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Full Length Research Paper

Physical and geotechnical characterization of unconsolidated sediments associated with the 2005 Mbonjo landslide, Limbe, Cameroon

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Laboratory analyses of unconsolidated sediments from the ruptured zone of the 2005 Mbonjo Landslide scar were carried out to characterize and evaluate their role as contributory factors in enhancing the slide. Colour, particle size (PS) and particle size distribution (PSD), Atterberg limits [liquid limit (LL), plastic limit (PL) and plasticity index (PI)] and basic geotechnical properties [bulk density (ρ), dry bulk density (ρ_d), dry unit weight (γ_d), moisture content (Mc), specific gravity (Gs), void ratio (e) and porosity (n)] were determined. Colour ranged from reddish brown to yellowish brown. Texturally, samples were classified as loam, silty clay loam and silty clay. Liquid limit ranged from [56 to 74 weight percentage (wt%)], PL (37 to 50 wt%) and PI (15 to 36 wt%). Values for geotechnical properties were ρ (2 to 2.25 g/cm^3), ρ_d (1.75 to 1.95 g/cm^3), Mc (14 to 15 wt%), Gs (2.67 to 2.69 g/cm^3), e (0.37 to 0.52) and n (0.27 to 0.34). From results of colour, PS and PSD, Atterberg limits and geotechnical analyses, the samples were reflective of clay-rich sediments with high plasticity and sliding potential. Based on the interpretative data, the studied sediments were qualified as landslide prone with clay interbeds serving as the slide surface.

Key words: Cameroon volcanic line, clay interbeds, geotechnical properties, ruptured zone, slide surface.

INTRODUCTION

Dramatic effects resulting from landslides on human life and the economy of many nations have been observed across the globe (Anbalagan, 1992; Ercanoglu and Gokceoglu, 2002; Ercanoglu et al., 2004; Micheal-Leiba et al., 2003). Ercanoglu et al. (2004) stated that the economic loses and casualties recorded due to landslides in many countries are greater than those commonly recognized. This situation is even more deplorable in developing countries which are less equipped technically and financially to handle natural disasters (Ngole et al., 2007). Cameroon is one of these countries hit by landslide hazards. The Cameroon volcanic line (CVL) (Figure 1), a 1600 km long volcanic line stretching from the Island of Pagalu to Oku through Sao Tome, Principe and Mount Cameroon (Ayonghe et al., 2004; Déruelle, 1982; Fitton, 1987), has in recent years been plagued by a series of natural hazards; volcanic eruptions, earthquakes and tremors (Suh et al., 2003), degasification of volcanic lakes and maars (Ekosse, 1998) and landslides and floods (Ayonghe et al., 1999, 2002, 2004). Of all these hazards, the most frequent and catastrophic has been landslides (Ayonghe et al., 2002, 2004; Diko, 2006).

According to Ayonghe et al. (2002), landslides along the CVL are of hydrologic, seismic and tectonic origins. The ease with which gravity pulls down a slope (landslide) is controlled by the interaction between triggering mechanisms and contributory factors (Ayonghe et al., 2004, 2002; Ercanoglu and Gokceoglu, 2002;

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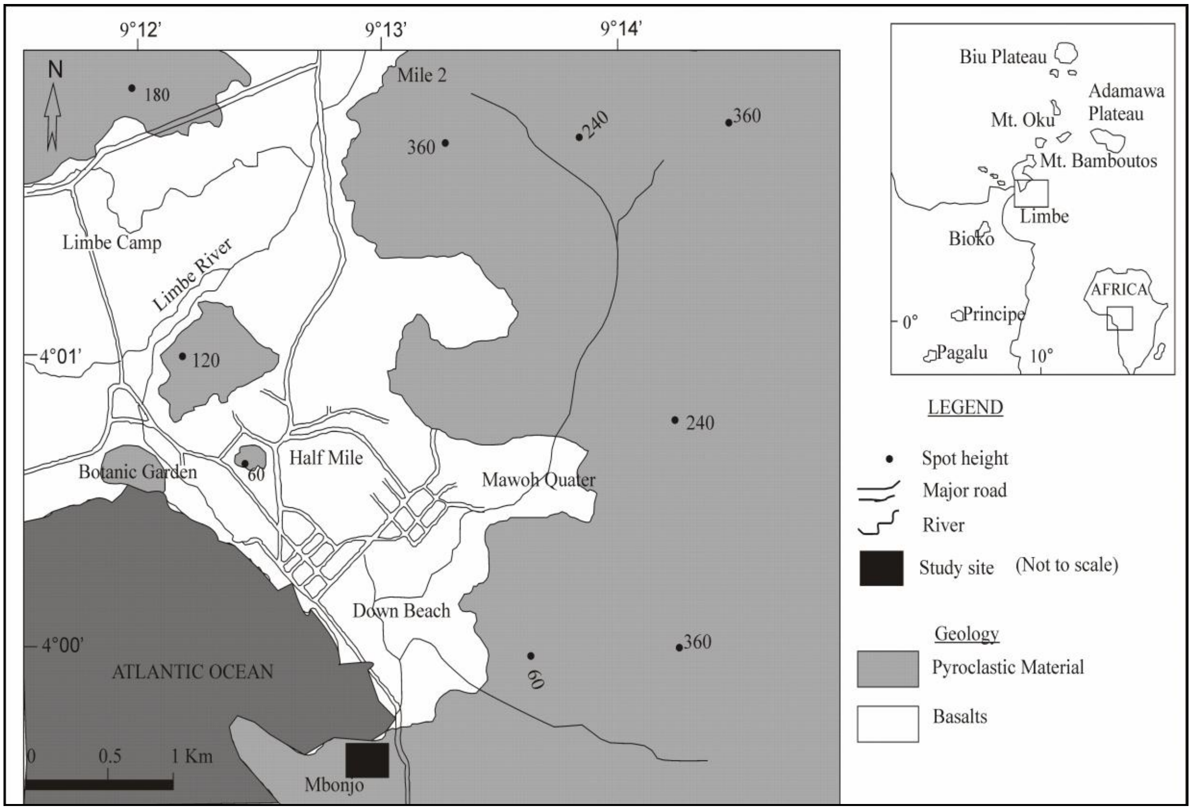

Figure 1. Map of the study area showing its geology, hydrology and location of study site (Ayonghe et al., 2004).

Ercanoglu et al., 2004; Guzzetti et al., 1999; Pachauri and Pant, 1992; Pachauri et al., 1998; Varnes, 1984; Van Western et al., 1997; Zezere et al., 1999). Contributory factors include geology, soil physical and mineralogical properties, geomorphology, land-use and hydrologic conditions within the vicinity of the slope (Ayonghe et al., 2004; Ercanoglu and Gokceoglu, 2002; Ercanoglu et al., 2004; Guzzetti et al., 1999; Zezere et al., 1999). Depending on their characteristics at a given time, they can be described as driving or resisting forces acting on a slope. In the case of the former, they help build the slope to a critical state (Anbalagan, 1992; Varnes, 1984). Triggering mechanisms (rainfall, earthquake and anthropogenic factors) are responsible for imparting the extra energy required to overcome inertia and set the slope in motion (Ayonghe et al., 2004; Ercanoglu and Gokceoglu, 2002; Ercanoglu et al., 2004; Guzzetti et al., 1999; Zezere et al., 1999).

Mbonjo, the site of the 2005 landslide event (9° 12′ 922″ E and 3° 59′ 724″ N) is situated towards the south of Limbe (Figure 1), a coastal town on the south eastern side of Mount Cameroon. The rocks of the area range in composition from picro-basalts and basalts through intermediate compositions to phonolite and rhyolite (Ngole et al., 2007). The parent materials of the unconsolidated sediments around Mount Cameroon have been petrochemically characterized by Suh et al. (2003). The sediments have been derived from weathering of volcanic cones and are characterized by alternating layers of volcanic ash and blocky lava (Ekosse et al., 2005; Suh et al., 2003). Soils are immature with hardly any distinct horizon development (Ngole et al., 2007). Details of the soil types, mineralogy and geomorphology around Limbe are documented in Ekosse et al. (2005), Fonge et al. (2005) and Samalang (2004). The landscape is undulating, with altitude ranging from zero at the shores of the Atlantic Ocean to a chain of horse-shoe hills measuring up to 240 m (Ayonghe et al., 2004). The climate is tropical with mainly two distinct seasons; a rainy season between April and September and a dry season from October to March. During the dry season, daily temperature rises above 25°C. Annual rainfall in the area varies from 2085 to 9086 mm (Fonge et al., 2005), with peak values obtained in the months of June and July (Ayonghe et al., 2004).

This study focused on physical and geotechnical characterization of unconsolidated sediments from the 2005 Mbonjo scar, in order to evaluate their role as contributory factors in enhancing the slide. This work equally aimed at enriching the landslide data bank of the study area and to contribute towards the understanding of this phenomenon. It is anticipated that findings shall be incorporated into the monitoring and/or control of similar events along the CVL in a bid to reduce the loss of

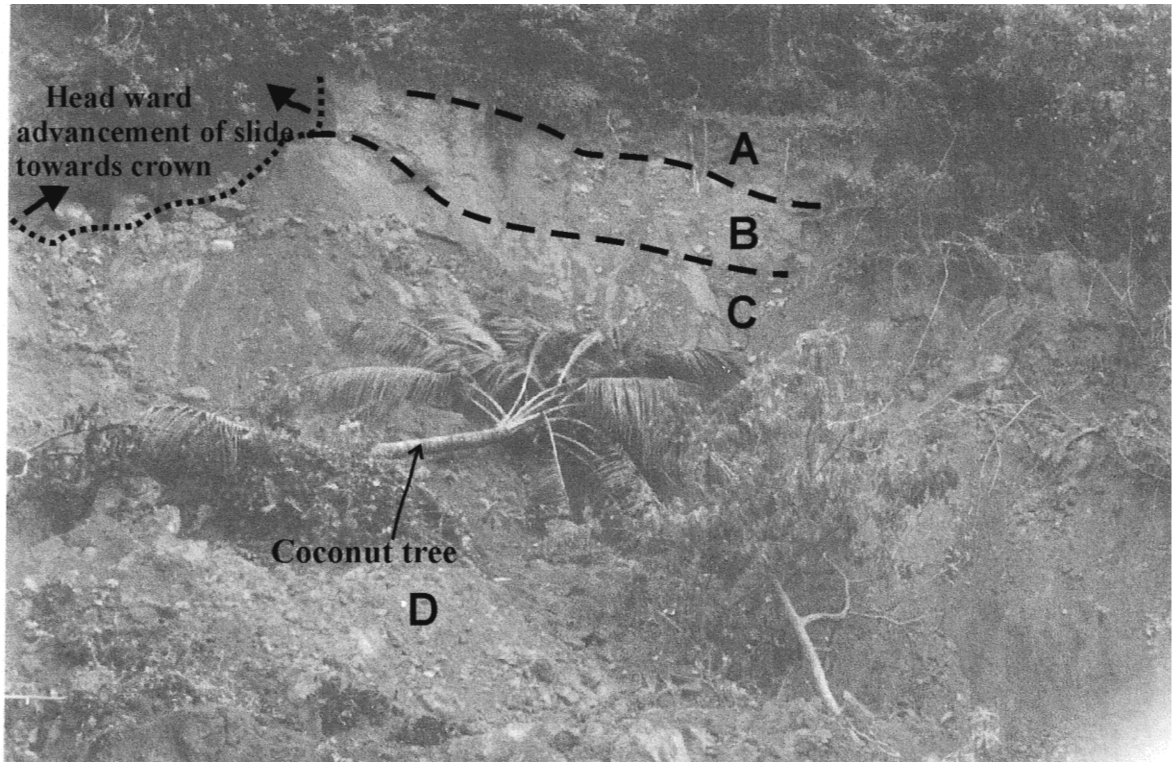

Figure 2. Partial view of Mbonjo 2005 scar highlighting slide character and main components; (A) top soil, (B) upper pyroclastic material, (C) lower pyroclastic material, and (D) regolith.

lives and destruction of property.

METHODOLOGY

Using judgmental and grab sampling technique (Crépin and Johnson, 1993), four samples were collected from the Mbonjo scar; one from the main scarp, two from the slide surface and one from the regolith. Samples were collected at depths between 10 and 30 cm with the aid of a machete.

Parameters analyzed for the ruptured zone sediments included colour, particle size distribution (PSD), Atterberg limits [liquid limit (LL), plastic limit (PL) and plasticity index (PI)] and basic geotechnical properties [bulk density (ρ), dry bulk density (ρ_d), dry unit weight (γ_d), moisture content (Mc), specific gravity (Gs), void ratio (e) and porosity (n)].

Colour was determined using the Munsell Soil Colour Book (1995). Samples were aerated for 24 h. Using a spatula, clayey aggregates were mounted on white cardboard sheets. The hue/value/chroma and colour of the mounted samples were obtained by visually comparing them to those of standard soils recorded in the Munsell Soil Colour Book. For PSD, both sieve and hydrometer analyses were carried out (Gaspe et al., 1994; Diko and Ekosse, 2012) while LL and PL tests were conducted using the Casagrande apparatus, following protocol described by Casagrande (1948). The PI was obtained from the arithmetic difference between LL and PL.

Determination of ρ, ρ_d and γ_d of the samples was according to the methods described by Tan (1996). Moisture content was obtained following the methods employed by Van Reeuwijk (1993) whereas, Gs was after ASTM (2000) norm. Void ratio and porosity were calculated from the following expressions:

$$e = Gs \times \gamma w / \gamma_d - 1 \quad (1)$$

$$n = e / 1 + e \quad (2)$$

where e is the void ratio, Gs is the specific gravity, γw is the unit weight of water (9.81 kN/m^3),
γ_d is the dry density, and n is porosity.

RESULTS AND DISCUSSION

Landslide description

The 2005 Mbonjo landslide occurred following a severe rainfall. The slope of the area was moderately steep, low relief and inclined at an angle of 35° towards the road. Vegetation cover within the vicinity of the slide was secondary succession dominated by coconut trees (Figure 2). The width of the main scarp was about 25 m, whereas the height varied across this width from 2 m at the side scarps to 4 m for the head scarp. The slide advanced head wards up slope to the crown for about 1 m, causing a non-uniform alignment of the head scarp (Figure 2). The ruptured zone measured an estimated 30 m between flanks, whereas the ruptured surface was about 7 to 8 m long with a depth of about 3 m.

Closer examination of the scarp revealed three horizons; a shallow top soil and a sub-soil zone divided into upper and lower pyroclastic material (UPM and LPM)

Table 1. Summary of soil profile as exposed at main scarp.

Stratum	Depth (m)	Hue/value/chroma	Colour
Top soil	0.4	5YR/4/4	Reddish brown
Sub-soil			
UPM: Less compact with angular to sub angular gravel-sized particles	2.6	10YR/5/8	Yellowish brown
LPM: More compact clay-sized particles	*	10YR/5/8	Yellowish brown

*Not determined.

Table 2. Particle size distribution and texture of the ruptured zone sediments.

Location	Sample	Particle size distribution (wt%)			Texture
		Sand	Silt	Clay	
UPM	MS1	41	37	22	Loam
LPM	SS2	34	24	42	Loam
	SS3	17	43	40	Silty clay loam
Regolith	RS4	15	42	43	Silty clay

Wt%: weight percentage.

(Table 1). The UPM was less compact than the LPM, with gravel-sized particles embedded within a fine-grained matrix. The long axis measured an average 4.5 cm for the pebble-size fractions to over 35 cm for the larger ones. The underlying LPM was much finer and compact with notable absence of volcanic bombs. The LPM served as the slide surface. The material involved in the slide was colluvium, consisting of poorly sorted matrix-supported mixture of angular rock fragments and fine-grained material. The landslide type was translational, involving an almost planar slide surface (Ayonghe et al., 2004, 2002).

Physical and basic geotechnical considerations

Results for hue, value, chroma, and colour are given in Table 1. Reddish brown and yellowish brown colours of the samples suggest the presence of hematite (α – Fe_2O_3), goethite (α – FeO.OH) and kaolinitic minerals ($Al_2Si_2O_5(OH)_4$). According to Ekosse et al. (2005), the saprolite in Limbe consists mainly of clinopyroxene ($Ca(TiMgAl)SiAl)_2O_6$), hematite, and goethite, whereas the soils comprises mainly anatase (TiO_2), annite ($KFe_3AlSiO_{10}(OH,F)_2$), augite ($Ca_2(Al\text{-}Fe)_4(Mg\text{-}Fe)_4Si_6O_{24}$), goethite, hematite, and kaolinitic minerals. These minerals are usually found in the parent materials (basalts) from which these sediments are derived.

Particle size distribution and texture of the ruptured zone sediments is presented in Table 2. The textural classification utilized in this study is as follows; ≤ 2 µm = clay, > 2 ≤ 50 µm = silt, and > 50 µm = sand (Tan, 1996). The PSD suggests that the LPM is more enriched in fines (< 2 µm fractions) relative to UPM. Numerous studies of landslides have established range of textures that are most prone to sliding (Howard et al., 1988; Talerico et al., 2004). A comparison of the textures from Mbonjo with those of materials from the Sparta slide, New Jersey (Talerico et al., 2004) and nine other landslides in San Francisco, California (Howard et al., 1988) which all occurred as a result of intense rainfall, qualified the Mbonjo sediments as unstable and landslide prone (Figure 3).

Atterberg limits of the samples are summarised in Figure 4. Liquid limit, PL and PI values for UPM were lower than those for LPM, reflecting the higher percentage of clay fractions in the latter. Bell and Coulthard (1997) argued that the clay fraction percent has a greater influence on the consistency and activity of bulk samples as compared to the silt and sand fractions. High plasticity of the LPM imparted by its higher clay fraction enhanced sliding of overlying UPM. The ability of sediments to swell is directly related to the percentage of clay-size fraction and type of clay mineral (Shaw-Shong, 2004; Shi et al., 2005). Atterbergs limits of the sediments equally suggest comparatively higher swelling potentials for LPM (Figure 5).

Results of ρ, ρ_d, γ_d, Mc, Gs, e, and n are presented in Table 3. LPM had a higher ρ, ρ_d, γ_d, and Mc as compared to UPM, whereas the UPM registered higher e and n values as compared to LPM. The grain-supported matrix of the latter magnified this effect. These results suggest a

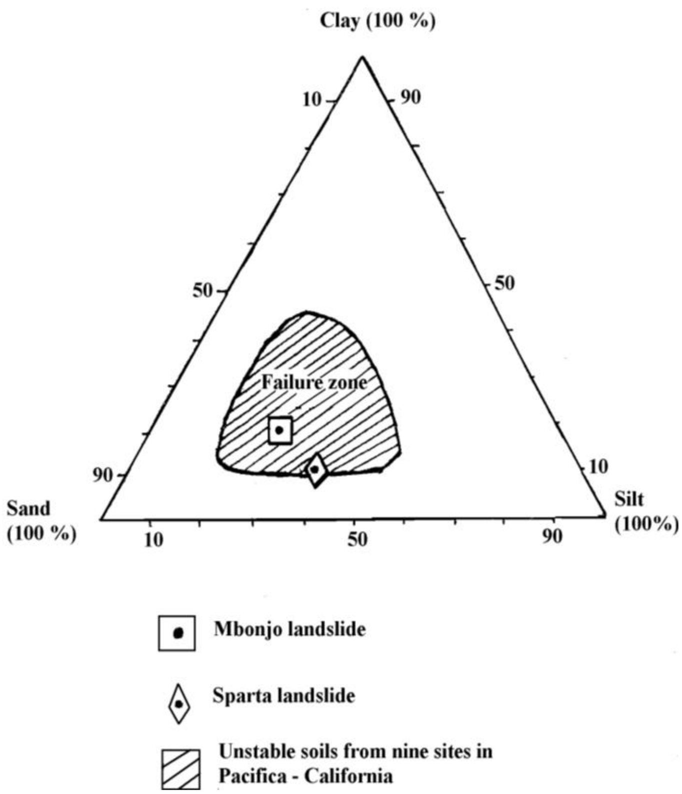

Figure 3. Location of Mbonjo unconsolidated sediments as compared to those from Sparta and Pacifica-Carlifornia on the landslide susceptibility ternary diagram (Talerico et al., 2004).

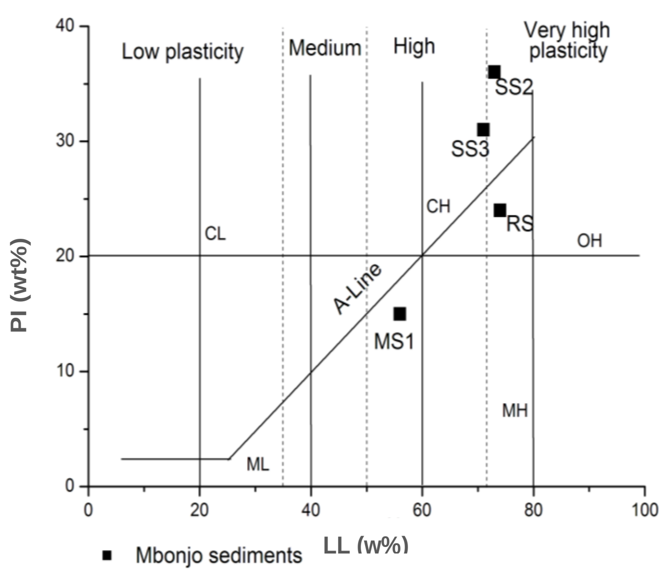

Figure 4. Atterberg limits for ruptured zone sediments. PI: plasticity index; LL: liquid limit.

more advanced state of weathering for LPM and a possible difference in mineralogy within both layers.

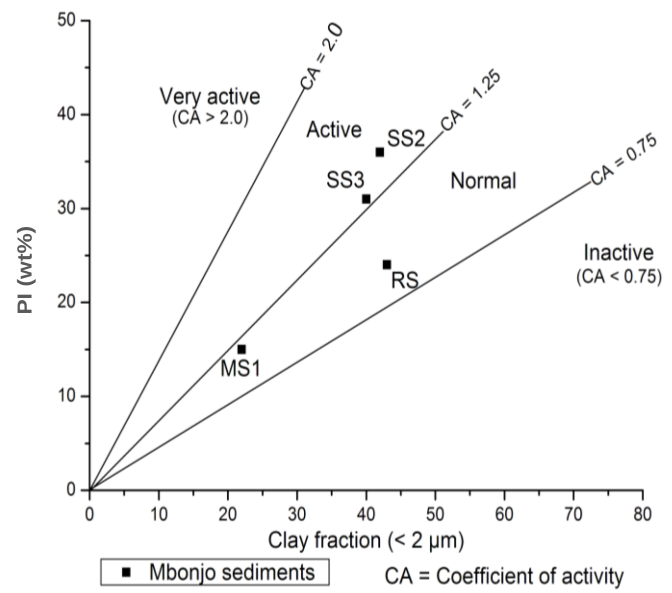

Figure 5. Activity diagram of the ruptured zone sediments. PI: plasticity index.

Accumulation of clay-sized particles in the underlying LPM may have resulted in slow infiltration rates with a consequent increase in water content trapped at clay interfaces between both layers, causing potential sliding of the overlying material. According to Kim and Park (2003) and Ngole et al. (2007), there is a positive correlation between the density of soil particles and its degree of weathering. This assertion is true for this study site as inferred from ρ, ρ_d, γ_d, e, and n values of the UP and LPM. Though, the LPM was denser and heavier than UPM, field observations equally suggested that the angular to sub-angular bombs added considerable weight to the UPM, enhancing its susceptibility to sliding.

Findings from this study corroborate those of Ayonghe et al. (1999) on seismically activated swarms of landslides in Bafaka, Cameroon, and those of Ekosse et al. (2005) working on landslides on volcanic cones in Mabeta, Limbe. Occurrence of impermeable clay-rich layers interbedded with permeable pyroclastic materials represents critical conditions for hill slopes (Ayonghe et al., 1999; Ekosse et al., 2005). Within cones, the clay layers commonly serve as perched aquifers. Under saturated condition parts of hill slopes end up giving way with these clays acting as slide surfaces. A similar phenomenon has been reported in the Tandayapa valley, Ecuador (Dykes and Welford, 2007), Oka City, Japan (Yasuhiko et al., 2007), Bugobero, Buteze sub-county and Mbale, all in the Mbale district of Eastern Uganda (Ngecu et al., 2004) where mechanically unstable slopes of deeply weathered tertiary volcanic rocks and soils gave way after extreme rainfall events. The Gatara village landslide in the Muranga district of Central Kenya is another example (Ngecu and Ichang'i, 1999). Although,

Table 3. Geotechnical properties of ruptured zone sediments.

Stratum	Samples	Bulk density (g/cm^3)	Dry bulk density (g/cm^3)	Dry unit weight (kN/m^3)	Moisture content (wt%)	Void ratio (e)	Porosity (n)	Specific gravity (g/cm^3)
UPM	MS1	2.0	1.75	17.16	14	0.52	0.34	2.67
LPM	SS′	2.25	1.95	19.13	15	0.37	0.27	2.69

SS′ = (SS2 + SS3) / 2; Wt%: weight percentage.

rainfall and anthropogenic factors were considered triggering mechanisms; Ngecu and Ichang'i (1999) argued further that the formation of a clay-rich weathering front between highly permeable Miocene pyroclastic materials and underlying impervious tertiary basalts helped build the slopes to a critical state.

Conclusion

This study was undertaken to ascertain the role of un-consolidated sediments in enhancing the Mbonjo landslide. The colour of the samples ranged from reddish brown to yellowish brown, indicating the presence of hematite, goethite, and kaolin-rich sediments. The loamy texture of the UPM was considered landslide prone. High plasticity of the LPM together with geotechnical evaluation of the ruptured zone sediments, attributed the primary cause of failure to the presence of clay interbeds between upper and lower pyroclastic materials. Within cones, the clays acted as perched aquifers, enhancing sliding of the slope under saturated conditions.

In a sequential manner therefore, heavy rain reduced friction between the upper and lower pyroclastic clay-rich layer. Increased saturation reduced cohesion of the UPM, while the underlying LPM absorbed water causing swelling. The additional weight of volcanic bombs together with in-built pore pressure within the UPM increased the shearing strength. Intense rainfall event was the triggering mechanism. These, together with moderate steepness of the slope, secondary vegetation dominated by coconut trees with shallow root systems, and the absence of any form of toe protection led to the 26th September, 2005 Mbonjo landslide.

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