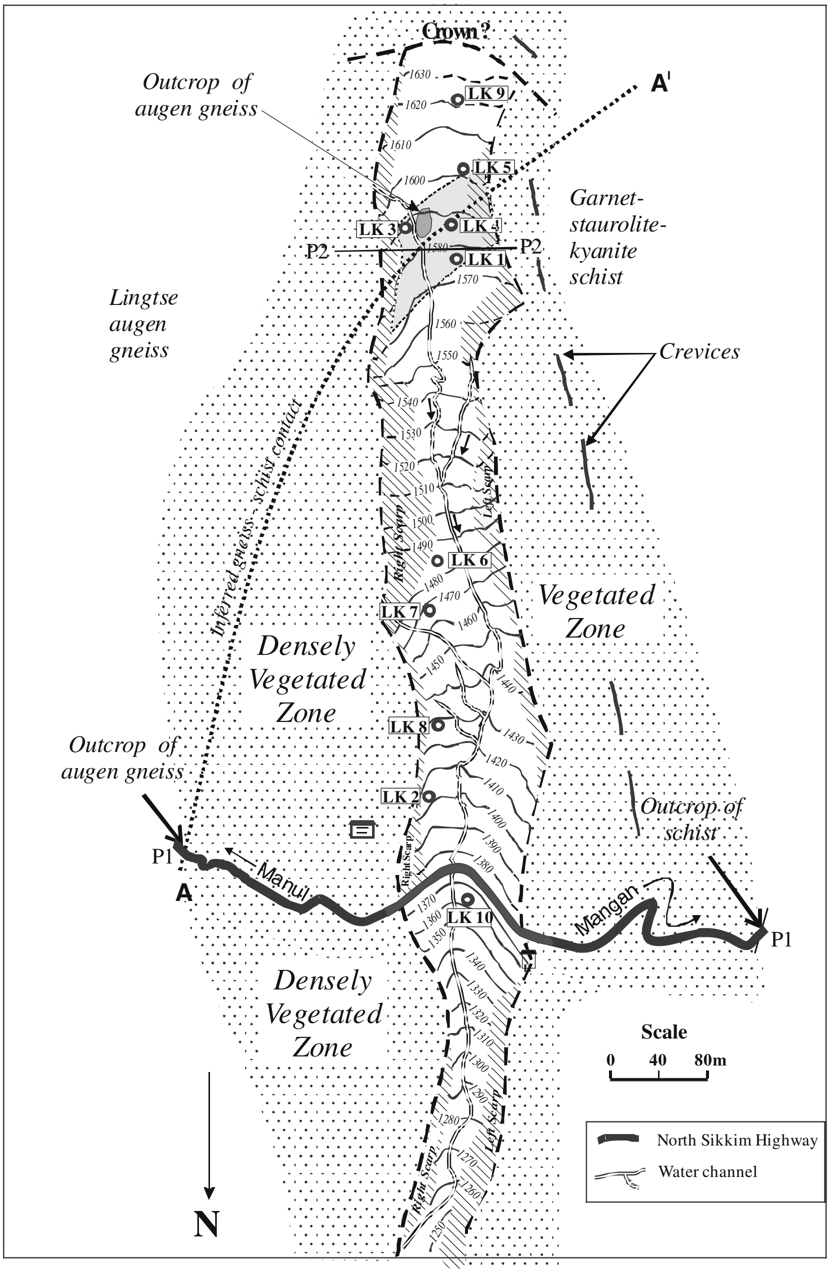
within the slide and those to the immediate east and west of the landslide at road level have been measured. Based on these measurements, a contact zone between the Lingtse augnen gneiss unit of the HHCS and mica schists of the LHS, delineated by the line A–A′ in Fig. 4, has been mapped. The strike and dip of the rock foliations at the Seven Sisters Fall, Mangan sinking zone, Myang slide, and Lanta Khola are found to be comparable with those for the MCT zone. The contact between the gneisses and schists intersects the NSH at two locations (Fig. 5)—in the vicinity of the Seven Sisters Fall, a stable zone, and in the locality of the Lanta Khola slide. The stereonet projections (in Fig. 5) of the near vertical road cuts and the strikes and dip of the rock foliations at both the locations reveal that due to the consistent orientation of the rock foliations with respect to the vertical road cut, the Seven Sisters Fall is a stable zone, but the Lanta Khola slide being located on the opposite face of the same mountain is intrinsically unstable. The superposition of landslide locations of the NSH on the geological map reveals an almost perfect correlation between the slide-prone zone and the ductile shear zone representing the MCT. A large number of slides, including Lanta Khola, occur within this zone (Fig. 5), which is characterized by widespread sinking, road collapse, and slope failure involving both rock fall and debris flow.

In the proximity of the contact, folds in the gneisses become increasingly asymmetric and the shear foliation is correspondingly prominent. Within the contact zone (essentially a ductile shear zone), the gneiss is transformed into biotite schist that is the dominant rock type in the contact region. Immediately below the biotite schists of the HHCS, folds within the underlying mica schists of the LHS are obliterated and the NW–SE trending foliation becomes dominant. S-C fabrics consistent with thrust sense movement become prominent within the schists of the contact zone. The NW–SE foliation in the schists corresponds to the contact direction in the overlying gneisses, and this attitude remains consistent in all contact zone rocks. This is also reflected in the microstructure of the rocks. In the gneisses, the earlier randomly oriented phyllosilicates are realigned and develop a strong preferred orientation parallel to the contact (Fig. 7a, b). In the underlying mica schists also, all phyllosilicates have a single preferred orientation, unlike in the folded rocks further to the southwest (Fig. 7c, d).

The geotechnical studies of the slide materials

Geotechnical studies have been conducted on the debris material collected from various levels of the Lanta Khola slide. Figure 4 shows the location of the sampling points. The slide materials at the Lanta Khola occur in a variety of grain sizes including boulders, cobbles, and pebbles along with slurry/fine masses. The slurry/fine masses consist of coarse-to-fine sand with 2% to 12% silt depending on the location. Between elevations 1,640 and 1,510 m,

Fig. 4 The contour map of the slide



the slide has a higher proportion of boulders. Most of the boulders are gneissic in nature since gneiss is relatively resistant to weathering as compared to the schist. Pebbles and fines show an increase toward the road bench (between elevations 1,510 and 1,375 m). These 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. The significant increase of fines at this level can be attributed to their removal from the upper part of the slide and their accumulation in the vicinity of the road bench. Within this most mobile part of the slide (elevations 1,510 to 1,375 m), boulders, cobbles, and pebbles essentially remain suspended/embedded within the slurry and fine mass. Below the road bench at elevation 1,375, the slide materials are mostly boulders of gneissic origin.

The debris samples collected were analyzed to constrain composition, water content, permeability, particle size, and shear strength. The compositions of the debris samples are determined by X-ray diffraction (XRD) analysis. Figure 8 shows the XRD results for three representative samples LK5, LK1, and LK6. Compositionally, all the debris samples contain biotite, quartz, and muscovite, common constituents of both the Lingtse augen gneiss (of the HHCS) as well as the mica schists (of the LHS). Kyanite and staurolite are found to be present in all the samples except sample LK5, collected from above elevation 1,590 m. Since kyanite and staurolite are restricted to the schists of the LHS and do not occur within the augen gneiss and amphibolite unit of the

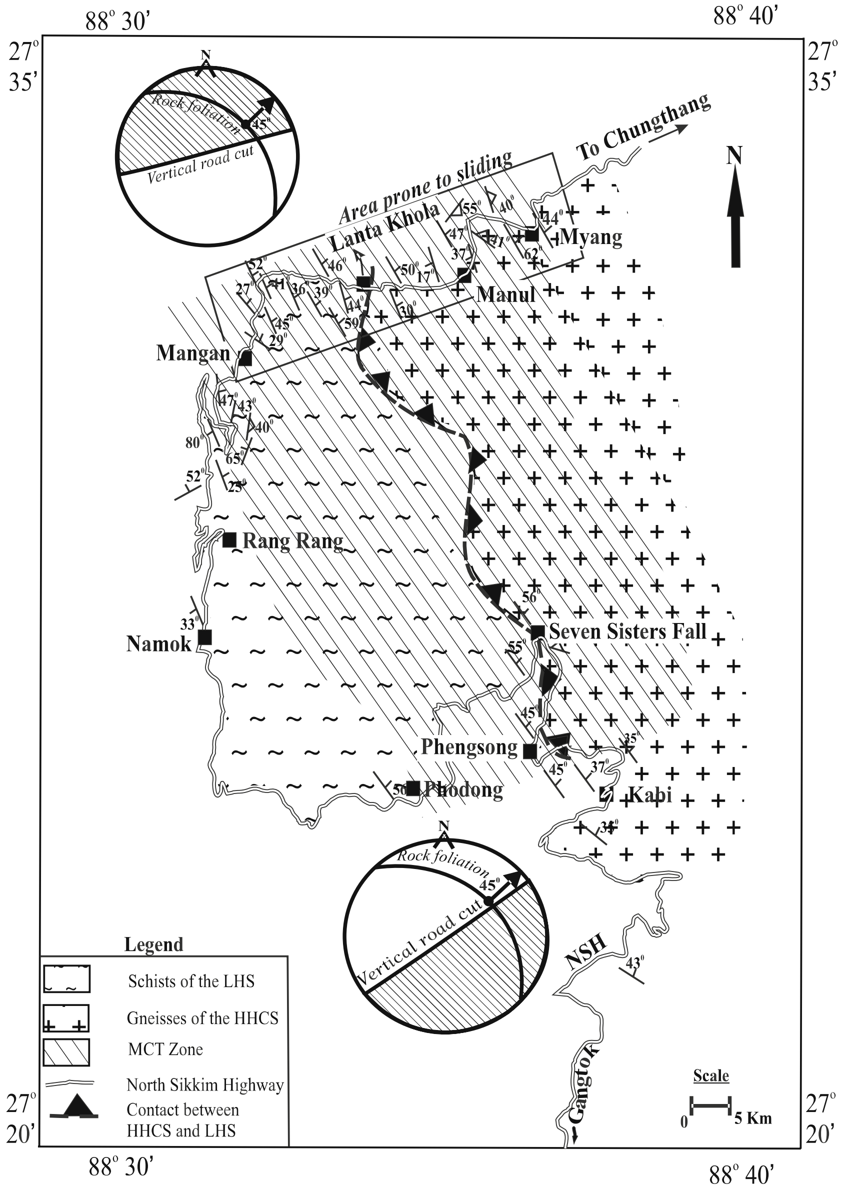


Fig. 5 The location of the contact zone with respect to the NSH

HHCS immediately overlying the schists, the debris sample LK5 most probably originated from gneissic bedrock.

The grain size distribution of the debris samples is determined by mechanical sieve analysis and hydrometer analysis of the fines as per American Society for Testing and Materials (ASTM) standards (D421-58 and D422-63). Figure 9 shows the grain size distribution curves for the samples. The fine contents (in percent) of the samples are shown in Table 2. All the samples are characterized as well-graded sand (SW) except for the samples collected from the contact zone, which are classified as SW–SM due to higher silt content. Intense shearing and presence of water have resulted in greater weathering of the original rock in the mica-rich, well-foliated contact zone. On the ground, an almost quick condition exists at this locality.

The natural water content and (constant head) permeability of the debris samples are determined in the laboratory as per ASTM (D2216-71 and D2434-68) standards. The samples (LK2, LK6, LK7, LK8) from below the contact zone contain 7% to 22% water, while the samples (LK3, LK5, LK9) which are from augen gneiss-derived debris have 11% to 32% water content. The samples collected from the contact zone show the highest water content (24% to 68%).

The permeability of the samples from the contact zone is around 10^{-4}cm/s, while those for the samples collected from other parts of the slide show an order of magnitude higher value (10^{-3}cm/s). This is attributed to the higher silt content in the debris collected from the contact zone.

The shear strengths of the sliding materials are determined by direct shear tests (ASTM standard D3080-72). In all, ten sets of samples were tested during the study. All the debris samples, reconstituted at the field density, were first saturated and then sheared under drained condition. The results of the individual samples are shown in Table 2. The results of the direct shear tests for samples collected from within and outside the contact zone are shown graphically in Fig. 10. As may be seen from this figure, the

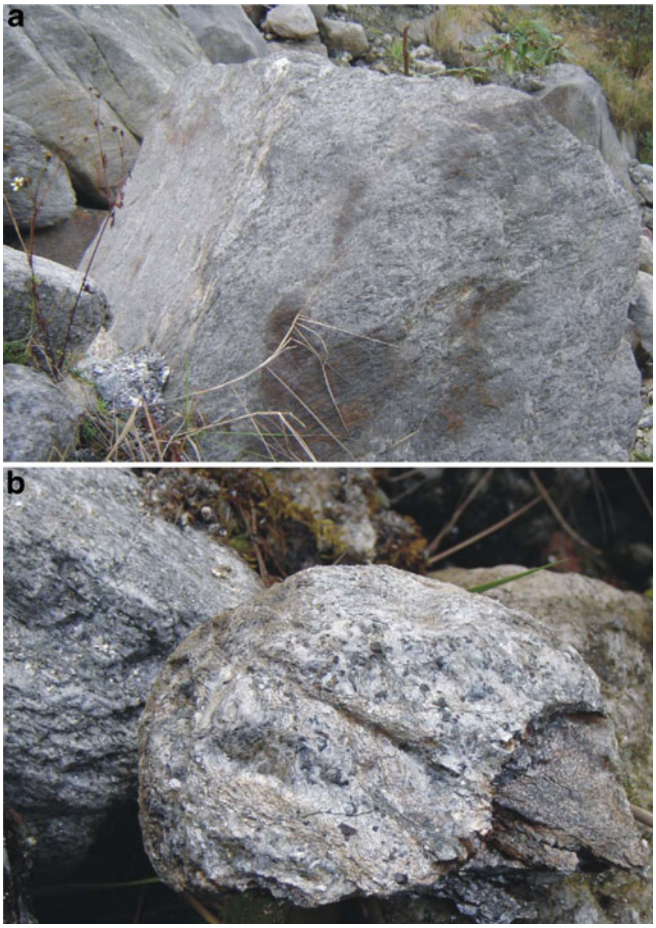


Fig. 6 **a** Gneiss and **b** schist boulders at the Lanta Khola slide

samples from the contact zone have an average drained shear strength of $\phi=20°$, while those from the upper and lower parts of the slide have $\phi=35°$. In general, the contact zone samples exhibit lower shear strengths and a small but finite cohesion due to the increase in the percentage of fines.

The precise location of the geological contact between the HHCS and the LHS (the MCT zone) within the body of the slide is reconfirmed by geotechnical analysis of the debris material. Debris samples that do not contain kyanite and staurolite (derived from gneisses of the HHCS) are found to be from above the contact zone (i.e., above line A–A′ in Fig. 4) where the debris is of gneissic origin. Therefore, this line demarcates the boundary between LHS and the HHCS within the slide itself. The geotechnical properties of the debris material at the contact zone are found to be distinctly different. This debris material is distinguished by its lower permeability, lower strength, higher fines content, and higher water content. Interestingly, the single rock outcrop of sheared gneiss within the slide lies immediately to the right of the inferred contact, thereby also confirming that the contact indeed passes through the slide and daylights at the Lanta Khola slide, between elevations 1,570 and 1,600 m.

The geophysical studies on the slide

Drilling boreholes is the best way to construct the subsurface profile at any place. However, only limited number of boreholes could be drilled in the Lanta Khola slide to find out the subsurface condition. The inhospitable nature of the terrain, the rugged topography, and inherent logistic difficulties on account of the remote nature of the area make it difficult to drill boreholes all along the slide to delineate the subsurface profile. Geophysical methods have been utilized to circumvent this problem. The subsurface profiling at different elevations of the slide is done by a relatively new method called very low frequency (VLF) electromagnetic method. This method works in the frequency band of 5–30 kHz and is suitable for depicting vertical and dipping conductors (Paal 1965, 1968; Paterson and Ronka 1971). A VLF transmitter (station code VTX) with frequency 18.2 kHz was picked up, which lies in a southerly direction (Vizianagaram, Andhra Pradesh, India) with respect to the study area. The results along only two locations, one at road level and another at the contact zone, are described here in terms of their distance from the starting point of each profile.

The VLF measurement carried out along the road section across the slide zone covers a distance of more than 150 m on either side. The apparent current density computed using the Kerous and Hjelt (1983) filtering approach is presented in Fig. 11. The cross section along this profile (P1) depicts very interesting subsurface features. A highly resistive structure is delineated between the points located at a distance of 70–170 m along this profile (Fig. 11b). This zone is

Table 1 Strike and dip of MCT and rock foliations

Location	Strike	Dip	Rock type
MCT zone foliation	N45° W	45° E	
Seven Sister Fall	N50° W	45° E	HHCS gneiss and LHS schist
Mangan sinking zone	N40° W	45° E	Mica schists (LHS)
Myang slide	N44° W	44° E	Metapelitic gneiss (HHCS)
Rang Rang	N60° E	52° E	Mica schist (LHS)
Manul slide	N50° E	37° E	Lingtse augen gneiss (HHCS)
Rock outcrop at elevation 1590 m at Lanta Khola slide	N37° W	50° E	Lingtse augen gneiss (HHCS)
Rock outcrop just east of Lanta Khola slide at road level	N32° W	40° E	Lingtse augen gneiss (HHCS)
Rock outcrop just west of Lanta Khola slide at road level	N54° E	44° E	Mica schist (LHS)
Namok slide	N50° W	33° W	Mica schist (LHS)

identified as stable bedrock, corresponding to the gneisses of the HHCS exposed in this stretch of the profile. Along this profile, the main slide zone lies between 170 and 250 m. In this part of the slide, it is estimated that loose saturated soil extends to a depth of more than 60 m. Loose, moist soil, apparently derived from mica schists of the LHS, occurs in the 250–300-m stretch of the profile. At the 325-m location, a resistive structure is again identified, which is interpreted to extend to a large depth. The apparent current density cross section along this profile suggests that the highly resistive structures between 70 and 170 m and around 325 m can be correlated with stable bedrock.

The apparent current density cross section along a profile (P2) around elevation 1,590 shows a wide reservoir-type conducting feature (Fig. 11a). Interestingly, this zone also distinctly dips toward the east. This region coincides with the water saturated debris zone mapped within the slide that has nucleated along the geological gneiss–schist contact, which passes through the slide at this location. Water percolating from above appears to have been retained in this zone as the debris in this zone has a lower permeability and higher fines content.

The VLF profiles confirm that even in the subsurface, the most saturated part of the debris is located parallel to the geological contact between the gneiss and schist, at and around elevation 1,590 m within the slide. This contact has a NW–SE strike and dips northeast at around 45°. This contact intersects the E–W striking, northerly dipping slide surface along a line that trends N30° E. On any E–W striking vertical plane (i.e., parallel to the calculated VLF profiles), this contact would intersect the slide surface along a line that dips at around 35–40° to the east. The conducting horizons on both the profiles exhibit this feature (that is, a conducting zone that dips to the east). This indicates that most of the water accumulates in and passes through the debris at the gneiss–schist contact. The water content in the debris at depth decreases in a northwesterly direction; however, at each level, the movement of water within the debris parallels the geological contact.

The proposed mechanism of sliding and numerical modeling

The present study indicates that a major contact zone between gneiss of HHCS and schist of LHS, known as the MCT, passes through and daylights at the Lanta Khola slide. The gneiss and schist at the contact zone is extensively weathered and reduced to fine sand and silt with relatively low values of shear strength and permeability. After heavy showers, the surface runoff and the perennial streams enter the contact zone through cracks and crevices in the gneiss above and flow laterally through the contact zone. The weathered shear zone at the contact also contains a band of less weathered, relatively impervious amphibolite, thereby rendering a far greater permeability in the horizontal as compared to the vertical direction. The fine materials and water are extruded laterally from within this zone to the surface. Subsequent downslope movement of this material causes instability in the

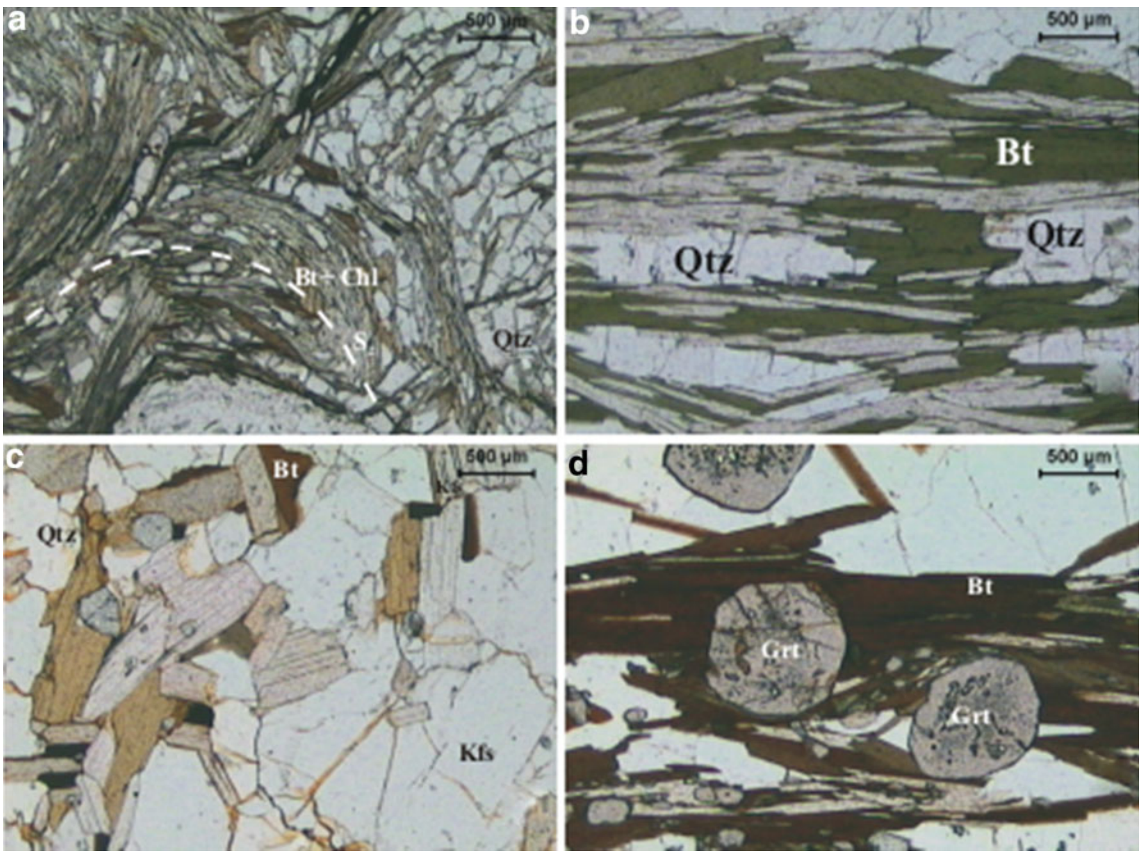


Fig. 7 The microstructure of the gneiss **a** outside the contact zone and **b** at the contact zone and that of the schist **c** outside the contact zone and **d** at the contact zone

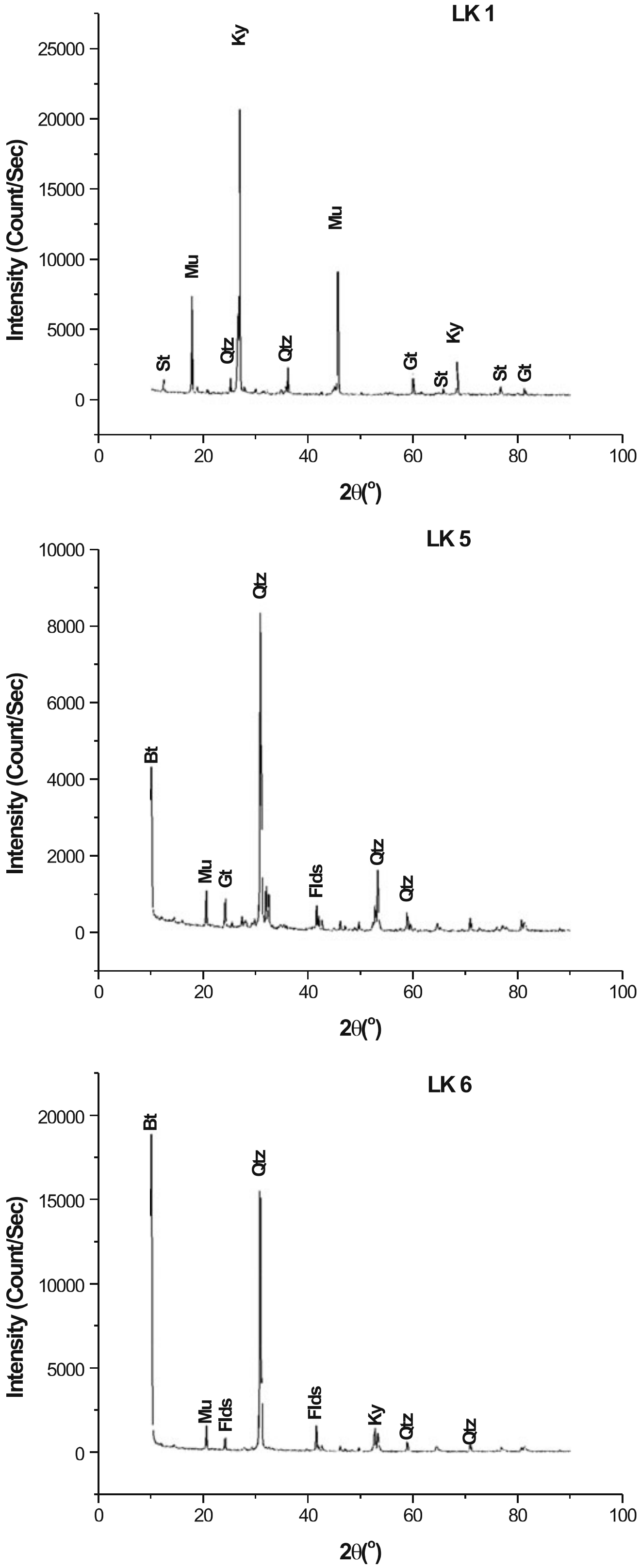


Fig. 8 Results of XRD analyses

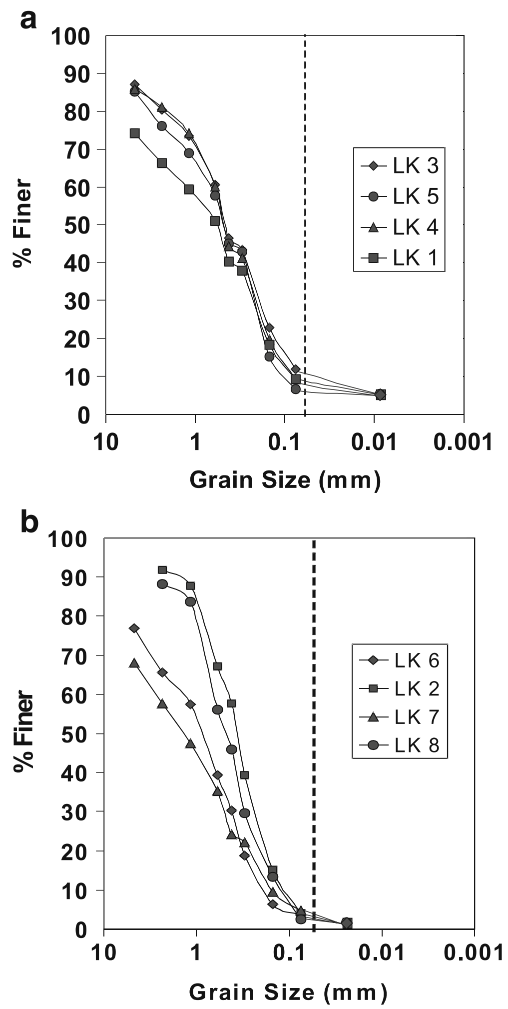


Fig. 9 Grain size distributions of the debris materials from **a** contact zone and **b** lower portion of the slide

overlying, less weathered gneiss unit. Subsequently, dislodged gneissic blocks roll down the slope during and after cloud bursts, resulting in further disintegration and grain size reduction within the slide debris. This process of debris generation is evident from the existence of loose gnessic boulders along the slope below the contact zone, along with weathered schist that has been reduced to coarse-to-fine sand including kyanite- and staurolite-bearing pebbles and gravel. Figure 12 schematically shows the mechanism of debris generation at the Lanta Khola landslide. A numerical model depicting the weak contact zone of the Lanta Khola slide has been developed, and the slope stability of the slide has been studied by the continuum method as well as by conventional limit equilibrium method (LEM).

The computer program Fast Lagrangian Analysis of Continua (FLAC) developed by the Itasca Consulting Group, Inc. (2005) is used for the continuum analysis of the Lanta Khola slope. The FLAC computes stresses and strains in continua by a finite

Table 2 Geotechnical properties of the debris samples

Location on slide	Sample no.	Permeability, *k* (m/s)	% fine (−0.075 µm)	Cohesion, *c* (kN/m^2)	Angle of internal friction, φ (deg)	Moisture content (%)
Contact zone	LK1	1.5×10^{-6}	9.2	10	16.3	23.7
	LK3	1.2×10^{-6}	11.8	30	24.0	32.4
	LK4	6.7×10^{-6}	9.3	5	21.7	68.4
Above contact zone	LK5	2.1×10^{-5}	6.9	0	35.0	11.3
	LK9	1.5×10^{-5}	7.0	0	35.0	10.0
Below contact zone	LK2	3.0×10^{-5}	5.0	15	33.0	21.9
	LK6	1.9×10^{-5}	3.7	0	33.4	22.6
	LK7	1.5×10^{-5}	4.7	0	30.4	6.6
	LK8	1.1×10^{-5}	2.4	0	36.3	7.4
	LK10	1.0×10^{-5}	2.7	0	36.3	6.0

Locations of the samples are shown in Fig. 4

difference method. It uses an explicit solution method. The Lagrangian analysis allows for distortion of the grid so that the end state at each node is the beginning state of the next stress cycle. The slide materials are assumed to be Mohr–Coulomb type. The cohesion, *c*, friction angle, ϕ, and unit weight, γ, are specified for all the materials. Table 3 summarizes the parameters used in the present analyses. The drained values of the frictional parameters and unit weights are based on laboratory test results. The FLAC program utilizes shear strength reduction technique for computing the minimum factor of safety. Cala and Flisiak (2001) provide a good overview of the method. In the method, the strengths (*c* and ϕ values) of the soil are lowered, and maximum unbalanced force is computed to determine if the slope is stable. If the force imbalance exceeds a certain value, the strengths are increased and the original stresses returned to the initial values and the deformations recomputed. This process continues until the force imbalance is representative of the initial movement of the slope, and the strengths for this condition are compared to those available for the soil to compute the factor of safety.

Two different cases are analyzed for the Lanta Khola slide—one with the steady-state phreatic surface above elevation 1,560 m on top of the contact zone and another with the phreatic surface above elevation 1,560 m along the existing surface slope. The former represents the normal condition while the latter represents the phreatic condition after cloud burst. Both the phreatic surfaces are based on observed water levels in a borehole drilled through the contact zone up to the top of the bedrock. However, no significant change in water table is observed throughout the year at and immediately above the road bench. Thus, the phreatic surfaces below elevation 1,560 m are assumed to be same for both the cases analyzed. The top of the bedrock assumed in the analyses is based on the borehole data and geophysical tests done at Lanta Khola. Figure 13 shows the geometry of the slide, subsurface profile, and phreatic surface assumed in both analyses. The results of both analyses are shown graphically in Fig. 13 in terms of factor of safety and shear strain rate contours. The critical sliding surface is found to be located in the vicinity of the contact zone above elevation 1,560 m for both the cases considered. The corresponding values for the minimum factor of safety are found to be 1.01 and 0.81 for the normal phreatic condition and for the phreatic condition that prevails after a cloud burst. Thus, as per FLAC analyses, the slope at the "soggy zone" should be failing during the monsoon season when water table rises up to the top of the slope, while the slope is just stable at other times of the year.

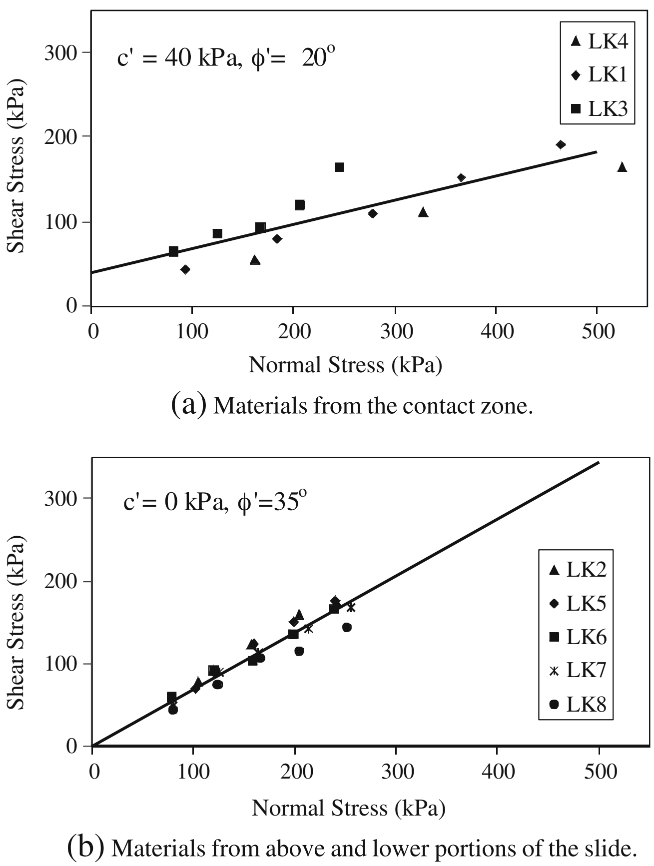
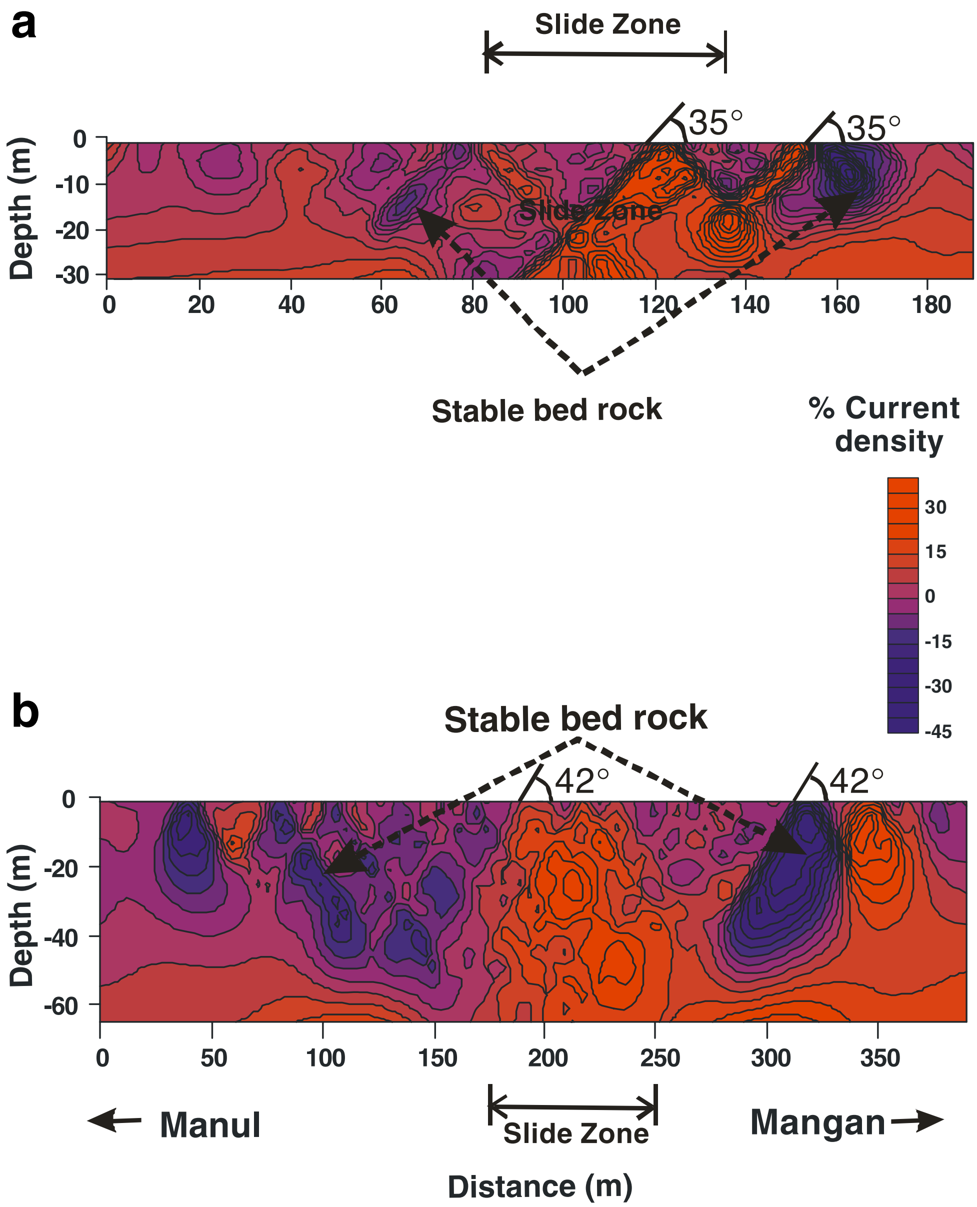


Fig. 10 Results of direct shear tests on the debris materials from **a** contact zone and **b** lower portion of the slide

Fig. 11 VLF profiles: **a** at contact zone and **b** at road level

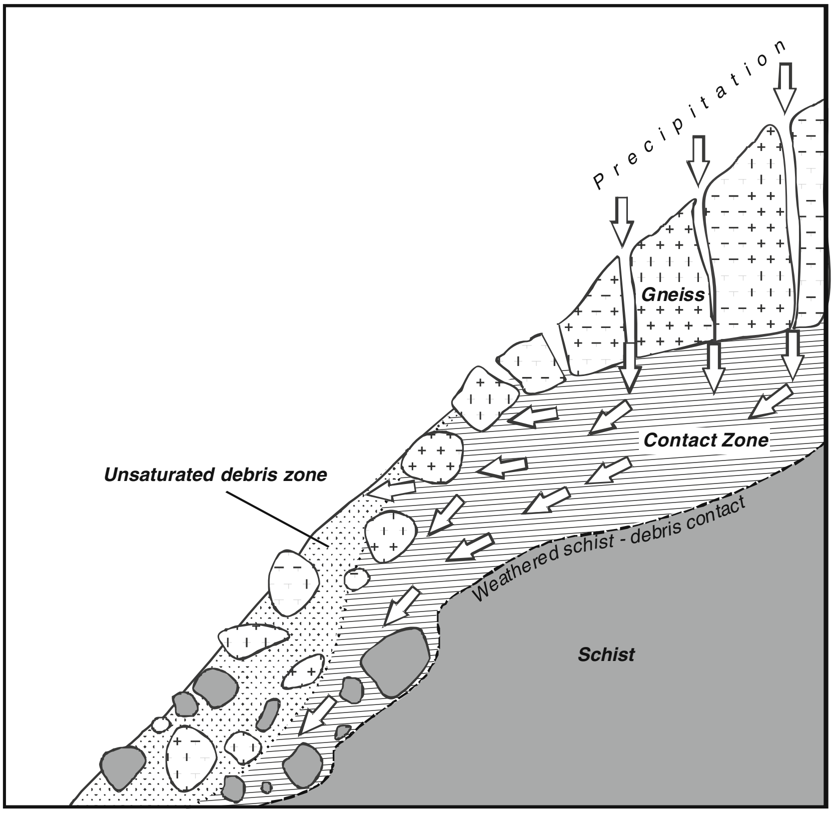


Both the analyses are repeated using a computer program UTEXAS2 (Edris and Wright 1992). The same average shear strengths of the slide materials (as shown in Table 3) are utilized in the analyses. In the computation, Bishop's method of limit equilibrium analysis is adopted. The search for both circular and noncircular (wedge) type of critical failure surface has been performed. The results of the stability analyses are shown graphically in Fig. 13. The critical failure surface and the corresponding minimum factors of safety for sliding by LEM are found to be comparable with those obtained from FLAC analyses. The results of the numerical analyses clearly show that the sliding shall initiate in the relatively weak contact zone located along the gneiss–schist contact after heavy rainfall when the phreatic surface is along the slope surface above elevation 1,560 m and confirms the proposed mechanism of sliding at Lanta Khola landslide.

Proposed mitigation measures

The present study reveals that rise of the water table or increase in pore water pressure and removal or piping of the finer materials with the water are the two main causes of sliding at Lanta Khola. If transport of finer materials and buildup of pore water pressure in the slide body are prevented, the landslide at Lanta Khola can be mitigated at least for a few seasons. With this in mind, a mitigation measure has been proposed which includes construction of gabion walls and two rows of pipe pile walls drilled up to a minimum depth of 15 m with drain materials (gneissic rock-fills) in between. A horizontal perforated drain pipe surrounded by geomembrane and drain materials, as shown in Fig. 14, is also proposed to drain surface runoff and ground water from behind the pipe pile walls and to prevent the migration of fines. Two rows of pipe pile walls with geomembranes on the sides are proposed to prevent movement of fines in the top 15 m of the slide body. However,

Fig. 12 Proposed mechanism of sliding at Lanta Khola



this shall allow water to percolate into the drain located between the two rows of the pipe piles. The drain essentially consists of a perforated polyvinyl chloride pipe with drain materials (gneissic rock-fills) around it. The perforated pipe shall collect water from the slide body and safely discharge it in natural depressions (drains) located on the two sides of the main slide body. Four rows of gabion walls (as shown in Fig. 14), each anchored to the bedrock beneath them, have been proposed in front of the front row of the pipe piles to provide them extra support against the longitudinal component of the gravitational force acting along the slide in the downstream direction. It is envisioned that this kind of wall system shall be placed at elevation 1,560 m (contact zone), elevation 1,440 m (an existing natural bench), and at elevation 1,380 m (just above the road level). With the proposed mitigation measures in place, the factors of safety of the Lanta Khola slide theoretically rise to 1.32 and 1.55 for the monsoon condition and the normal condition, respectively.

Conclusions

The geological, geotechnical, and geophysical studies together indicate that a major contact zone between gneiss of HHCS and schist of LHS, known geologically as the MCT zone, passes through and daylights at the Lanta Khola slide. The gneiss and schist at the contact zone are intensely weathered and reduced to fine sand and silt with relatively low values for shear strength and permeability.

As observed in the field, slide movement and surface slope modification occur mostly from below a height of elevation 1,560 m, the base of the so-called contact zone, up to the road level. The present study confirms that this contact zone is of pivotal importance during the process of slide activation. The numerical analyses also strengthen the model that sliding and debris generation initiate along this contact zone only after heavy rainfall.

Table 3 Material properties assumed in the numerical analyses

Material	Unit weight, γ (kg/m^3)	Friction angle, φ (deg)	Cohesion, c (kN/m^2)
Debris material	2,040.0	35	0.0
Material from contact zone	1,938.0	20	40.0
Schist	2,651.0	45	140.0
Gneiss	2,855.0	45	207.0

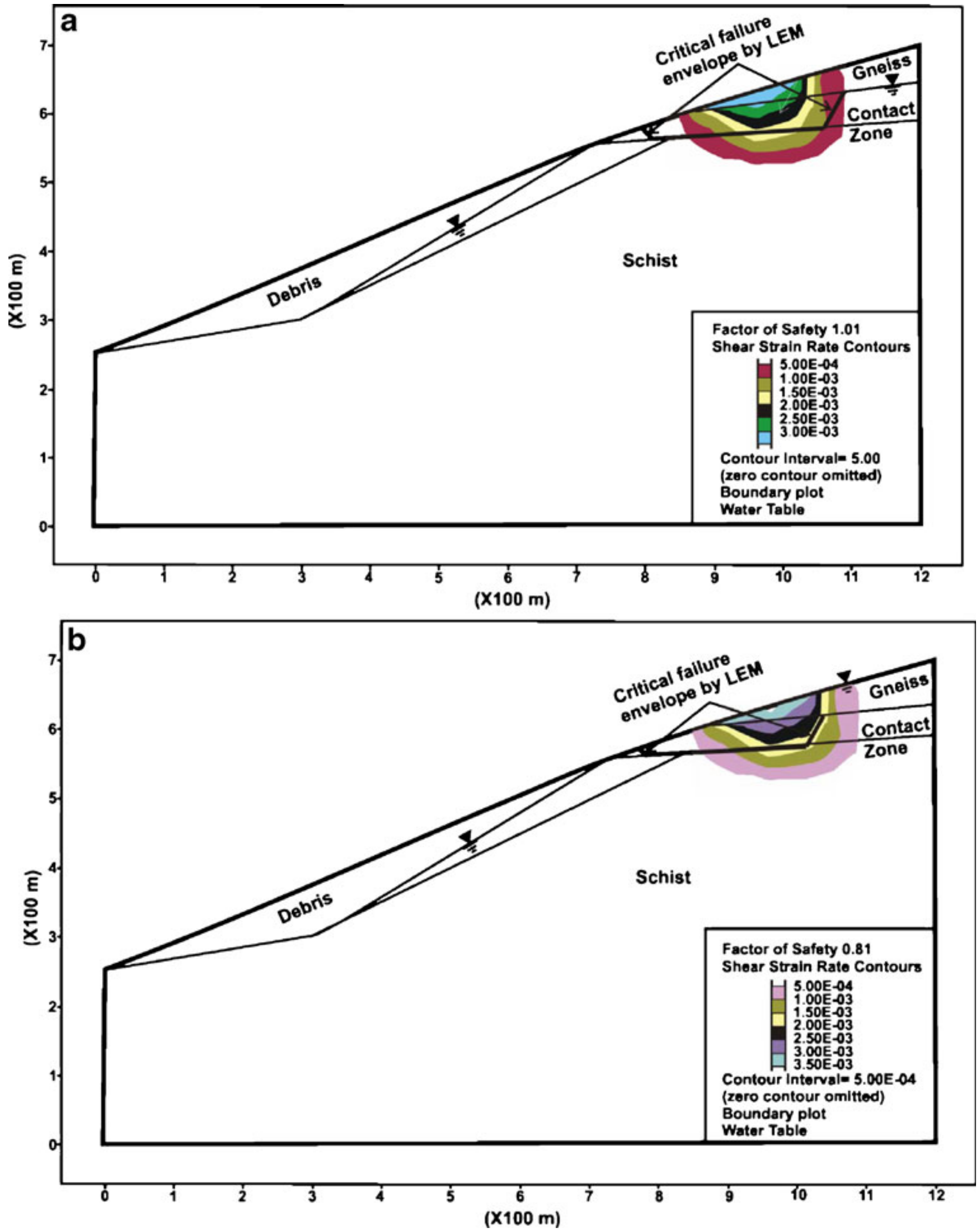


Fig. 13 Results of the numerical analyses for **a** normal case and **b** flood case

An implication of the proposed model is that slide movement at Lanta Khola is dictated by the collapse of the contact zone and that 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 weak contact zone and transported downslope as slide debris. Mass depletion leads to volume reduction within the zone, causing subsidence under the weight of the overlying rock overburden. This causes instability in the overlying gneiss unit and blocks of the gneiss collapse onto and are ultimately incorporated within the debris of the slide. A series of mitigatory measures including the construction of gabion walls, two rows of pipe piles, and an underdrainage system behind the wall have been envisioned to facilitate safe drainage of surface and ground water and prevention of migration of fines at three different elevations along the Lanta Khola slope between the contact zone and the road level.

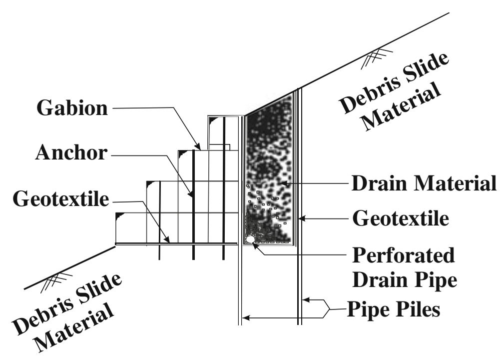


Fig. 14 Proposed mitigation measures at Lanta Khola

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