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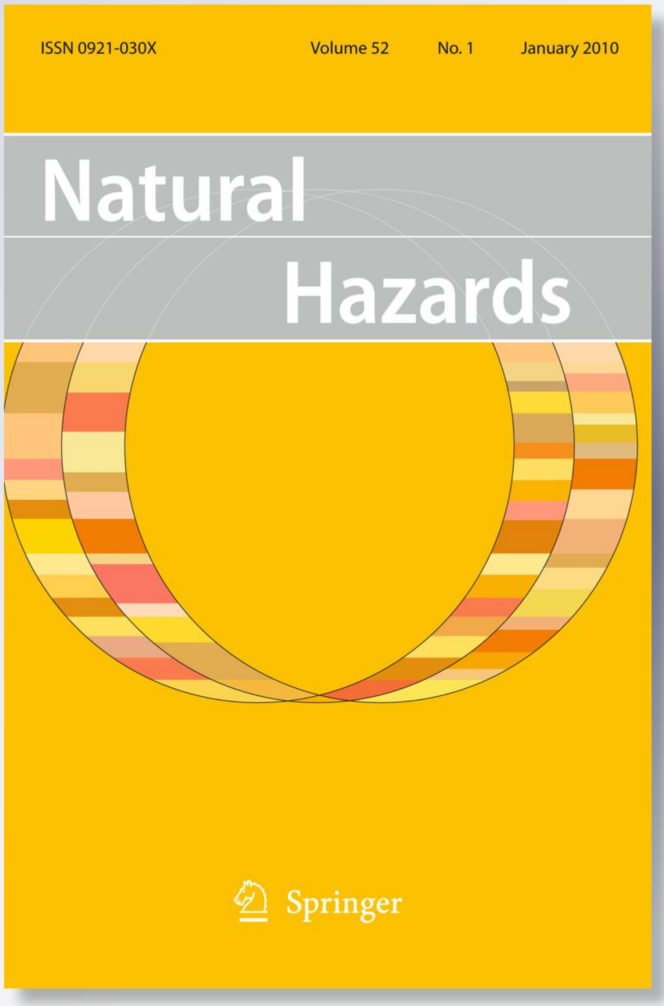

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ORIGINAL PAPER

A characterisation of the physical properties of soil and the implications for landslide occurrence on the slopes of Mount Elgon, Eastern Uganda

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Abstract Soil properties of major landslides that occurred recently on the mid-altitude slopes of Mount Elgon, eastern Uganda were analysed. A mudflow, located at the Kitati protected forest site, and two deep debris flows on the Nametsi and Buwabwala deforested steep slopes (36°–58°) were surveyed. In order to test the hypothesis that 'soils at the landslide sites are particularly 'problem soils' and thus prone to landslides', the following analyses were undertaken: particle size distribution, Atterberg limits, shear strength and factor of safety (F_s). Soils at the Kitati and Buwabwala sites exhibited expansive potential, owing to clay contents well above 20%. A clay content exceeding 32% was identified at the Nametsi debris flow site implying an extremely high expansive potential of the soil. High liquid limits (LLs) at Kitati (59%) and Buwabwala (53%) meant that the soils qualified as vertisols susceptible to landslides. High plasticity indices (PIs) (averaging 33%) also confirmed the vertic nature of soils at the Nametsi debris flow site. Whereas the value of $F_s < 1$ for the Kitati site signifies an inherently unstable slope, Nametsi and Buwabwala are supposedly stable slopes ($F_s > 1$). Despite this finding, the stable sites could be described as only conditionally stable because of the interplay of various physical, pedological and anthropogenic factors. The results point to the fact that soils at the landslide sites are inherently 'problem soils' where slope failure can occur even without human intervention. Therefore, the hypothesis that soils at three landslide sites are inherently 'problem soils' and prone to landslides, is accepted.

Keywords Atterberg limits · Clay content · Expansive potential · Mount Elgon · Problem soils · Vertic soils

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1 Introduction

Mass movements are recognised and well-documented global geomorphic hazards due to their major role in the development of slopes in mountainous areas, and their considerable economic, social and geomorphological impacts (Knapen et al. 2006). However, literature on landslides in East Africa's highlands is still rather restricted (Ngecu and Mathu 1999; Knapen et al. 2006; Claessens et al. 2007). Some of the landslide studies that have been conducted in the East African region include those of Ngecu and Ichangi (1989); Davies (1996); Westerberg and Christiansen (1998); Ngecu and Mathu (1999); Westerberg (1999); Inganga et al. (2001) in Kenya; Muwanga et al. (2001); Kitutu et al. (2004); Knapen et al. (2006); Claessens et al. (2007); Kitutu et al. (2009) in Uganda; Rapp et al. (1972); Christiansen and Westerberg (1999) in Tanzania and Moeyersons (1989, 2003) in Rwanda. These studies suggest anthropogenic factors, such as slope disturbance, and particularly deforestation related to population pressure as the major causes of landslides in the East African highlands (Ngecu and Mathu 1999; Muwanga et al. 2001; Breugelmans 2003; Knapen 2003; Glade and Crozier 2004; Kitutu et al. 2004; Knapen et al. 2006; Kitutu et al. 2009).

Knapen et al. (2006) attribute landslide occurrences in the stable, marginally stable and actively unstable slopes of Mount Elgon to a combination of preparatory and triggering, causal factors. Pre-conditioning factors, including topography (slope angle, length, aspect, gradient and curvature), lithology, shrink-swell soil properties and annual rainfall receipts all act as catalysts to allow other destabilising factors to act more effectively. On the other hand, preparatory factors, including human activities (such as cultivation, excavation for housing, foot paths and deforestation) tend to place slopes in a marginally stable state, making them susceptible to mass movement without actually initiating it. Triggering factors shift slopes from being marginally stable to becoming actively unstable by initiating movement. Such factors include seismic activity, extreme rainfall events related to the El Niño phenomenon and the concentration of runoff in restricted infiltration zones, such as hollows (Glade and Crozier 2004; Knapen et al. 2006).

Specific soil parameters, particularly physical properties, such as bulk density, cohesiveness and shear strength have been noted to affect stability on disturbed slopes (Sidle et al. 1985; Zẽzere et al. 1999; Kitutu et al. 2004; Kitutu et al. 2009; Zung et al. 2009). Other scholars (see Van Der Merwe 1975; Schwartz 1985; Bell and Maud 1994; Bell and Walker 2000; Baynes 2008) have used similar properties to characterise the problem nature and behaviour of soils. According to Baynes (2008), problem soils comprise expansive, soft clays and collapsible and dispersive soils. Problem soils may induce slope failure, due to their distinct shrink-swell properties at various moisture contents (Van Der Merwe 1964; MoW 1999; Baynes 2008). The PI and clay content percentage within the vertic and melanic topsoil horizons can be used to characterise expansive soils (Van Der Merwe 1964, 1975; SCWG 1991; Green and Turner 2009).

Vertic soils are considered highly expansive with a PI of $> 32\%$, whilst soils with a melanic A horizon are defined as those which, amongst other attributes, have a PI of $< 32\%$ (Van Der Merwe et al. 2002). Despite not being considered in many landslide studies, problem soils were noted by William et al. (1985) to be widespread around the world. Their prevalence in the tropics is particularly favoured by climatic conditions (Baynes 2008). Particle size and the distribution of pores within the soil matrix were observed by Sidle et al. (1985) to influence slope stability. Knapen et al. (2006) attributed landslide occurrence on East Africa's highlands to rainfall, steep slopes, slope curvature and high clay contents in the soils. More recently, Kitutu et al. (2009) compared soil

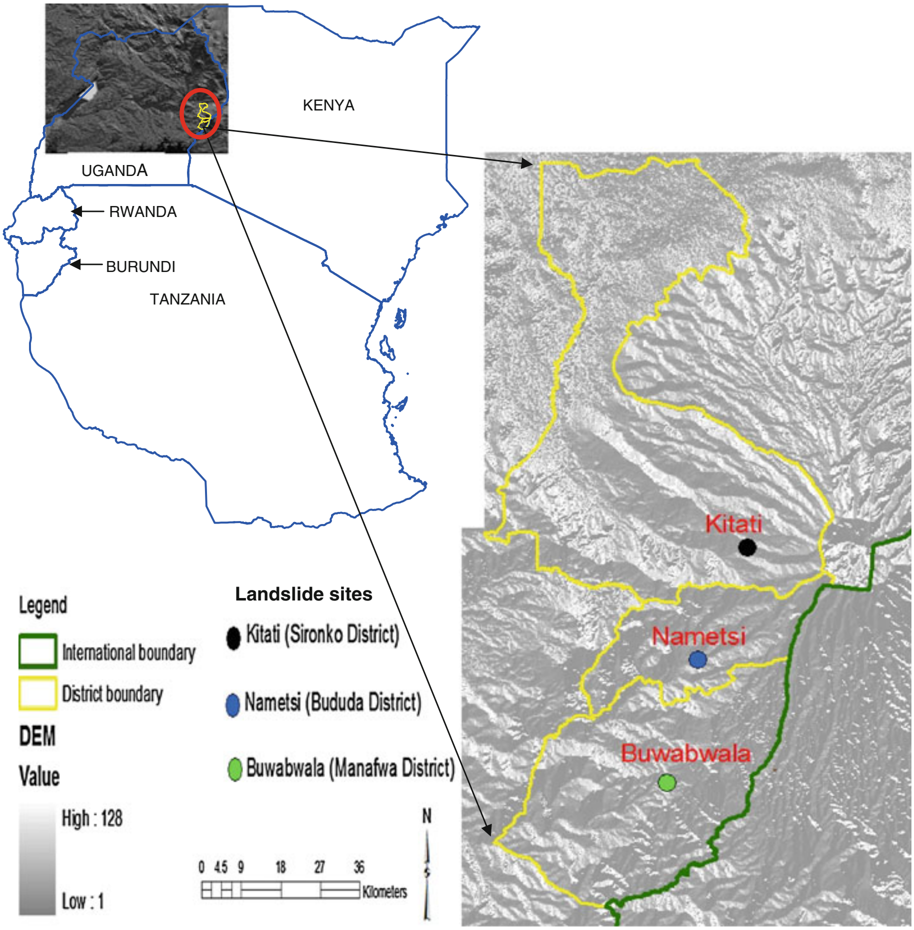

Fig. 1 Location of the study area on the Mount Elgon Volcano. The study sites within the three districts are shown

properties along transects across a series of shallow landslides and zones without landslides within villages on the disturbed foothills of Mount Elgon. Whereas previous landslide studies focused on the disturbed Mount Elgon foothills, the present study compares landslides on the mid-slopes within and outside Mount Elgon National Park (Fig. 1). One of the landslides occurred in a protected pristine forest environment within the Park, whilst the other two are located at sites deforested for cultivation within and outside the National Park. In the main, it is hypothesised that soils at three landslide sites are inherently 'problem soils', where slope failure can occur even without any human intervention.

2 The study area

Mount Elgon (1°25′N and 34°30′E) is situated on the Kenya–Uganda border, approximately 100 km north-east of Lake Victoria (Fig. 1). Mount Elgon, a solitary volcano, is one of the oldest in East Africa (Scott 1994), rising to a height of about 4,320 m above sea level. The region experiences a bimodal rainfall distribution, with the wettest months occurring from April to October. The mean annual rainfall ranges from 1,500 mm on the eastern and northern slopes to 2,000 mm in the south and the west. Mid-slope locations at elevations between 2,000 and 3,000 m tend to receive more rainfall than either the lower slopes or the summit (UWA 2000).

On the lower slopes, the mean maximum temperatures increases from 25 to 28°C and mean minimum temperatures are in the vicinity of 15–16°C. A vast area of the mountain was built up from lava debris blown out from a greatly enlarged vent during the Miocene (Scott 1994). The relatively young and fertile calcium–sodium–potassium-rich soils on the slopes are shallow, dark, humus loams that are permanently moist. On the steep slopes in the high altitude moorlands, very shallow soils are found. However, red-brown clay loams have formed on the gentle slopes (MCEP 1997).

The vegetation of Mount Elgon reflects the altitudinally controlled zonal belts commonly associated with large mountain massifs. Howard (1991) recognised four broad vegetation communities, namely: mixed montane forest up to an elevation of 2,500 m, bamboo and low canopy montane forests from 2,400 to 3,000 m, and moorland above 3,500 m.

2.1 The study sites

2.1.1 Buwabwala site

Buwabwala is situated in the Tsekululu Sub-County on the mid-slopes (1,900–2,500 m above sea level, slope angle 36°–58°) of Mount Elgon in Bubulo County, Manafwa District, Eastern Uganda. Despite being inside the Mount Elgon National Park boundary, this area has been heavily encroached for agriculture, grazing, the collection of firewood, harvesting of construction materials and the poaching of animals. A series of periodic deep and shallow debris flows were reported to have occurred in this area in the past. A deep debris slide which occurred in June 2006 (one of the wettest months in this area) after a spell of torrential rainfall events was surveyed and mapped in the present study (see Fig 2).

2.1.2 Kitati site

This is a deep mudflow that occurred during the intense rainfall spell experienced in December 2008 (see Fig. 3). The Kitati site is located in Bumulegi Village, Budadiri East County, Sironko District. It lies at an altitude range of 2,000 to 2,500 m above sea level; and it is part of the steep (33°–56°) pristine densely forested slopes of the gazetted National Park. Given that previous landslide investigations in the area (Breugelmans 2003; Knapen 2003; Kitutu et al. 2004; Knapen et al. 2006; Claessens et al. 2007; Kitutu et al. 2009) were conducted at sites impacted by human activity, this site presented the unique and intriguing scenario of having occurred in a pristine protected area, particularly as there was a need to gain an understanding of the underpinnings of landslide occurrence in an area that was devoid of any human impacts.

2.1.3 Nametsi site

Nametsi is located on the western slopes of Mount Elgon in Bukalasi Sub-County, Bududa District. It is dissected by streams radiating from the Mount Elgon crater flowing over

Fig. 2 Part of the deep debris flow site at Buwabwala

Fig. 3 Part of the Kitati landslide site on the pristine densely forested slopes of Mt. Elgon National Park

rugged, steep slopes ranging between 36° and 56°. Field observations revealed that this landslide was a deep debris flow at an altitude of 1,900 m above sea level. It occurred on 1 March 2010, after a series of torrential rains. It moved enormous volumes of soil mass and boulders (Fig. 4), burying three villages and killing over 300 people who had gathered on a market day.

3 Materials and methods

3.1 Landslide surveys

Field surveys entailed mapping the deep landslide complex at Buwabwala, using a Magellan Professional MobileMapper™ CX. One longitudinal and three cross-sectional profiles were undertaken using an Abney level and a tape measure. The longitudinal profile was positioned in the centre of the landslide. Two of the cross-sectional profiles were positioned within depletion (CD) and debris slide zones (C^2D^2), whilst the third was in a zone of accumulation (C^1D^1), as illustrated in Fig. 5. The cross-sectional profiles were positioned to highlight variations in slope angle and to show the accumulation of debris within the landslides. Three lobes were identified at the points of intersection between the longitudinal and cross-sectional profiles.

At each point of intersection, pits were dug to a depth of 150 cm. Soil samples were obtained at different depths (at an interval of 30 cm) using sampling cores. These were kept in plastic bags. Owing to the freshness and highly fragile nature of the moist material at the Nameitsi and Kitati sites at the time of the fieldwork, surveying was limited to capturing co-ordinates using a MobileMapper, and soil sampling at both sites was limited to the top 80 cm. That notwithstanding, the deep and rotational nature of the flows at the two sites provided a reasonable idea as to the soil characteristics at greater depths.

Three sampling spots were identified at either site and samples were obtained at intervals of 20 cm. The depth of the debris flow material at the Nameitsi killer landslide was estimated by comparing the MobileMapper elevation reading of the different co-ordinates captured to a 15 m DEM of the area.

Fig. 4 Killer landslide at Nametsi Village. Over 300 people, homes and a community health centre were buried by the debris flow

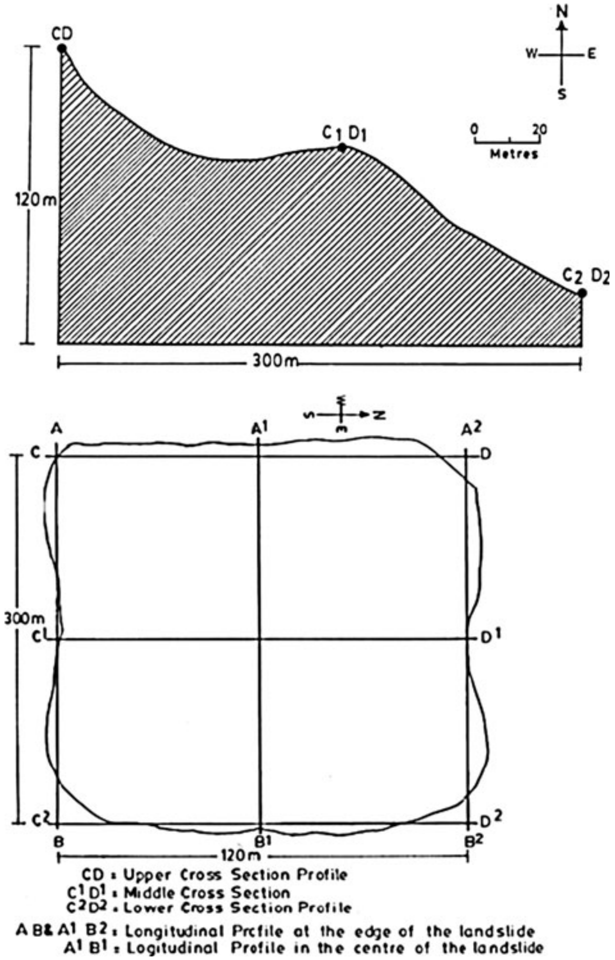

Fig. 5 Schematic presentation of the landslide complex at Buwabwala showing cross-sectional and longitudinal profiles

3.2 Laboratory analyses

In order to establish and characterise the problem nature of the slope material in terms of its implications for slope stability, a range of analyses was carried out at the Geotechnical Laboratory, Faculty of Technology, Makerere University. The analyses focused on the distribution of the soil particles, Atterberg limits (liquid and plastic limits) and shear strength. Particle size distribution was conducted in accordance with the British Standard test (BS) 1377: Part 2 sub-clause 9.2: 1990. The percentage of clay, in particular, gives a clear indication as to the problem nature of the soils.

The determination of Atterberg limits is an important component of soil analysis, as it also points to the problem nature or otherwise of the soil, particularly in terms of its expansion potential at different moisture and clay contents (Selby 1993). Such behavioural properties can be used to explain the susceptibility of slopes to various slope processes. In the present study, the plastic and LLs were determined, in accordance with BS 1377: Part 2, sub-clause. 4.5: 1990. The lower the organic matter content and, conversely, the higher the clay content of the soil, the higher the PI (Hartmann and De Boodt 1974; De La Rosa 1979; Husein Malkawi et al. 1999). The plasticity of the soil samples was further determined using the unified soil classification system (USCS) plasticity chart, which also enabled further classification of the fine material.

Shearing strength in soils is the result of the resistance to movement at inter-particle contacts, due to particle interlocking, physical bonds across contact areas and chemical bonds. Shear strength parameters (cohesion and internal friction) are crucial for slope stability analyses. A Shear Box Test was carried out on the undisturbed samples, in accordance with BS 1377: Pat7: 1990. This method allows a direct shear test to be made by relating the shear stress at failure to the applied normal stress. It enables the determination of the effective shear strength parameters of the soil, namely: the cohesion (C) and the internal angle of friction (φ) values. These are then used to calculate the F_s of slopes.

Theoretically, if the F_s is > 1, then the slope is naturally stable; its failure may be due to external factors. Conversely, if $F_s < 1$, then the slope is inherently unstable (Berry and Reid 1987). The F_s was calculated thus;

$$F_s = \left[1 - \frac{\rho_w}{\rho_s} \cdot \frac{D_w}{D}\right] \frac{\tan \varphi}{\tan \alpha} + \frac{2C}{\rho_s g D \sin 2\alpha}$$

where D_w = depth of landslide, C = cohesion, D = slip depth, φ = internal angle of friction, α = slope angle, ρ_w = unit weight of water (1 Mg/cm^3), ρ_s = unit weight of soil, g = gravitational acceleration (9.81 m/s^2).

4 Results

4.1 Field surveys and mapping

Field observations revealed that, at the Buwabwala and Nametsi landslide sites, a rotational debris slide and flow had occurred, respectively. Evidence from pits dug at the Buwabwala site clearly indicated an inversion of materials from a greater depth to the surface and vice versa (Fig. 6). The Kitati site had experienced a mudflow, given the enormous amounts of unconsolidated earth and fluid debris (see Fig. 7). Using a 15 m DEM, failure at all three sites was found to have occurred on concave slopes ranging between 36° and 58° slope angles (Mugagga 2011). The dimensions of the depletion zone of the Buwabwala landslide site are summarised in Table 1.

Field measurements revealed that the depletion zone of the Buwabwala landslide covered an area of approximately 208 by 165 m, with an average scarp depth of 4.5 m. The accumulation zone occupied an area of 125 m by 55 m, whilst the debris slide zone, with an average debris diameter of 2.125 m, covered 270 m by 27.5 m, burying the maize crop at the freshly cleared site. The depth of the Nametsi killer landslide calculated, as described earlier, was ≥ 8 m.

4.2 Soil texture

Soil texture data from the three sites is presented in Table 2. Soil samples for Nametsi have, on average, clay content exceeding 32%, implying extremely high expansive potential. The

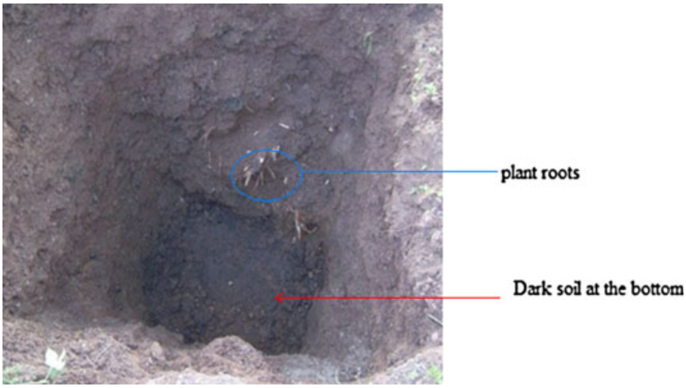

Fig. 6 Evidence of rotation as shown by dark top soil and the plant roots that were found buried at a depth of 2 m

Fig. 7 Mudflow at the Kitati landslide site

soils at Buwabwala and Kitati sites also exhibit an expansion potential, owing to the clay content that is, on average, well above 20%. Such clay content has implications for the shrink-swell properties of the soil. A 10% clay threshold has been used as an indicator of the expansion potential, whilst $> 32\%$ clay content exhibits extreme expansion potential (Van Der Merwe 1964; Baynes 2008). The particle distribution presented in the subsequent sub-section further characterises the landslide-prone nature of the soils.

4.3 Soil particle distribution

Particle distribution curves for the three sites are presented in Fig. 8. Soils from the respective sites were generally fine grained, with more than 50% of the material passing the 0.075 mm sieve. However, soils from the Nametsi site are finer than those from the

Table 1 Dimensions of the Buwabwala landslide site

	Length (m)	Width (m)	Scarp depth (m)
Depletion zone			
Minimum	15	30	0.5
Maximum	180	110	8.4
Average	97.5	70	4.45
Accumulation zone			
Minimum	30	40	
Maximum	220	70	
Average	125	55	
Debris slide zone			
Minimum	40	15	
Maximum	500	40	
Average	270	27.5	

other two sites. The extremely fine-textured nature of the material at the sites also has strong implications for landslide occurrence, as will be discussed.

4.4 Atterberg limits

In order to gain insights into soil behaviour in response to water content, and the subsequent implications for landslide occurrence, Atterberg limits were calculated (Table 3). The LL for all the sites is way above the threshold of 25%, indicating the high expansion potential of the soils. The high LL and PI (> 32%), further confirm the extremely high expansion potential for Nametsi soils. This points to the inherent problem nature of the soils. The PI, which demonstrates the volume-change characteristics of the soils, is illustrated by the plasticity chart (Fig. 9).

The plasticity chart reveals that all the soils at the respective sites contain clay of high plasticity. Specifically, soils from Buwabwala are blackish sandy clays, classified as inorganic clays of high plasticity (MH), whilst Kitati soils are yellowish brown sandy silts, described as inorganic silts of high plasticity (CH) groups. The soils from Nametsi are dark brown sandy silty clays, classified as inorganic clays of high plasticity (CH). The highly plastic nature of Nametsi and Buwabwala sites is demonstrated by their plotting above the boundary A-line. An idea as to the general natural slope stability at the respective sites, as depicted by the F_s, was calculated from the shear strength parameters, as presented below.

4.5 Shear strength and F_s

Plots of shear strength versus normal stress were used to compute the angle of internal friction and cohesion which were then used to calculate the slope F_s for the three sites. Curves for Buwabwala, Nametsi and Kitati sities are presented in Fig. 10 a, b, c, respectively. The F_s and shear strength parameters at the three sites, as calculated from the shear strength versus the normal stress curves, are presented in Table 4. As depicted by the F_s, which is higher than the critical factor of 1, slopes at Buwabwala and Nametsi sites are supposedly stable, whilst those at Kitati ($F_s < 1$) are unstable. The Kitati landslide, therefore, occurred on inherently unstable, pristine, forested slopes. It is noteworthy, however, that even slopes where $F_s > 1$ are conditionally stable. The stability is compromised once external and internal factors exert their influence, as will be discussed.

Table 2 Texture analysis

Profile depth (cm)	%OM	%Sand	%clay	%Silt	Textural class
Buwabwala landslide site					
Upper slope profile					
0–30	2.4	56	20	24	Sandy clay loam
30–60	1.6	60	20	20	Sandy clay loam
60–90	1.6	56	20	24	Sandy clay loam
90–120	1.2	48	26	26	Sandy clay loam
120–150	1.4	52	23	25	Sandy clay loam
Middle slope profile					
0–30	1.5	44	26	30	Loam
30–60	0.6	46	32	22	Sandy clay loam
60–90	0.7	44	30	26	Clay loam
90–120	0.5	56	24	20	Sandy clay loam
120–150	1.3	42	27	31	Loam
Lower slope profile					
0–30	3.6	56	24	20	Sandy clay loam
30–60	1.0	76	10	14	Sandy loam
60–90	1.2	56	18	26	Sandy loam
90–120	1.2	48	24	28	Sandy clay loam
120–150	0.9	52	19	29	Sandy clay loam
Kitati landslide site					
Sampling spot 1					
0–20	7.1	40	32	28	Sandy clay
20–40	6.1	64	14	22	Sandy loam
40–60	8.0	42	30	28	Sandy clay loam
60–80	6.8	43	26	31	Sandy clay
Sampling spot 2					
0–20	7.1	44	27	29	Sandy loam
20–40	6.0	56	18	26	Sandy loam
40–60	5.8	62	17	21	Sandy loam
60–80	7.0	40	28	32	Sandy loam
Sampling spot 3					
0–20	6.8	44	26	30	Sandy loam
20–40	6.4	46	30	24	Sandy clay loam
40–60	5.4	41	27	32	Sandy loam
60–80	6.6	60	19	21	Sandy loam
Nametsi landslide site					
Sampling spot 1					
0–20	3.3	6	48	46	Silty clay
20–40	4.2	11	43	46	Silty clay
40–60	2.9	15	46	39	Clay
60–80	3.2	7	48	45	Silt clay
Sampling spot 2					
0–20	3.0	9	42	49	Silty clay

Table 2 continued

Profile depth (cm)	%OM	%Sand	%clay	%Silt	Textural class
20–40	2.7	22	36	42	Silty clay
40–60	1.7	18	39	43	Silty clay
60–80	2.5	19	42	39	Clay
Sampling spot 3					
0–20	1.2	25	38	37	Clay
20–40	1.3	28	32	40	Silty clay
40–60	1.4	27	34	39	Silty clay
60–80	3.2	14	42	44	Silty clay

Take note of the > 10% clay content at the three sites

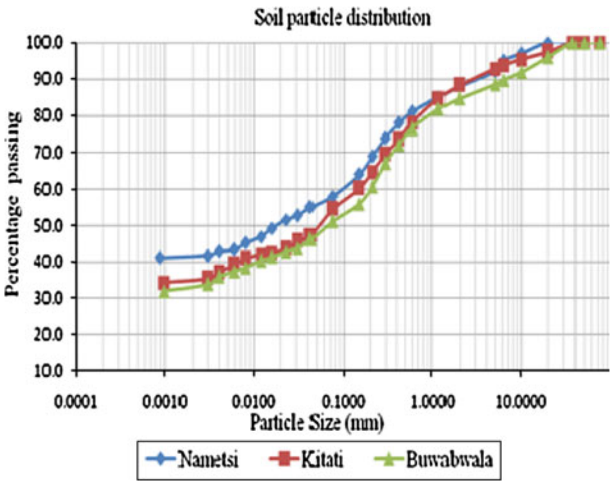

Fig. 8 Soil particle distribution curves for the landslide sites

Table 3 Atterberg limits for the respective sites

Atterberg limits (%)	Buwabwala	Kitati	Nametsi
Liquid limit (LL)	53.5	59.0	47
Plastic limit (PL)	29.7	38.7	14
Plasticity index (PI)	23.8	20.3	33

5 Discussion

The steep concave nature of the slopes (36°–58°, mid-altitude; 1,900–2,500 m a.s.l.), as observed at the three landslide sites, has important implications for slope hydrology. According to Coker and Flores (1999), Westerberg (1999), Glade (2002) and Knapen et al. (2006), deep rotational landslides on concave slopes can be attributed to the concentration of runoff and sub-surface water which reduces slope shear resistance. Yang et al. (2007) and Wati et al. (2010) noted that steep slopes, particularly those at high elevations, are

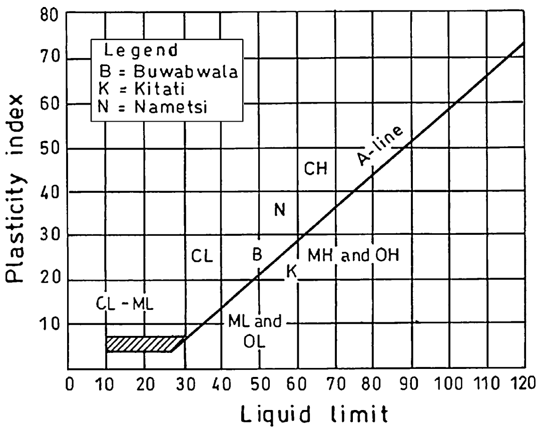

Fig. 9 USCS plasticity chart for Buwabwala, Kitati and Nametsi soils

susceptible to failure, owing to the increasing shear stress against reducing shear strength. An overlay of several landslide sites on a curvature surface by Mugagga (2011) also revealed the spatial correlation between landslide occurrence and topographical concavity. This highlights the susceptibility of concave elements of Mount Elgon slopes to failure, which should be taken cognisance of as restoration and conservation hotspots.

The clay fraction, which is well above the 10% threshold, identified from analyses of soil samples from the respective sites, explains the shrink-swell properties such that the soils exhibit extreme expansion potential and are hence, susceptible to landslides. The implications of such high clay content for landslide occurrence have been demonstrated by, *inter alia* Knapen et al. (2006), Yang et al. (2007), Kitutu et al. (2009) and Wati et al. (2010). Kitutu et al. (2009) identified the dominant clay minerals on selected slopes of Mount Elgon as highly plastic kaolinite and illite. According to Ohlmacher (2000), and Yalcin (2007), illite clays are associated with landslide occurrence owing to their low shear strength and high swelling potential. In the same vein, soil particle distribution curves revealed the fine-textured nature of the soils at all three sites. Fine-textured clayey soils have small pores and liberate water gradually, which renders them susceptible to landslides because of their high water retention capacity (Yang et al. 2007; Jadda et al. 2009; Wati et al. 2010). Their low permeability also exacerbates this vulnerability (Wati et al. 2010).

The plasticity chart revealed that the soils at the respective sites are inorganic clays and silts of high plasticity. Previous studies observed positive correlations between high plasticity and fine-grained inorganic clay and silts (Orazulike 1988; Chartwin et al. 1994; Isik and Keskin 2008). Highly plastic inorganic soils are prone to sliding during rainfall events, due to the reduction of shear resistance (Dai et al. 2002). The same scenario plays out on the slopes of Mount Elgon, where highly plastic inorganic clays become susceptible to sliding even under moderate rainfall events. The soils from the Nametsi site exhibit a higher PI than the other two sites (33%, as opposed to 23.8% and 20.3% for Buwabwala and Kitati, respectively). Owing to the high clay content (41% on average) and PI $>$ 32%, the soils at the Nametsi site are categorised as vertisols; soils which are known for inducing mass wasting.

The role of LLs in characterising the problem nature of soils has been noted by various scholars (Van Der Merwe 1964; Mario et al. 1996; Msilimba and Holmes 2005; Fauziah et al. 2006; Baynes 2008). The extremely high LLs for Buwabwala and Kitati (53% and 59%, respectively) confirm the problem nature of the soils at the two sites, as categorised

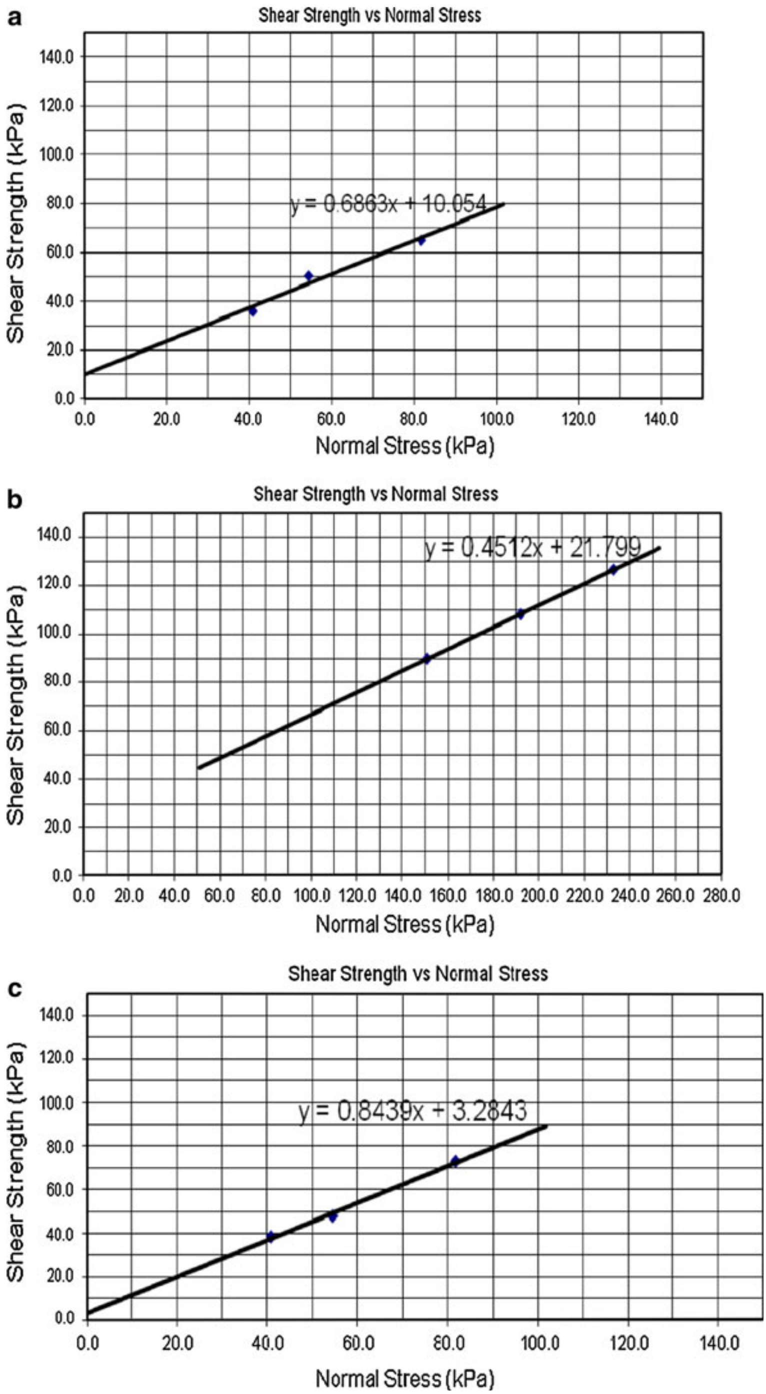

Fig. 10 Shear strength versus normal stress curves for Buwabwala, Nametsi and Kitati sites

Table 4 Shear parameters and factor of safety at the three sites

Bulk density g_b (Mg/m)^3	Normal stress δ_n (kPa)	Shear strength t_s (kPa)	Cohesion C (kPa)	Angle of Internal friction, f (°)	Factor of safety
Buwabwala					
	40.9	36.0	10	34	2.16
2.04	54.5	50.6			
	81.8	65.1			
Nametsi					
	151.0	90.0	22	24	1.88
2.29	192.0	108.3			
	233.0	127.0			
Kitati					
	40.9	38.7	3	40	0.96
2.04	54.5	47.9			
	81.8	72.7			

by Van Der Merwe (1964) and Baynes (2008). The high LLs coupled with high clay content and vertic soil properties at the Nametsi site qualify the soils at the three sites as 'problem soils' that are susceptible to landslides.

The F_s for the Buwabwala and Nametsi sites suggests slope stability in both instances, whilst the reverse is true of the Kitati slope. That notwithstanding, slope failure often occurs as a result of localised deformation in a thin zone of intense shearing. Consequently, using overall stress–strain measurements may not be representative of such intense shear behaviour (Finno et al. 1997; Gonghui et al. 2010). 'Conditional stability' would be the appropriate description of the slopes at the supposedly stable sites, owing to the interplay of various physical, pedological and anthropogenic factors. Fig. 11 is a conceptual model depicting the interplay between these factors. As noted by Sidle et al. (1985), Gupta and Joshi (1990), Inganga et al. (2001), Nyssen et al. (2002), Knapen et al. (2006), Claessens et al. (2007), NEMA (2007) and Kitutu et al. (2009), high rainfall coupled with human intervention through deforestation, cultivation and excavation are external factors that induce slope instability even on hitherto stable slopes.

In the same vein, human activity on the slopes of Mount Elgon has drastically decreased the margin of hillslope stability, especially in densely populated and intensively cultivated steep areas. The steep and concave nature of the slopes and the implications for soil hydrology alluded to earlier, compounds this interplay. In the present study, two sites with inherently problematic soils were deforested for cultivation, rendering them susceptible to failure, despite their ostensible stability. The inherently unstable slopes at Kitati forested site ($F_s < 1$) explain the landslide occurrence even without any human intervention.

It is noteworthy, however, that the problem nature of the soils, as identified in this study, is not unique to the mid-altitude sites investigated. Similar observations were made by studies that focused on the densely populated lower slopes of Mount Elgon (Breugelmans 2003; Knapen 2003; Kitutu et al. 2004; Knapen et al. 2006; Claessens et al. 2007; Kitutu et al. 2009). By implication, the problem nature of the soils on Mount Elgon slopes is ubiquitous; it is recommended that conservation-based land use options are undertaken, particularly, on the mid-altitude slopes.

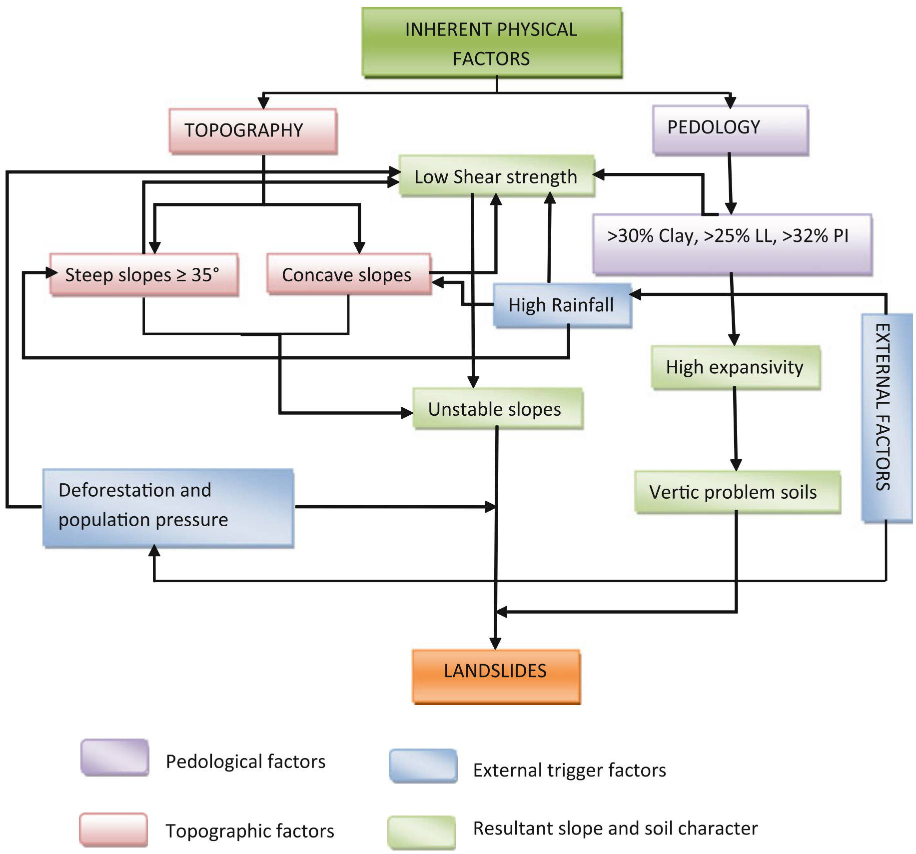

Fig. 11 Conceptual model depicting the interplay between internal and external factors to induce landslides

6 Conclusion

This study has characterised the physical properties of soils on both disturbed and pristine slopes of Mount Elgon, and their implications for landslide occurrence. The soil at the sites is characterised by high clay content, fine texture and high plasticity. Whilst high PIs at Nametsi confirm the vertic properties of the soil, the extremely high LL of Buwabwala and Kitati soils signifies their inherent problem nature. On the basis of the F_s (<1), the Kitati landslide is confirmed to have occurred on inherently unstable pristine forested slopes. The conditional stability at Buwabwala and Nametsi sites was compromised by an interplay of physical, pedological and anthropogenic factors. In a nutshell, the hypothesis that soils at the three landslide sites are inherently 'problem soils' where slope failure could occur even without any human intervention, is now generally accepted.

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References

Baynes FJ (2008) Anticipating problem soils on linear projects. In: Conference proceedings on problem soils in South Africa, 3–4 November 2008, pp 9–21

Bell FG, Maud RR (1994) Dispersive soils. A review from a South African perspective. Q J Eng Geol Hydrol 27(3):195–210. doi:10.1144/gsl.qjegh.1994.027.p3.02

Bell FG, Walker DJH (2000) A further examination of the nature of dispersive soils in Natal, South Africa. Q J Eng Geol Hydrol 33(3):187–199. doi:10.1144/qjegh.33.3.187

Berry PL, Reid D (1987) An introduction to soil mechanics. McGraw-Hill Book Company (UK) Limited, UK

Breugelmans W (2003) The influence of soil, land use and deforestation on the occurrence of landslides in Mount Elgon area, Eastern Uganda. Unpublished Msc thesis, Catholic University Leuven, Belgium

Chartwin SC, Howes DE, Schwab JW, Swanston DN (1994) A guide for management of landslide-prone terrain in the Pacific Northwest. Ministry of Forests, Victoria

Christiansen C, Westerberg LO (1999) Highlands in East Africa: unstable slopes, unstable environments. Ambio 18:419–429

Claessens L, Knapen A, Kitutu MG, Poesen J, Deckers JA (2007) Modelling landslide hazard, soil redistribution and sediment yield of landslides on the Ugandan footslopes of Mount Elgon. Geomorphology 90(1–2):23–35. doi:10.1016/j.geomorph.2007.01.007

Coker I, Flores R (1999) Implications of live barriers for slope stability in Andean hillside farming systems. Mount Res Dev 19(4):300–306

Dai FC, Lee CF, Ngai YY (2002) Landslide risk assessment and management: An overview. Eng Geol 64(1):65–87

Davies TC (1996) Landslides research in Kenya. Afr Earth Sci 23:41–49

De La Rosa D (1979) Relation of several pedological characteristics to engineering qualities of soil. Eur J Soil Sci 30(4):793–799. doi:10.1111/j.1365-2389.1979.tb01028.x

Fauziah A, Yahaya AS, Farooqi MA (2006) Characterization and geotechnical properties of Penang residual soils with emphasis on landslides. Am J Environ Sci 2(4):121–128. doi:10.3844/ajessp.2006.121.128

Finno RJ, Harris WW, Mooney MA, Viggiani G (1997) Shear bands in plane strain compression of loose sand. Geotechnique 47(1):149–165

Glade T (2002) Landslide occurrence as a response to land use change. A review of evidence from New Zealand. Catena 51(3–4):294–314

Glade T, Crozier GM (2004) The nature of landslide hazard impact. In: Glade T, Anderson MG (eds) Landslide hazard and risk. Wiley, Chichester, pp 43–74

Gonghui W, Suemine A, Schulz WH (2010) Shear-rate-dependent strength control on the dynamics of rainfall-triggered landslides, Tokushima Prefecture, Japan. Earth Surf Proc Land 35(4):407–416. doi:10.1002/esp.1937

Green PP, Turner D (2009) The preliminary identification of problem soils for infrastructure projects. In: Proceedings of the conference on problem soils in South Africa, Midrand, Gauteng. ISBN: 978-0-620-42511-7

Gupta RP, Joshi BC (1990) Landslide hazard zoning using the GIS approach. A case study from the Ramganga catchment, Himalayas. Eng Geol 28:119–131

Hartmann R, De Boodt M (1974) The influence of the moisture content, texture and organic matter on the aggregation of sandy soil and loamy soils. Geoderma 11(1):53–62. doi:10.1016/0016-7061(74)90006-8

Howard PC (1991) Nature conservation in Uganda's forest reserves. Gland, Switzerland

Husein Malkawi AI, Alawneh AS, Abu-Safaqah OT (1999) Effects of organic matter on the physical and the physicochemical properties of an illitic soil. Appl Clay Sci 14(5):257–278. doi:10.1016/s0169-1317(99)00003-4

Inganga SF, Ucakuwun EK, Some DK (2001) Rate of swelling of expansive clays: a critical factor in the triggering of landslides and damage to structures. Doc Nat 136:93–98

Isik Y, Keskin Y (2008) GIS based statistical and physical approaches to landslide susceptibility mapping (Sebinkarahisar, Turkey). Bull Eng Geol Environ 68:459–471

Jadda M, Shafri HZ, Mansor S, Sharifikia M (2009) Landslide susceptibility evaluation and factor effect analysis using probabilistic–frequency ratio model. Eur J Sci Res 33:654–668

Kitutu M, Muwanga A, Poesen J, Deckers J (2004) The relationship between geology and landslides in Manjiya County, south west of Mount Elgon, Eastern Uganda. Geoscience Africa 2004 Conference. Abstract volume 1. University of Witwatersand, Johannesburg, South Africa, pp 349–350

Kitutu MG, Muwanga A, Poesen J, Deckers JA (2009) Influence of soil properties on landslide occurrence in Bududa district, Eastern Uganda. Afr J Agr Res 4(7):611–620

Knapen A (2003) Spatial and temporal analyis of landslides in Manjiya county, Mount Elgon area, Eastern Uganda. Unpublished Msc thesis, Catholic University Leuven, Belgium

Knapen A, Kitutu MG, Poesen J, Breugelmans W, Deckers J, Muwanga A (2006) Landslides in a densely populated county at the footsteps of Mount Elgon (Uganda): characteristics and causal factors. Geomorphology 73:149–165

MA NE (2007) State of environment report for Uganda for 2006/07. National Environment Management Authority, Kampala

Mario P, Pasuto A, Silvano S, Soldati M (1996) Temporal occurrence and activity of landslides in the area of Cortina d'Ampezzo (Dolomites, Italy). Geomorphology 15(3–4):311–326. doi:10.1016/0169-555X(95)00077-I

MCEP (1997) Mount Elgon National Conservation and Development Project (MECDP). Final report, Ministry of Natural Resources, Kampala, Uganda

Moeyersons J (1989) A possible causal relationship between creep and sliding in Rwaza hill, southern Rwanda. Earth Surf Proc Land 14(6):597–614. doi:10.1002/esp.3290140615

Moeyersons J (2003) The topographic thresholds of hillslope incisions in southwestern Rwanda. Catena 50:381–400

MoW (1999) Pavements and materials design manual. The United Republic of Tanzania

Msilimba GG, Holmes PJ (2005) A landslide hazard assessment and vulnerability appraisal procedure: Vunguvungu/Banga catchment, Northern Malawi. Nat Hazards 34(2):199–216. doi:10.1007/s11069-004-1513-2

Mugagga F (2011) Land use change, landslide occurrence and livelihood strategies on Mount Elgon slopes, eastern Uganda. Unpublished PhD thesis, Nelson Mandela Metropolitan University, Port Elizabeth

Muwanga A, Schuman A, Biryabarema M (2001) Landslides in Uganda—documentation of a natural hazard. Doc Nat 136:111–115

Ngecu WM, Ichangi DW (1989) The environmental impact of landslides on the population living on the Eastern footslopes of Aberdare Ranges in Kenya. A case study of Maringa village. Env Geol 38(3):259–264

Ngecu WM, Mathu EM (1999) The El Nino-triggered landslides and their socioeconomic impact on Kenya. Environ Geol 38(4):277–284

Nyssen J, Moeyersons J, Poesen J, Deckers J, Mitiku H (2002) The environmental significance of the remobilization of ancient mass movements in the Atbara–Tekeze headwaters near Hagere Selam, Tigray, Northern Ethiopia. Geomorphology 49:303–322

Ohlmacher GC (2000) The relationship between geology and landslide hazards at Atchison, Kansas and vicinity. Curr Res Earth Sci 244(3):1–16

Orazulike DM (1988) Hazardous earth processes in parts of Bauchi state, Nigeria. Their causes and environmental implications. Nat Hazards 1(2):155–160. doi:10.1007/bf00126612

Rapp A, Berry L, Temple P (1972) Landslides in the Mgeta area, Western Uluguru Mountains, Tanzania. Bureau of Resource Assessment and Land Use Planning, University of Dar es salaam and Department of Physical Geography, University of Uppsala

Schwartz K (1985) Collapsible soils. Civil Eng South Afr 27(7):379–393

Scott P (1994) An assessment of natural resource use by communities from Mount Elgon National Park, UNDP/Technical report No. 15

Selby MG (1993) Hillslope materials and processes. Oxford University Press, New York

Sidle RC, Pearce AJ, Loughlin CLO (1985) Hillslope stability and land-use. American Geophysical Union, Washington, DC, p 125

Soil Classification Working Group (SCWG) (1991) Soil classification. A taxonomic System for South Africa. Department of Agricultural Development, Pretoria

Van der Merwe DH (1964) The prediction of heave from the plasticity index and the percentage clay fraction of soils. Trans South Afr Inst Civil Eng 6(6):103–107

Van der Merwe DH (1975) Plasticity index and percentage clay fraction of soils. In: Proceedings of the fourth regional conference in Africa on soil mechanics and foundation engineering, vol 2, pp 166–167

Van Der Merwe GME, Laker MC, Buhmann C (2002) Factors that govern the formation of melanic soils in South Africa. Geodarma 107(3):165–176. doi:10.1016/s0016-7061(01)00119-7

WA U (2000) Mount Elgon National Park. General Management Plan, Final Report

Wati SE, Hastuti T, Wijojo S, Pinem F (2010) Landslide susceptibility mapping with heuristic approach in mountainous area. A case study in Tawangmangu sub District, Central Java, Indonesia. Int Arch Photo RS Spat Inf Sci 38(8):248–253

Westerberg LO (1999) Mass movements in East African highlands: processes, effects and scarp recovery. Dissertation 14, Department of Physical Geography, Stockholm University, Sweden

Westerberg L, Christiansen C (1998) Landslides in East African Highlands. Slope instability and its interrelation with landscape characteristics and land use. Adv GeoEcol 31:317–325

William AAB, Pidgeon JT, Day PW (1985) Expansive soils. Trans South Afr Inst Civil Eng 27:367–397

Yalcin A (2007) The effects of clay on landslides: a case study. Appl Clay Sci 38:78–85

Yang H, Adler R, Huffman G (2007) Use of satellite remote sensing in the mapping of global landslide susceptibility. Nat Hazards 43(2):245–256. doi:10.1007/s11069-006-9104-z

Zêzere JL, Ferreira AB, Rodrigues ML (1999) Landslides in the North of Lisbon Region (Portugal): conditioning and triggering factors. Phys Chem Earth A 24(10):925–934. doi:10.1016/S1464-1895(99)00137-4

Zung AB, Sorensen CJ, Winthers E (2009) Landslide soils and Geomorphology in Bridger/Teton Forest Northwest Wyoming. Phys Geogr 30(6):501–516