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Integrated very low-frequency EM, electrical resistivity, and geological studies on the Lanta Khola landslide, North Sikkim, India

Abstract Landslides are very common in high-altitude Himalayan terrains. Major roads in the Himalayas are frequently blocked due to heavy landslides and remain closed for long periods of time. Permanent mitigatory solutions to these landslides are required to keep the highways open. Lanta Khola, located 71.2 km north of Gangtok (capital of the Indian state of Sikkim), is one of the oldest landslides on the North Sikkim Highway and is active since 1975. The rock types on either side of the landslide are different (augen gneiss in the east and metapelitic schist in the west), and it is believed that the Main Central Thrust passes through the slide zone. Since the slide is invariably activated in the aftermath of heavy rainfall, it is important to identify the subsurface structures that channel water below the landslide surface in order to understand the triggers of slide activity. This can only be accomplished by geophysical survey; however, an appropriate geophysical technique that can be applied in such terrains must be identified. Very low-frequency (VLF) electromagnetic survey was performed over the Lanta Khola landside in order to delineate subsurface structures. Although a very limited number of VLF transmitters are available worldwide, it was possible to pick up VLF signals from a number of VLF stations even in this high-altitude mountainous terrain. VLF measurements along five profiles perpendicular to the geological strike were recorded, and a high conducting zone was delineated from the VLF observations. This conducting zone correlates with the low resistive zone identified from gradient resistivity profiling. The anomalies confirm that there is a water-saturated zone (soggy zone) even in the subsurface of the slide parallel to the geological gneiss–schist contact within the Lanta Khola slide. This indicates that the conductive feature correlates with a weak water-saturated debris layer that lies along the slide and is parallel to the geological contact. Resistive structures on either side of the landslide zone can thus be correlated with the stable ground. It is necessary to drain out water from the soggy zone to minimize slide activity since this zone appears to penetrate into the body of the slide.

Keywords Landslide · VLF survey · Gradient profiles · Resistivity · Main Central Thrust · Himalaya

Introduction

The Himalayan state of Sikkim lies in northeastern India and is bordered by China (Tibet) in the north (Fig. 1). The North Sikkim Highway (NSH) connects Gangtok (the capital of Sikkim) with the Tibet border. The Lanta Khola slide is located 71.4 km north of Gangtok on the NSH. The slide initiated as a sinking zone in 1975 and has been active since. The initial small subsidence area along the Lanta Khola road bench has subsequently evolved into one of the largest destabilized zones on the NSH. In 1983, a 200-m-long stretch of the road bench was washed away due to high-velocity surface runoff during heavy precipitation on the 10th and 11th of September (Verma 1984). During the landslide, heterogeneous, non-cohesive soil and boulders were carried down along the Khola bed with such momentum that the road bench along with the culvert was washed away. As a result, a 10-m-deep, 150-m-wide scar formed and extended down to the Tista River along Lanta Khola. The crown of the scar had reached a height of about 196 m above the road level in 1983. Since 1999, the slide has again become severely active after modifying its shape and dimension. This leads to long periods of roadblock during the monsoon season after periods of heavy rainfall. Due to sliding in 2001, the NSH at Lanta Khola was blocked in phases for 54 days. A permanent solution to the Lanta Khola landslide problem is therefore of utmost importance. To achieve this, it is very important to delineate the subsurface structures below the slide along the sliding zone. The two questions that need to be answered are: (1) what subsurface channel way is followed by water within the slide body since slide movement generally follows heavy rainfall and (2) what is the bedrock depth below the slide? Answers to both questions are required for designing effective remedial/mitigatory measures and can only be achieved by geophysical survey.

In the past, different geophysical techniques have been applied for the characterization of landslides (Bogoslovsky and Ogilvy 1977; McCann and Forster 1990; Godio and Bottino 2001; Jongmans and Grambois 2007). Seismic and electrical resistivity survey was conducted around the La Clapière landslide in the French Alps by Jomard et al. (2007). DC resistivity and electromagnetic and GRP geophysical survey were conducted around the Machu Picchu landslide, Peru (Best et al. 2009). Electrical resistivity tomography is commonly used for landslide monitoring (Suzuki and Higashi 2001; Lapenna et al. 2003; Friedel et al. 2006). However, not all these methods can be applied in each case, especially in places where the slope is perpetually unstable. Therefore, the most appropriate geophysical technique or combination of techniques must be identified for the Lanta Khola slide zone. The technique must be chosen after considering its feasibility in the terrain to be surveyed and without aggravating slope instability in the vicinity of the slide zone.

The results of geological investigations on the Lanta Khola slide zone (Anbarasu et al. 2009) indicate that the landslide is located on a highly weathered weak zone characterized by a major lithological and tectonic contact. Owing to increased hydrological activity along such contact zones, electrical conductivity changes significantly (by several orders of magnitude) on either side of the slide and within the slide zone itself due to weathering and high groundwater saturation. Electrical and electromagnetic geophysical methods were therefore considered suitable for mapping the

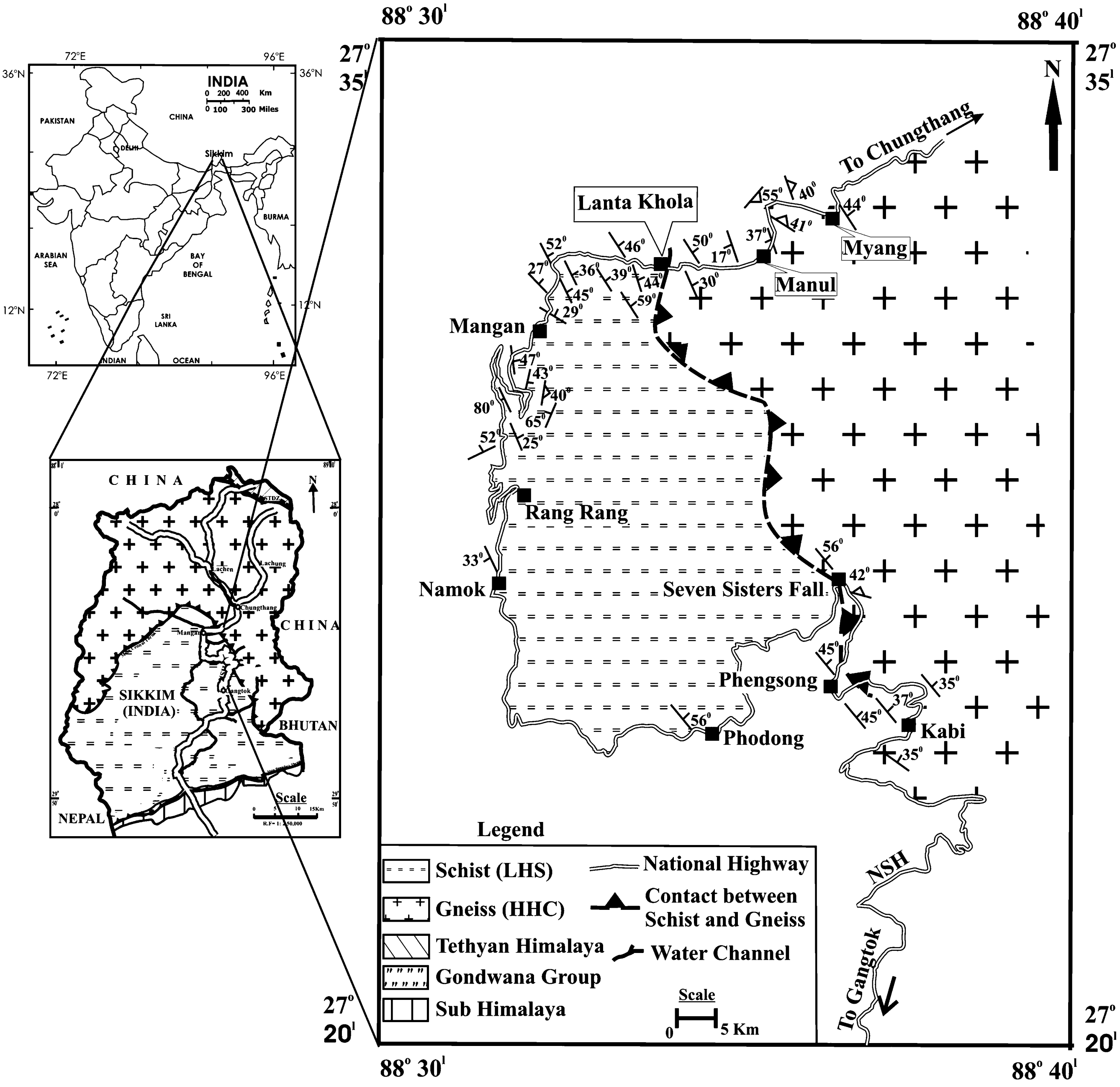


Fig. 1 Location, structure, and lithology along the Kabi-Myang stretch of the North Sikkim Highway north of Gangtok, mapped during the present study, showing the position of the Lanta Khola landslide. *Inset* geological map of Sikkim shows the HHCS and LHS separated by the Main Central Thrust. The *white double line* demarcates the major roads in Sikkim; the *black line* is the River Tista

variation in the subsurface resistivity to understand the geological nature of the subsurface (Baranwal and Sharma 2006; Flavio et al. 2007). Moreover, due to heterogeneous and loose near-surface structures, current flow will diffuse and reliable measurement could be problematic over the slide zone.

Groundwater movement or seepage through a contact zone between two geological formations (gneiss and schist) forms a suitable vertical to dipping plate-like conductor (Aina and Emofurieta 1991). Such conducting zones can be very accurately delineated by plane wave VLF electromagnetic (EM) method. VLF EM equipment is very suitable for this purpose (Beamish 1994) as it can be transported easily across the slide zone for measurement. Attempts have been made to delineate subsurface structures using VLF EM method over the Lanta Khola landslide. Results of the VLF survey are correlated with the gradient resistivity profile carried out along the NSH.

Geological background

The Himalayas consist of several lithotectonic zones separated by major discontinuities, all of which broadly parallel the trend of the orogen. One of the most well-known discontinuities is the Main Central Thrust (MCT) which separates the Higher Himalayan Sequence in the north from the underlying Lesser Himalayan Sequence in the south. 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). In the Darjeeling-Sikkim area, the base of the HHCS is represented by a strongly deformed granitic body called the Lingtse Gneiss (Acharyya 1978). The underlying Lesser Himalayan Sequence (LHS; 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. During metamorphism, pressures and temperatures in the LHS did not exceed the greenschist facies. Movement along the MCT involved ductile shearing of the lowermost part of the HHCS and the upper part of the LHS. This resulted in the formation of a penetrative shear foliation defined by micas (muscovite and biotite) in the contact zone that trends NW–SE and dips 45° toward northeast, parallel to the sharp lithological contact between the HHCS gneisses and LHS schists (Anbarasu et al. 2009). The consistent orientation of the foliation is characteristic of the contact region. Outside this zone, the orientation of the penetrative foliation varies even on meter scale because of repeated folding (Anbarasu et al. 2009; Gupta et al. 2009). Interestingly, the contact zone is characterized by the highest frequency of landslides along the North Sikkim Highway.

Geomorphology, rainfall, and landsliding along the NSH

The NSH extends northwards from the city of Gangtok toward the border with Tibet. The elevation varies from over 1,500 m near Gangtok to around 4,000 m near the border. All regions below a height of ~2,500 m are densely vegetated; vegetation becomes increasingly sparse toward the north. Geologically, the southern stretch of the NSH is dominated by schists of the LHS, and the northern parts are predominantly gneissic rocks of the HHCS. Although landslides occur infrequently throughout the NSH, the frequency of landslides is abnormally high within a 16-km stretch of the road that coincides precisely with the ductile shear zone along the LHS–HHCS contact across the MCT. The high proportion of mica in rocks of the contact zone leads to enhanced weathering and rock quality degradation in this region. The slope failures in this zone include both rock and debris slides.

The correlation between rainfall and landslides in Sikkim is well known, with most landslides becoming active during or immediately after the monsoon season (e.g., Bhasin et al. 2002; Dubey et al. 2005). Although rainfall is clearly related to slope instability in the region, slide activity is not directly correlated with each individual cloudburst event or with every period of prolonged precipitation. In a study of the available rainfall data from North Sikkim, Sengupta et al. (2009) observed that landslides tend to occur in the region following a certain threshold amount of rainfall involving the cumulative rainfall during a certain event spanning several days. It was suggested (Sengupta et al. 2009) that slides were initiated wherever the rock or debris became saturated and where the penetrative foliation was favorably oriented for landslides. Precipitation and accumulation of water is clearly the trigger for landslides in the Sikkim region.

The Lanta Khola slide

Slide morphology

Geological mapping along the NSH indicates that the MCT passes directly through the body of the Lanta Khola landslide (Fig. 2). The gneisses structurally overlie the schists. Although Lanta Khola is a predominantly debris slide, the location of the schist–gneiss contact can be demarcated on the slide surface from a mineralogical analysis of the debris material (Anbarasu et al. 2009). The contact has a NW–SE strike and dips 45° toward the northeast. This contact plane intersects the slide surface along a line that trends approximately N30°E. Figure 3a shows an actual cross-section through the slide; Fig. 3b shows the relationship between the slide surface, the contact plane, and the VLF profile sections (see this section) in the form of a sketch, with the stereographic projection (Fig. 3c) depicting the angular relationships.

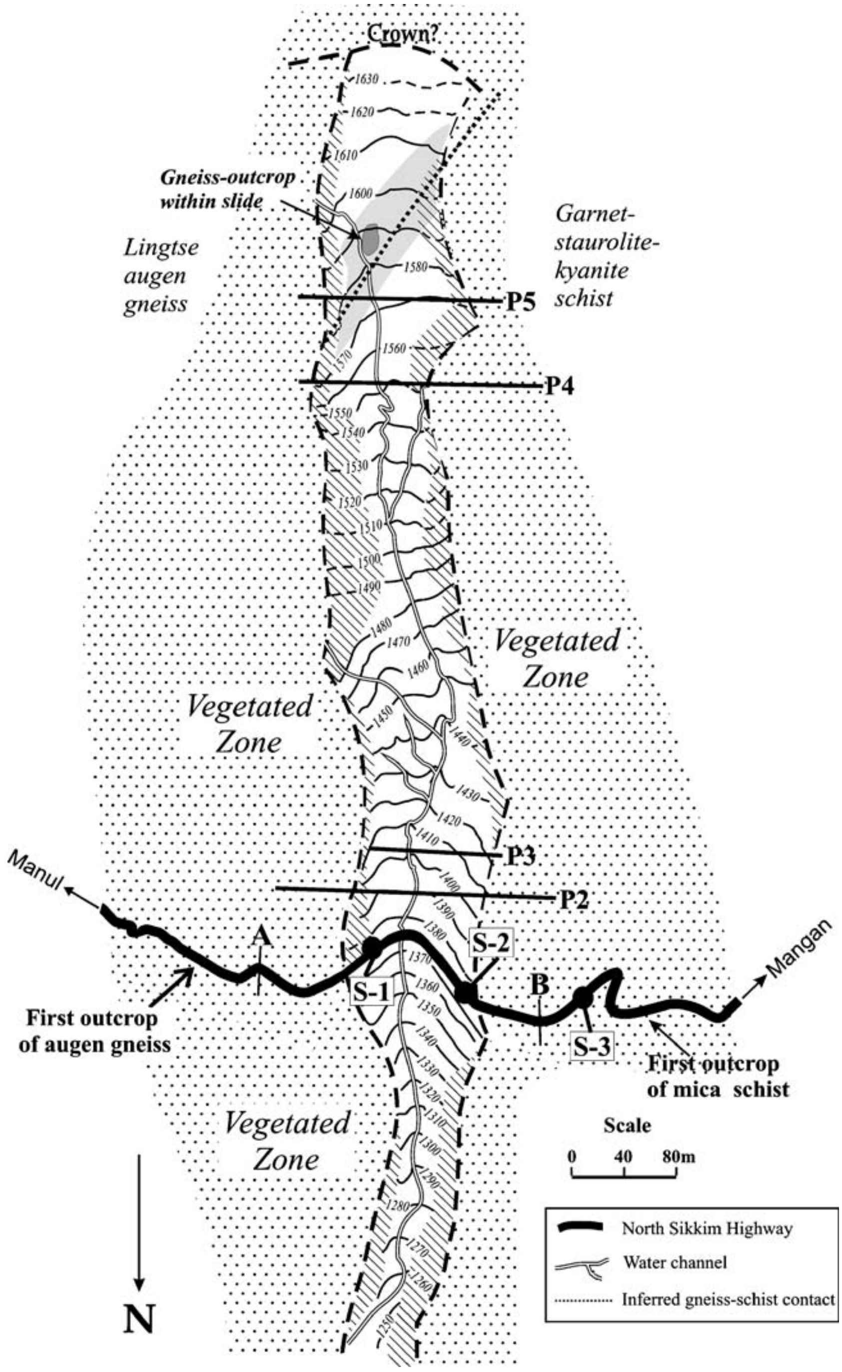
The slide surface has been surveyed in detail using a total station equipment. After survey, a contour map of the slide surface was generated (Fig. 2), and this has been used as the base map for all subsequent investigations. The inferred schist–gneiss contact is depicted on the base map (Fig. 2). As shown in the map, the slide width varies from 50 to 70 m (Fig. 2) and has a longitudinal extent of over 900 m with an average surface slope (of the debris material) of around 24°. The crown of the slide is at a height of 1,650 m, while the toe occurs close to the Tista River. Prominent scarps demarcate the sides of the slide. The road bench is located at a height of 1,375 m and other natural benches at heights of 1,440 and 1,600 m.

The most prominent part of the debris material within the slide is a water-saturated zone where the ground is extremely soggy which is located along and parallel to the schist–gneiss contact (Fig. 2). This “soggy zone” is about 25 m wide on the surface. Below the soggy zone, the debris material has greater consistency and contains comparatively less water. Importantly, surface runoff is absent within the soggy zone itself, but the lower part of the slide is characterized by a number of anastomosing streams. Parts of the slide above the soggy zone are now largely vegetated, suggesting stabilization after initial movement. In contrast, the part below the soggy zone is comparatively devoid of vegetation due to frequent reactivation. 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.

Geotechnical characterization of the debris material

A number of geotechnical tests have been carried out on the debris material collected from various parts of the Lanta Khola slide (Anbarasu et al. 2009). The results relevant to this study are summarized here. Essentially, the debris consists of boulders, cobbles, pebbles, and granules that are suspended within a finer matrix, indicating that the movement of the slide is controlled by the strength of the fines. This finer matrix consists of coarse to fine sand with some silt; the soggy zone debris samples show a higher silt fraction (>5%). The soggy zone debris has a high water content (>50%) and low permeability (10^{-4} cm/s); debris samples from the lower part of the slide have lower water content (<35%) and higher permeability (10^{-3} cm/s). Direct shear tests also show that debris samples from the soggy zone have lower shear strength than debris from other parts of the slide. Monitoring of slide activity over an entire year indicates that all movement of debris material during sliding occurs from immediately below the soggy zone. According to Anbarasu et al. (2009), this indicates that the water-saturated, relatively impermeable soggy zone near the head plays a pivotal role in activating the Lanta Khola slide.

Fig. 2 Contour map of the Lanta Khola landslide (elevations in meters), location of resistivity soundings (S-1, S-2, and S-3), VLF profiles P1 (between A and B), P2, P3, P4, and P5



Results of geophysical surveys

VLF survey

Very low-frequency electromagnetic method works in the frequency band of 5–30 kHz and is suitable for delineation of vertical and dipping conductors (Paal 1965, 1968; Paterson and Ronka 1971). The strike of the investigated slide zone is approximately N–S. Therefore, a VLF transmitter in the N–S direction is suitable for VLF measurement in E-polarization. A VLF transmitter (station code VTX) with a frequency of 18.2 kHz was picked up which lies in a southerly direction (Vizianagram, India) with respect to the study area. In spite of the highly rugged Himalayan terrain, a good strength of the primary field was available in the area. Five traverses were taken across the slide zone, from the road level to the top of the slide, close to the crown. It was not possible to take VLF measurements parallel to the strike (N–S) of the slide due to the nature of the slope and unsuitability of such a traverse from the perspective of conducting systematic geophysical investigation. The results along each profile are described in terms of their distance from the starting point of each profile. This was consistently on the right (i.e., eastern) side of the slide for each profile.

The first VLF measurement was carried out along the road section across the slide zone covering a sufficient distance on either

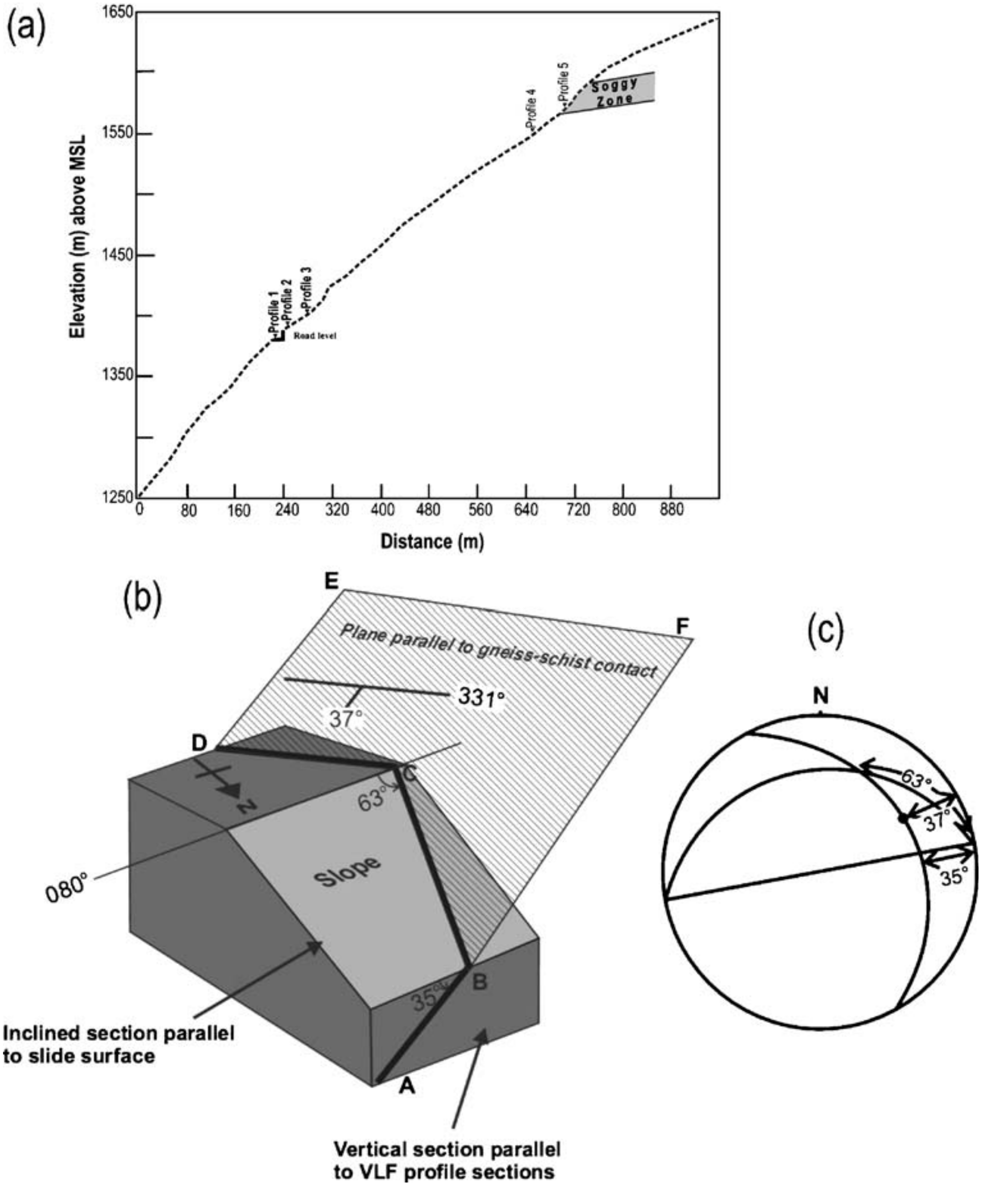


Fig. 3 **a** Cross-section through the Lanta Khola slide showing the position of the road and the location of the VLF profile sections. **b** Schematic diagram showing the relationship between the slide surface, the contact plane, and the VLF profile sections. **c** Stereographic projection showing the angular relationships between the planes shown schematically in **b**

side of the slide. The apparent current density computed using filtering approach (Karous and Hjelt 1983) is presented in Fig. 4a. The cross-section along this profile (P1) depicts very interesting subsurface features. A conducting zone is delineated at a distance of 50–70 m from the starting point along this profile. This corresponds to a small depression (sinking zone) formed on the road. A highly resistive structure is delineated between the points located at a distance of 70–170 m along this profile. This zone is identified as stable ground and corresponds 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 (Fig. 4a, marked between two inverted triangles), and a braided water channel continuously flows through this part of the profile. 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- to 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. A conducting zone is again observed at location 350 m, which corresponds to a narrow depression containing a water channel. 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 a correlated with stable ground. These two locations also correspond to the positions where bases for a temporary ropeway have been constructed, along which essential goods are transferred on an air trolley during road blockage following activation of the landslide.

The next profile (P2) is taken on the hill slope above the road bench, in a southward direction from profile P1. Due to lack of approach space, this profile covers only 280 m. However, the apparent current density along this profile also has a very good correlation with profile P1 (Fig. 4a, b). A conducting zone dipping toward the east can be delineated at a distance of 100- to 150-m locations, suggesting that a water-rich conducting zone intersects the vertical profile along this line. A water channel passes through 125-m location on this profile and marked by inverted triangle.

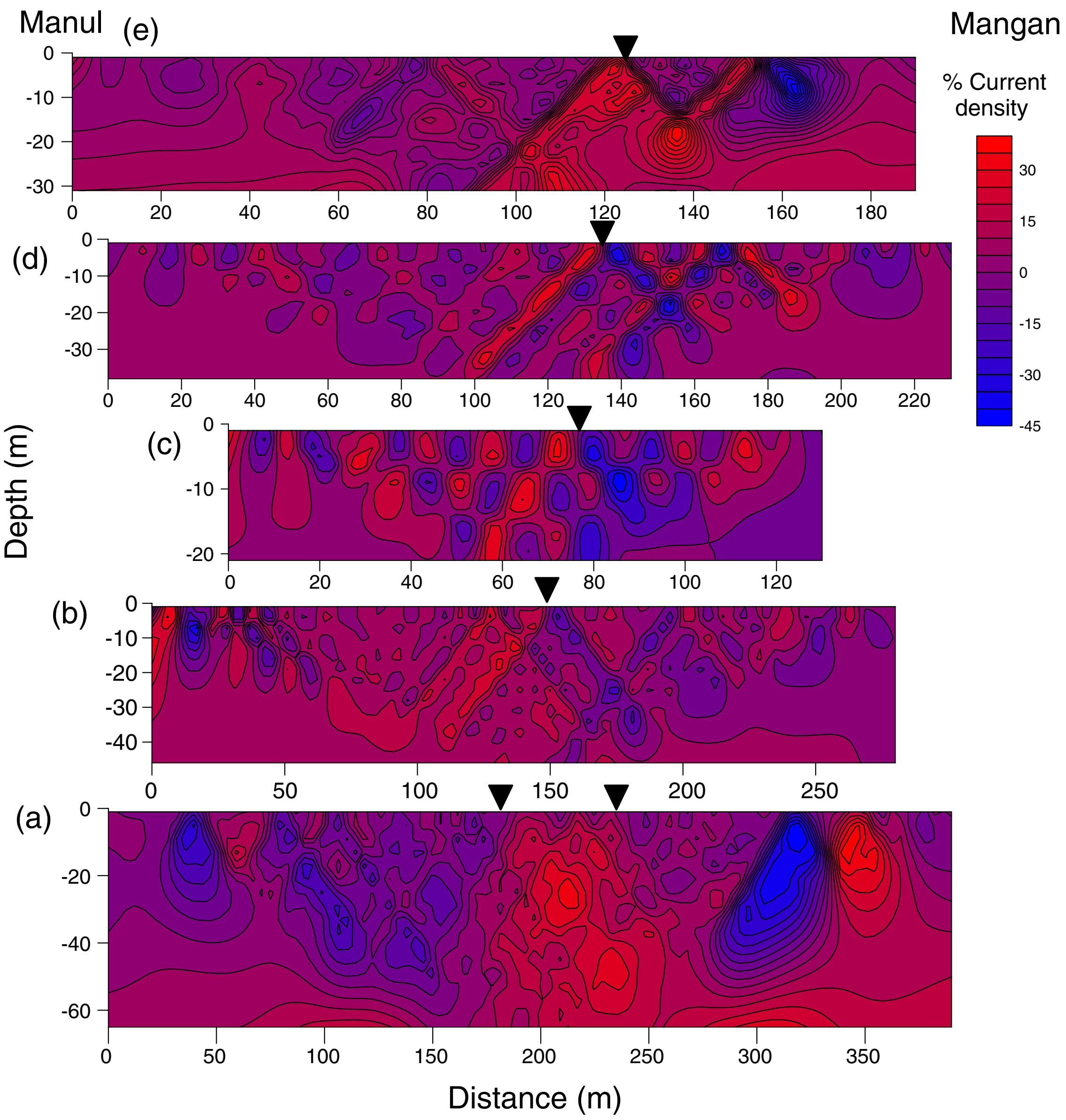


Fig. 4 Apparent current density cross-section along various profiles: **a** Profile P1, **b** Profile P2, **c** Profile P3, **d** Profile P4, and **e** Profile P5

Resistive features are clearly seen on either side of this contact plane.

The third profile (P3) is further to the south and at a higher elevation on the slide than profile P2. A distance of only 130 m could be surveyed along this profile owing to the extremely steep nature of the side scarps on either side of the slide zone at this elevation. However, even within this restricted profile, a conducting zone dipping toward the east can be delineated at a distance of 70 m from the initial point (Fig. 4c). A water channel passes at 70-m location on this profile and marked by inverted triangle in Fig. 4c.

The next profile, P4, is located at a considerable distance upslope from profile P3 since the surface of the slide in the intervening zone between the two profiles was not conducive for profiling across the slide. However, the trend of the profile is parallel to all the previous traverses. Figure 4d shows the apparent current density cross-section along profile P4. Along this profile, an east-dipping conducting zone could be identified at a distance of 130 m, which is consistent with apparent current density contoured for other profiles. A water channel passes at 130-m location on this profile and marked by inverted triangle in Fig. 4d.

Profile P5 is taken at the head of the slide, very close to the crown. The apparent current density cross-section along this profile shows a wide reservoir-type conducting feature (Fig. 4e). Interestingly, in keeping with the observations in the other profiles, this zone also distinctly dips toward the east. It is important to mention that this region coincides with the soggy debris zone mapped within the slide that has nucleated along the geological gneiss–schist contact and passes through the slide at this location. Water channel could not be seen at this location, but absolutely soggy area on this profile is marked near inverted triangle in Fig. 4e. Water percolating from above appears to have been preferentially retained in this zone. Permeability tests have demonstrated (Anbarasu et al. 2009) that the debris in this zone has a lower permeability and consequently higher water content. Therefore, the most consistent feature seen in the various VLF current density cross-sections is a conducting zone that dips to the east. The significance of this conducting zone is discussed later.

It is evident from the apparent current density cross-section presented in Fig. 4 that gneiss–schist contact attains a deeper depth and water flows through this contact zone. A soggy ground acts as a feeding reservoir. Schist, which lies below this contact, is unable to hold the pressure and starts slipping slowly and then massive landslide triggers. This can be ascertained by the fact that the road made by Border Road Organization slips rapidly below the actual road level, and after massive landslide, it is completely washed away into the Tista River.

Furthermore, a plan view (Fig. 5) of the apparent current density at an apparent depth of 10 m has been computed for each profile and contoured. This plane is therefore parallel to the hill slope at a depth of 10 m. At this shallow depth, a resistive feature occurs on the left side of the slide, while the right side is more conducting. By correlation with the surface morphology, the observed greater abundance of gneissic boulders on the left side probably constitutes the resistive feature. As a result of which, subsurface water flow at this depth is channeled through the left side of the slide where finer debris is more common.

Another plan view of the apparent current density (Fig. 6) has been computed and contoured for an apparent depth of 20 m. This plane is therefore parallel to the hill slope at a depth of 20 m. The contour map clearly depicts that the resistivity decreases normal to a line that trends N30°E; interestingly, this line is parallel to the contact between the gneisses of the HHCS, and schists of the LHS on the surface, as demonstrated from geological mapping. A conducting groundwater zone can be seen toward the left side of the slide in Fig. 6. The highly conducting broad reservoir type zone is depicted on the top.

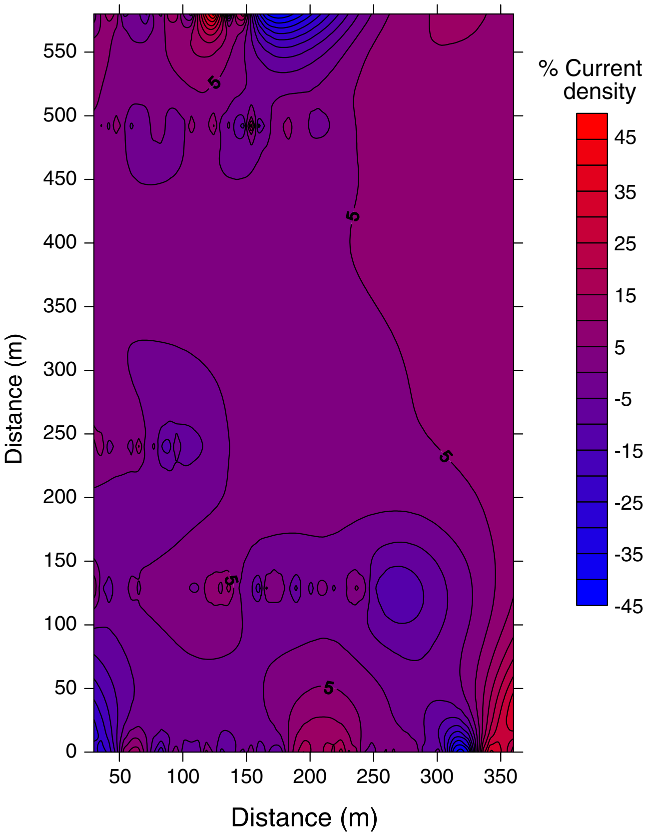


Fig. 5 Apparent current density at 10-m depth below the slide surface

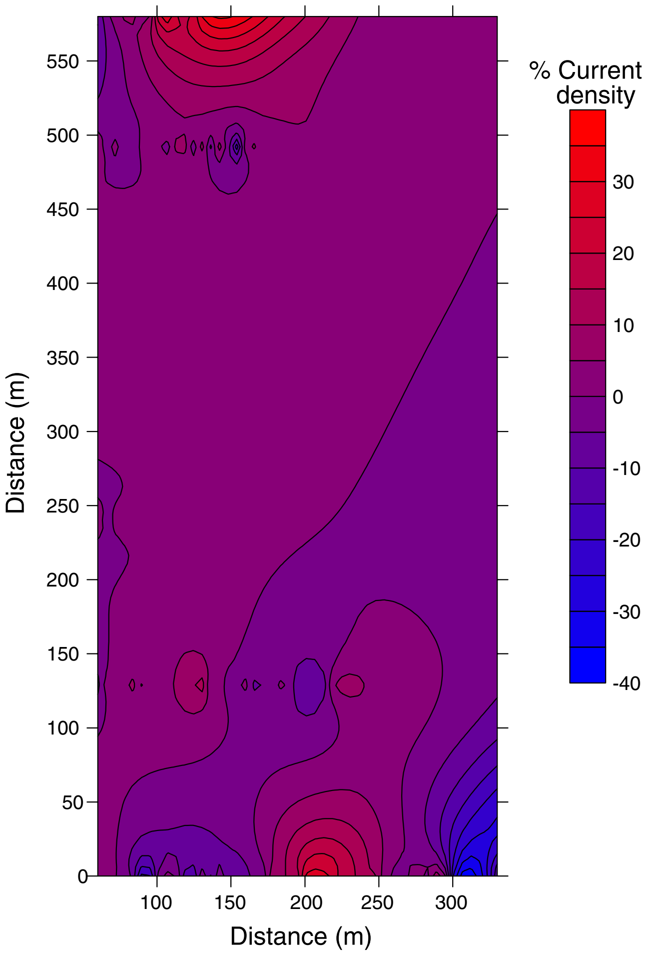


Fig. 6 Apparent current density at 20-m depth below the slide surface

Gradient profiling survey

Profiling is a common resistivity technique used for the determination of lateral variations in electrical conductivity. Gradient profiling is carried out by placing current electrodes at a large distance and measuring the potential in the central part of the profile (Furness 1993; Yadav and Singh 2007). First, current electrodes are spread up to 1.0 km keeping the main landslide roughly at the center. Potential electrodes are kept 20 m apart, and the start of the gradient profile is such that first observation exactly coincides with the VLF profile on the road level (profile 1). Subsequently, potential electrodes move at regular intervals of 10 m, keeping the distance between them consistently at 20 m. Apparent resistivity is computed for each position of the potential electrodes and assigned a value corresponding to the center of the potential electrodes. Apparent resistivity computed from such measurements gives the resistivity variation at a greater depth. Assuming that the penetration depth is approximately one fifth of the current electrode separation, we have mapped resistivity variations corresponding to a depth of 200 m.

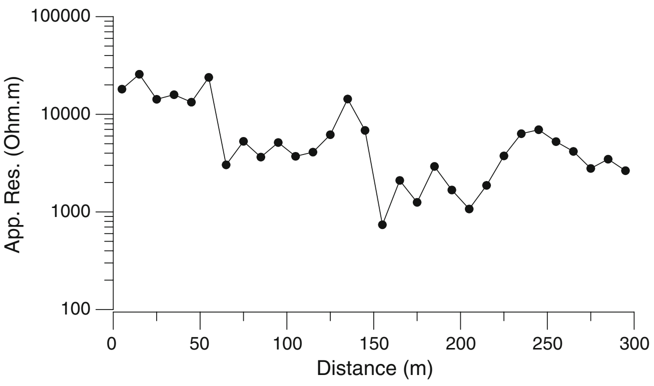


Fig. 7 Apparent resistivity variation at a large depth derived from gradient resistivity profiling along the road section, coinciding with the VLF profile section P1. The landslide body is located between distances 130 and 230 m

At the start of the profile (Fig. 7) apparent resistivity varies between 15,000 and 20,000 Ωm. This high resistivity corresponds to basement gneisses lying to the east of the landslide and stable zone. Apparent resistivity suddenly drops to 2,000–3,000 Ωm after the 50-m location on the profile. This low resistive zone corresponds to a sinking zone. This sinking zone is also clearly depicted in VLF profile 1 (Fig. 4a) and shows a very good correlation between gradient resistivity profiling and the VLF current density cross-section. From 100- to 130-m location on the gradient resistivity profile, resistivity gradually increases and depicts a stable zone. After 130-m location, apparent resistivity drops and is lowest at 150-m location. The computed apparent resistivity clearly shows a low over the main stretch of the landslide (i.e., 150 to 210 m in Fig. 7). This indicates that the depth of the low resistivity loose material is very large within the slide zone. On either side of the slide, apparent resistivity gradually increases, depicting highly resistive basement rocks, and is therefore interpreted as stable ground. Two bases have been constructed on the stable ground on either side of the landslide. The eastern base (toward Manul) is located between 100 and 130 m, while the western side base (toward Mangan) is built at the 250-m location. A ropeway constructed between these two bases is used for transporting materials in north Sikkim when the road link is cut off due to the landslide.

Resistivity survey

Direct current resistivity is the most commonly used method for delineation of near-surface resistivity distribution. However, the technique needs a suitable stretch of open space for electrode spreading as well as stable ground to place electrodes. At the Lanta Khola landslide location, such an open space for performing electrical resistivity sounding is only present along the road stretch across the landslide. However, resistivity measurements are affected by near-surface concrete material used in construction of roads. Nevertheless, an attempt was made to perform Schlumberger resistivity sounding with limited current electrode spacing. Resistivity soundings were attempted at a number of locations; however, only the soundings at three locations (S-1, S-2, and S-3) were partly successful in generating information that could be interpreted in conjunction with geological and VLF information. Apparent resistivity data were interpreted using global inversion approach (Sharma and Kaikkonen 1999; Sharma and Baranwal 2005) to derive the 1D subsurface resistivity variation. Ten runs are performed for a model, and covariance matrix is computed to determine the uncertainties in each model's parameters. Uncertainties are quite small compared to the absolute values of interpreted model parameters and not shown in Table 1. It is important to mention that structure in the area is gently dipping and mostly 2D and 3D. However, spread in the E–W direction is quite small, and resistivity data interpretation is performed using 1D structure.

Sounding 1 (S-1) was conducted on the right side of the landslide, on the road stretch that leads to Manul. The measured apparent resistivity data shown in Fig. 8a are interpreted using a four-layer (KH-type) model. Interpreted true resistivities and thicknesses of the various layers are presented in Table 1. Third layer indicates the presence of a water-rich horizon. Stable bedrock seems to be present at a depth of 9.5 m. Sounding 2 (S-2) was taken on the road stretch to the left side of the landslide, which proceeds toward Mangan. Apparent resistivity computed from field measurements (Fig. 9a) shows a three-layer (K-type) sounding curve. Table 1 depicts the interpreted layer parameters. It is concluded that the third layer is a highly saturated formation, while the bedrock depth at this location could not be interpreted due to lack of space for conducting resistivity sounding with larger electrode separations. However, measured data indicate that the stable bedrock could be at larger depth at this location. Sounding 3 (Fig. 10a) was also taken on the left side of the landslide, on the road that leads to Mangan (Fig. 2). This sounding also shows a four-layer structure (KH type). Interpreted model parameters presented in Table 1 show that thickness of conductive layer is very small. The bedrock at this location appears to be present at a depth of about 8 m.

Apparent resistivity is the bulk resistivity of the medium and cannot be used to interpret subsurface structure in cases where the subsurface is heterogeneous (as expected in landslides) using layered earth assumption. The nature of the subsurface can be better ascertained by studying the normalized current flow (Baranwal and Sharma 2006). Normalized electric current is the current flow in the subsurface for a unit applied voltage. Figures 8b, 9b, and 10b show the normalized current flow at different electrode separations. Figures 8b and 9b show increasing trend of current flow for later electrode separations that correspond to

Table 1 Interpreted model parameters for various resistivity soundings

Soundings	Resistivities (Ωm)				Thicknesses (m)		
	ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3
S-1	332	80168	548	99698	0.23	4.14	4.85
S-2	818	24146	1.38	–	2.00	8.33	–
S-3	513	2739	368	64720	0.52	4.76	2.12

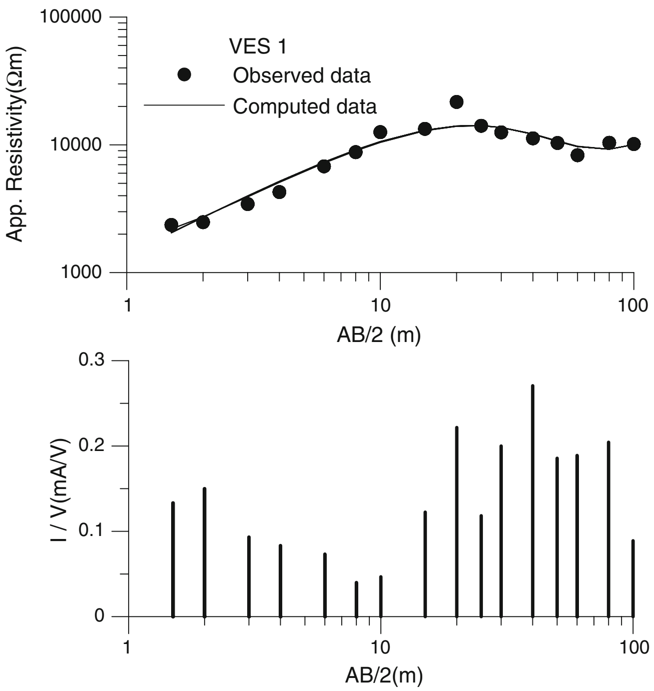


Fig. 8 **a** Fitting between the observed and calculated apparent resistivity. **b** Normalized current flow pattern for sounding 1

deeper structures. It shows that structures at depth are water-saturated for sounding in the slide zone (S-1 and S-2 in Fig. 2) compared to structures at S-3 which are conducted away from the slide zone (Fig. 2). Normalized current flow presented in Fig. 10b decreases with electrode separation and reveals resistive, compact, and unsaturated formations at depth.

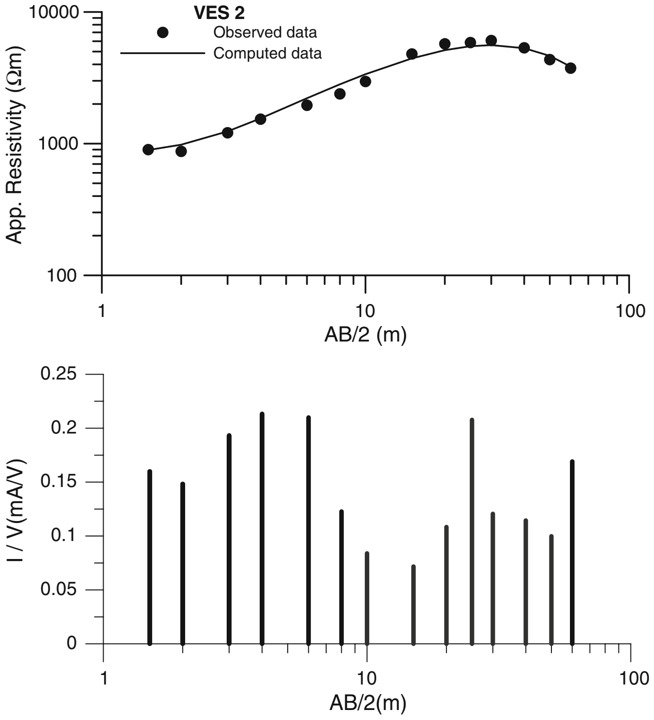


Fig. 9 **a** Fitting between the observed and calculated apparent resistivity. **b** Normalized current flow pattern for sounding 2

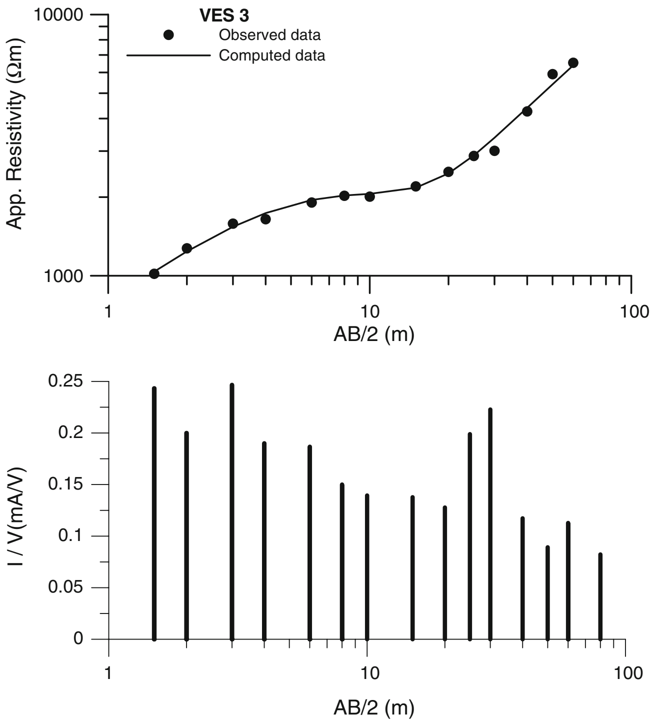


Fig. 10 **a** Fitting between the observed and calculated apparent resistivity. **b** Normalized current flow pattern for sounding 3

Discussion

The activation of the slide in the monsoon period, particularly after spells of heavy rainfall, indicates the involvement of water in debris slide movement. It is therefore important to delineate horizons along which water is transported below the slide surface. However, the inhospitable nature of the terrain, the rugged topography, the unpredictable, mobile nature of the landslide surface in the monsoons, and the inherent logistic difficulties on account of the remote nature of the area imply that drilling into the slide to delineate subsurface water channels is not a feasible proposition. The resistivity survey, however, indicates that the debris material may be quite deep and may extend to depths in excess of 10 m. The VLF profiling clearly depicts that on all the profiles, water is channeled along horizons that dip to the east. Also, the apparent current density at 20 m suggests that there is a general decrease in water content within the debris toward the northwest.

The above results can be satisfactorily interpreted in conjunction with the surface geology. The most saturated part of the debris is located parallel to the geological contact between the gneiss and schist, at the head of 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 along a line that dips at around 35–40° to the east. The conducting horizons on each profile show this feature and are parallel to the resistive geological formations on the left side of the slide. This indicates that most of the water accumulates in and saturates 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. As suggested by Anbarasu et al. (2009), this soggy zone at the contact becomes saturated with water following a particular minimum threshold precipitation (Sengupta et al. 2009). This reduces the shear strength within the soggy zone, ultimately leading to its failure and triggering of slide activity.

It can therefore be concluded that the main water reservoir within the debris is located in the soggy zone at the head of the slide and lies parallel to the geological contact between the gneiss and schist even in the subsurface. It can be demonstrated that slide movement initiates in this zone (Anbarasu et al. 2009) as the part above the soggy zone is vegetated, suggesting stability of the underlying ground surface. Interestingly, even within the debris in the lower part of the slide, the water content decreases in a direction normal to the geological contact and associated foliation below the debris. The geology of the bedrock therefore controls the distribution of water even in the debris material.

Conclusions

The Lanta Khola landslide in North Sikkim is invariably activated in the aftermath of periods of sustained and heavy rainfall. Water accumulation and passage below the exposed surface of the slide is believed to be responsible for sliding, and therefore, identification of sites of subsurface water accumulation is of paramount importance. Geophysical surveys using VLF electromagnetic and DC resistivity were carried out to delineate the subsurface structure below the Lanta Khola landslide. High conducting zones were delineated below the slide surface from VLF observations. These zones are also correlatable with the low resistive zone in the gradient resistivity profiling, and therefore, these anomalies confirm that there is no stable ground up to a large depth below the Lanta Khola slide at road level. Highly resistive structures delineated on either side of the main slide indicate stable bedrock. A prominent water reservoir can be identified below the surface near the crown of the slide; this zone parallels the geological contact between gneisses and schists in the bedrock. This water-saturated zone outcrops on the slide surface as a "soggy zone."

The results of these studies suggest that the water accumulated near the top of the slide must be drained to contain slide movement after rainfall. At present, this may be the only way to minimize slide activity since the absence of stable ground below the slide suggests that constructions made on the slide body may not be permanent and would remain susceptible to every movement of the slide.

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