Geotechnical and physico chemical properties of clays associated with landslides in volcanic and metamorphic terrains in Cameroon, Central Africa

Philip A. Motaka+, Kennedy F. Fozao+, Bernard P. K. Yerima++, Veronica N. Ngole*, Edwin B. Ntasin, George Ivo Ekosse*** and Samuel N. Ayonghe+**

+Department of Geology and Environmental Science, Faculty of Science, University of Buea, P.O. Box 63 Buea, Cameroon
++Department of Soil Science, Faculty of Science, University of Dschang B.P. 222 Dschang, Cameroon
*Department of Geography, Environmental Science and Planning, University of Swaziland, PMB 4, Kwaluseni M201, Swaziland, South Africa
** Environmental/Economic Geologist 2104 Yager Creek Dr Apt H Charlotte, North Carolina, 28273, United States of America.
*** Department of Geology, Mining and Minerals, University of Limpopo, P/Bag X1106, Savenga, 0727, Limpopo Province, South Africa

ABSTRACT

Comparative studies of geotechnical properties of soils from landslide scars within volcanic rocks in Alou Sub-Division located in the Bambouto caldera and from a major landslide scar within Precambrian metamorphic rocks (gneisses and granites) located at Kekem indicated a range of bulk densities of 0.93 to 1.12 g/ml and water content from 27 to 44% from the volcanic terrains while bulk densities and water content in the metamorphic rocks ranged from 1.14 to 1.52 g/ml and 7 to 35% respectively. Granulometric analyses based on the determination of Atterberg's limits indicated the predominance of silts of high plasticity in both areas although the proportion of the fine fraction (clay, silt and fine sand) was generally higher in the volcanic rocks. Mineralogical properties obtained from X-ray diffraction (XRD) patterns indicated the predominance of feldspars, chiefly microcline and gibbsite, with appreciable proportions of clays (montmorillonite, kaolinite, goethite, chlorite and halloysite) within the volcanic rocks while the gneisses were dominated by quartz and muscovite with some proportions of montmorillonite, kaolinite and feldspars with the clay fractions being more variable in the volcanic rocks (13 to 44%) than in the metamorphic rocks (23 to 29%). The presence of montmorillonite, a type of clay which has the ability to absorb water and swell, is an indication of a major contributor to the susceptibility of both terrains to sliding when subjected to high rainfall. This was revealed by data on intense precipitation during the specific months of the landslide events which led to elevated groundwater levels with raised pore water pressure in the highly weathered and loose materials resulting in increased shear stress and reduced shear strength with the eventual failures of the slopes causing the landslide disasters witnessed in both geological terrains.

Keywords: Landslide scars, geotechnical properties, montmorillonite, Cameroon Volcanic Line, metamorphic rocks, high rainfall.

Résumé

Les études comparatives des propriétés géotechniques des sols issus des niches de décollement observées sur les roches volcaniques dans l'arrondissement d'Alou situé dans la caldera de Bambouto de même que celles relatives à la niche de décollement majeure relevé sur les roches métamorphiques précambriennes (gneiss et granites) à Kekem révèlent des poids volumétriques variant entre 0,93 et 1,12 g/ml ainsi qu'une teneur en eau allant de 27 à 44%, laquelle émane des terrains volcaniques. Par ailleurs, les poids volumétriques et la teneur en eau du gneiss à Kekem varient entre 1,14 et 1.52 g/ml et de 7 à 35%, respectivement. Les analyses granulométriques basées sur la détermination des limites d'Atterberg indiquent une prédominance de limons à plasticité élevée dans ces deux zones en dépit du niveau généralement haut de la proportion de fraction fine (argile, limon et sable fin) contenue dans les roches volcaniques. Les propriétés minéralogiques obtenues à partir des diagrammes de diffraction des rayons X (XRD) révèlent une prédominance de feldspaths, notamment du microcline et de la gibbsite, avec des proportions substantielles d'argiles (montmorillonite, kaolinite, goethite, chlorite et halloysite) contenues dans les roches volcaniques. Par ailleurs, les gneiss sont essentiellement composés du quartz et de la muscovite, avec un certain pourcentage de montmorillonite, de kaolinite et de feldspaths. Toutefois, il convient de noter que les fractions d'argile varient plus au niveau des roches volcaniques (soit de 13 à 44%) que des gneiss (de 23 à 29%). La présence de la montmorillonite, type d'argile capable d'absorber de l'eau et de gonfler, constitue le principal agent susceptible de provoquer des glissements de terrain dans ces deux zones en période de pluies abondantes. Ce fait a été révélé par des données relatives à d'intenses précipitations enregistrées à des mois précis durant lesquels ont été observés des cas de glissements de terrain ayant entraîné une surélévation des niveaux de l'eau souterraine, avec une hausse des pressions d'eau de porosité aussi bien sur les matériaux altérés que sur les matériaux meubles. Cette surélévation provoque une force de cisaillement élevée et une résistance au cisaillement réduite, avec une probabilité d'inclinaison des pentes de la ligne d'eau, d'où les catastrophes de glissements de terrain survenus dans ces deux zones géologiques.

Mots clés: niches de décollement, propriétés géotechniques, montmorillonite, Ligne Volcanique du Cameroun, roches métamorphiques, pluies abondantes

Corresponding author: Samuel N. Ayonghe (Email:<samayonghe@yahoo.com>)

INTRODUCTION

Landslides constitute major natural disasters in Cameroon with frequent destructive and fatal occurrences mainly in volcanic rocks along the Cameroon Volcanic Line (CVL) (Ekosse et al., 2005; Ayonghe and Ntasin, 2008), and occasionally within sedimentary and Precambrian metamorphic rocks in various parts of the country, mainly during the rainy seasons from June to October. Although the general geology of the country is constituted by 80% Precambrian metamorphic rocks, 12% Cretaceous and Cenozoic sedimentary rocks and 8% Cenozoic volcanic rocks, most of the landslide occurrences are common along the CVL, which is a major morphological feature extending over a distance of 1600 km with strings of volcanoes from the Atlantic Ocean to the continental segment in Cameroon and northern eastern Nigeria (Fitton, 1987; Halliday et al., 1988, Marzoli et al., 1999; Marzoli et al., 2000). Updated archived records of landslides in the country give a total death toll of about 146 persons from landslides during the last three decades (Figure 1) and previous studies of landslide disasters have accordingly been restricted to the CVL while relatively few landslide occurrences have been recorded on metamorphic terrains.

Consequently, little work has been done on the geotechnical properties of soils and rocks in the landslide prone areas of the country and comparative studies of the geotechnical and mineralogical properties of different geologic terrains are practically inexistent. Results of studies of landslides within the volcanic terrains have been linked to rainfall, with topography, extent of weathering of rock types and their mineralogy, and human activities as contributing factors (Ayonghe and Ntasin, 2008) but without due consideration of the geotechnical properties of the soil types.

Clays play a crucial role in the stability of slopes and a concise understanding of the geotechnical properties of soils in landslide prone areas is therefore essential for the successful evaluation of their occurrences but studies on the clay mineralogy in these landslide occurrences are few, (Ekosse et al., 2005). According to Okagbue and Ene, (2009), the clay mineralogical content of highly weathered pyroclastic rocks are a determinant factor of their geotechnical properties.

This work was therefore centred on volcanic rocks within the south western flanks of the Bambouto

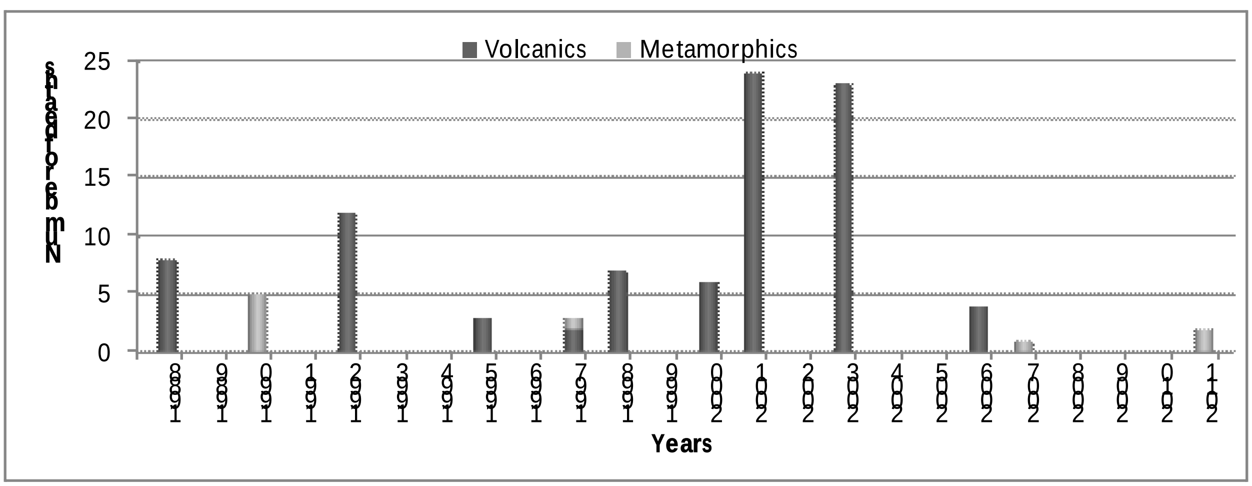


Fig.1: Histogram of death toll from landslides from 1988 to 2011 (Modified after Ayonghe et al., 2004)

caldera, and on Precambrian metamorphic rocks at Kekem (Figure 2). It seeks to investigate variations in the geotechnical properties of the soils, their mineralogy with interest on the clay types, and their roles amidst other contributing factors in the triggering mechanism of the landslides. Both areas are characterized by humid tropical climate which favours intensive weathering. The fertile soils especially on the volcanic terrains attract agricultural activities, resulting in human interference with the natural vegetation and slope stability.

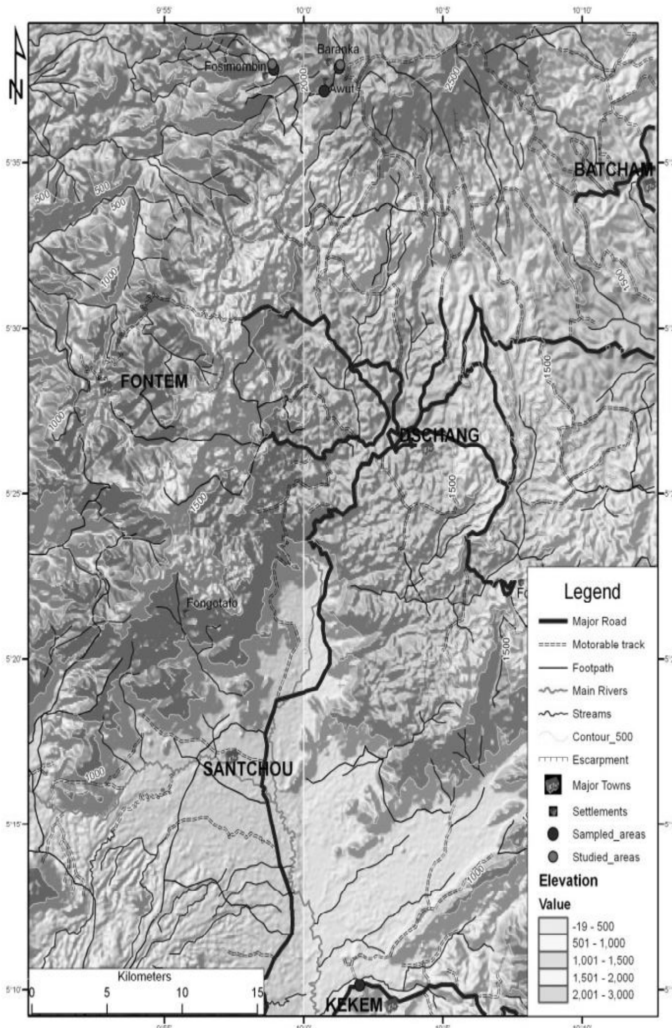


Fig.2: Location of study areas

MATERIALS AND METHODS

Fieldwork

Fieldwork on the volcanic terrains involved the collection of samples from the scarps and regoliths of landslide scars which occurred on 20thJuly 2003. This was followed by fieldwork on the Kekem landslide of 20th October 2007 where the soil profile of the head scarp was studied and four samples collected from the head scarp, regolith and slide surface (Figure 3) for laboratory analysis.

Laboratory Analyses

Analysis of geotechnical properties was carried out in the laboratory of the Local Materials Promotion Authority (MIPROMALO), Yaounde where bulk and dry densities of samples were determined.

Water content and granulometric analyses were equally carried out on homogenized samples. Using 500g per sample, grain size analysis was determined by wet sieving which involved separating the fraction less than 100μm for sedimentation analysis, from that more than 100μm for dry sieving through a column of sieves, which were later combined for the complete particle size distribution. Atterberg's limits were determined through wet sieving using a 400μm sieve to form a paste. Limits were obtained using the Casagrande's apparatus and thread rolling tests (Wilun and Starzewski, 1975).

X-ray diffraction (XRD) analysis was carried out in the laboratory of the Department of Geology, University of Liege (Belgium) where X-ray diffraction patterns were obtained using a diffractometer (the Bruker Advance 8) equipped with Ni filtered Cukα radiation, with automatic slit and on-line computer control. The samples were scanned from 2° to 40° 2θ. Mineral identification on the diffractograms and a semi quantitative mineralogical composition were processed using EVA software. Measurements of XRD patterns were performed on randomly oriented powder preparation from bulk samples.

RESULTS AND DISCUSSION

Field perspective

The two areas share an undulating topography, characterized by a typically humid tropical climate. As a result, the areas are intensely weathered, producing soils which are generally termed pedalfers. The scars on the volcanic terrains were located on steep slopes with gradients of 50 to 70^o and deeply weathered soil profiles exceeding 1m. Undercutting of the slope by a road at one of the landslide scars on the volcanic rocks at Apang and on the metamorphic rocks at Kekem is a possible contributing factor to the occurrences of these landslides. A tension crack of about 50m runs across the Betika landslide within the volcanics (Figure 3a) and according to Ayonghe et al., (2004) and Panek et al., (2011), such a crack represents a pending landslide in the future. These soils generally have a fine grained texture and are very loose rendering them susceptible to landslides. Soil colour varies from pale grey to reddish-brown (Figure 3a and b) and the soils were damp (Table 1). Other works on the Bambouto caldera environment by Marzoli et al., (1999); Marzoli et al., (2000); Ayonghe and Ntasin, (2008); and Dongmo et al., (2010) reveal the presence of young volcanic rocks rich in andisols with high organic matter content (about 60cm) which according to Mermoz et al.,(2008) and Tefogoum et al., (2009) attract agriculture.

The Kekem area on the other hand, is characterized by gneisses, amphibolites, and pyribolites with some granitoids (Tchaptchet Tchato, 2010). The soils which develop here are mainly lateritic with about 20 - 30cm of humus layer as indicated in the profile of the head scarp of the landslide (Table 2). The texture is a mixture of coarse and fine grains, with the sand fraction being clearly visible. The soil is highly compacted and dry with a yellowish-brown colouration along the profile.

Results from Laboratory Analyses

Volcanic terrain

It is evident from the results of the geotechnical analysis and complete particle size distribution curves (Figures 4 and 5) that the samples were of very high water content which ranged from 27 to 44 %, with a corresponding low bulk densities ranging from 0.93 to 1.12 g/ml, similar to those reported by Ngole et al., (2007) on the 2001 Limbe landslide, along the CVL. Low soil density favours permeability which when coupled with an abundance of loose fine fraction, constitutes a potential for high natural water content based on its high porosity.

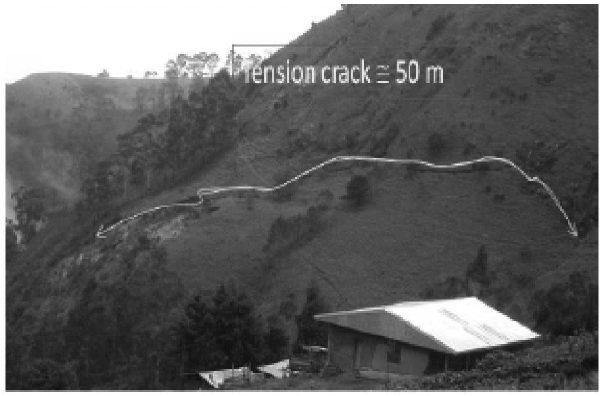
Higher plasticity indexes were recorded from samples L2P4 and L4S2 (Figure 4) and this is indicative of high clay content and a high water retention potential (Jeong et al., 2011). Such behaviour is evidence of a leaching action of the finest materials (clay fraction) from the surface horizons to deeper ones, forming a layer of fine materials sandwiched between coarser materials above and below. The layer below the surface is capable of absorbing and retaining huge volumes of water, giving it a tendency to act as a sliding surface for the materials above the surface in events of increase weight or shear stress beyond the shear strength (Serrano and Jimenez, 2010).

Grain size properties which are crucial for understanding landslide characteristics (Brajam 1998, Erginal et al., 2009) were analysed (Figure 5a) and plotted as three different classes of soils (Table 3), corresponding to the 3 different sampled locations. The fine fraction was dominant in all the sampled locations, which is in line with observations by Gratchev and Towhata (2010) for volcanic areas. According to Wang and Sassa (2007), grain size distribution of soil media plays an important role in the movement of a landslide mass after slope failure with the slope failure time of finer materials being shorter than that of coarser materials due to the decreased permeability. Thus, the fine andisols render these slopes highly susceptible to mass movement.

The XRD patterns (Table 3) from samples L2R1 and L2P4 collected about 2cm and 100cm below the surface respectively, down the profile indicate high content of feldspars, chiefly microcline in these volcanic rocks (Table 4). Sample L2P4 showed an increase in microcline, sigloite, halloysite and montmorillonite, suggesting a leaching action of these minerals from the surface horizons to deeper horizons or depletion

Table 1: Field observations of physical properties of samples collected

Terrains	Volcanic				Precambrian			
Samples/ Properties	L2R1	L2P4	L3R1	L4S2	K1S1	K1R1	K1R2	K1N1
Colour	Dark gray	Dark gray	Reddish brown	Reddish brown	Pale yellow	Pale yellow	Pale yellow	Pale yellow
Texture	Fine-clayey	Fine-clayey	Fine-grained	Coarse-grained	Clayey sand	Clayey sand	Clayey sand	Clayey sand
Moisture content	Damp	Moist	Damp	Dry	Dry	Wet	Wet	Wet
Collection point	Regolith	Below regolith	Regolith	Regolith	Scarp	Regolith	Regolith	Out of scar



a) Betika Landslide showing a tension crack (~50m)

b) Chief Folemu's palace slide head scarp plunging into the caldera wall

c) Kekem Landslide scar

d) Kekem landslide head scarp

Fig. 3: Landslide scars in volcanic (a, b) and metamorphic (c, d) terrains

Table 2: Head scarp soil profile of the Kekem landslide (metamorphic terrain)

Depth range (cm)	Description						
	Structure	Consistence	Presence of roots	Insect Activity	Porosity	Stonyness	Boundary
0 - 15	Composed of organic material	Moist decaying organic material	Many, fine to medium and coarse	Many	Many	common	Diffuse
15 - 30	Granular	Friable	Many, fine to medium and coarse	Many	Many, fine-medium pores	Common, variable diameter of 2 – 40 cm	Clear
30 - 50	Weak, angular, blocky to granular	Friable, moist	Many, fine to medium	Many	Many, fine to medium size cracks and pores	Common diameter 3 – 6 cm	Diffuse
50 - 110	Angular, blocky	Extremely hard, dry	Many, fine to medium	Common	Common, fine to medium	Common, diameter 3 – 50 cm	Diffuse
110 - 194	Angular, blocky	Dry, firm to very firm	Many, fine to medium	Common	Fine pores	Few pebbles, diameter 3 – 8 cm	Diffuse
194 - 234	Angular, blocky, massive in places	Very firm, dry	Common, fine to medium	Few	Few pores, fine	Few pebbles diameter 3 – 20 cm	Clear
234 - 274	Moderate to weak, angular, blocky, massive in places	Slightly firm to friable	Common, fine to medium	None	None	Few pebbles, 3 – 20 cm	Diffuse
274 - 309	Angular, blocky, massive	Firm to friable	Common, fine to medium	None	None, some cracks	Few, diameter 3 – 20 cm	Clear
309 – 336/380	Weak, angular, blocky	Friable	Many, fine roots along fracture and crack surfaces	None	None	None	Undulatin g
381 and above	Granular granite-gneiss in the process of decomposition with roots along cracks						

Table 3: Geotechnical parameters of the study areas

	Terrains							
	Volcanic				Metamorphic			
Properties of Samples	L2R1	L2P4	L3R1	L4S2	K1S1	K1R1	K1R2	K1N1
ρd (g/ml)	0.87	0.64	0.77	0.84	1.07	1.09	0.88	1.19
w (%)	28.69	44.10	35.86	27.05	7.27	34.61	30.44	28.11
ρ (g/ml)	1.12	0.93	1.05	1.07	1.14	1.47	1.14	1.52
Plastic limit	57.07	44.56	61.88	73.97	34.15	38.58	36.12	-
Liquid limit	64.02	64.68	72.15	99.01	54.41	51.77	47.84	-
Plasticity index	6.95	20.13	10.28	25.08	20.26	13.19	11.72	-
Plasticity chart	MH	MH	MH	MH	MH	MH	MI	-
Clay (%)	13	25	13	44	25	29	23	29
Silt (%)	67	59	27	27	25	30	27	22
Sand (%)	20	16	60	29	50	41	50	49
Feret's triangle classification (USDA)	Silt loam	Silt loam	Sandy loam	Clay	Sandy clay loam	Clay loam	Sandy clay loam	Sandy clay loam

from the surface horizons. Lower proportions of other minerals, such as chlorite, sanidine, plagioclase, K-feldspars and kaolinite in the lower horizon (L2P4) can be attributed to limited weathering extent with depth to form these minerals. Identified clay minerals in the samples include montmorillonite, gibbsite, kaolinite, chlorite, goethite, halloysite, showing almost the same total proportion in the two samples (about 23%).

However, the proportion of montmorillonite clay which has the ability to absorb water and swell, increased in sample L2P4, thus rendering the area susceptible to landsliding. The proportion of quartz decreased down the profile, and thus can be attributed to the preferential leaching of the finer minerals down the profile. Samples L3R1 and L4S2 collected at about 20cm below the scar (Figure 3a) and about 100cm along the scarp (Figure 3b) respectively, show very high proportions of gibbsite (40.6% and 32.2% respectively), indicating intense weathering (Velde, 1992). Other minerals of significant proportions included quartz, microcline and chlorite from sample L3R1; and kaolinite, quartz and microcline from sample L4S2. Both samples (L3R1 and L4S2) show high proportions of clay minerals (montmorillonite),

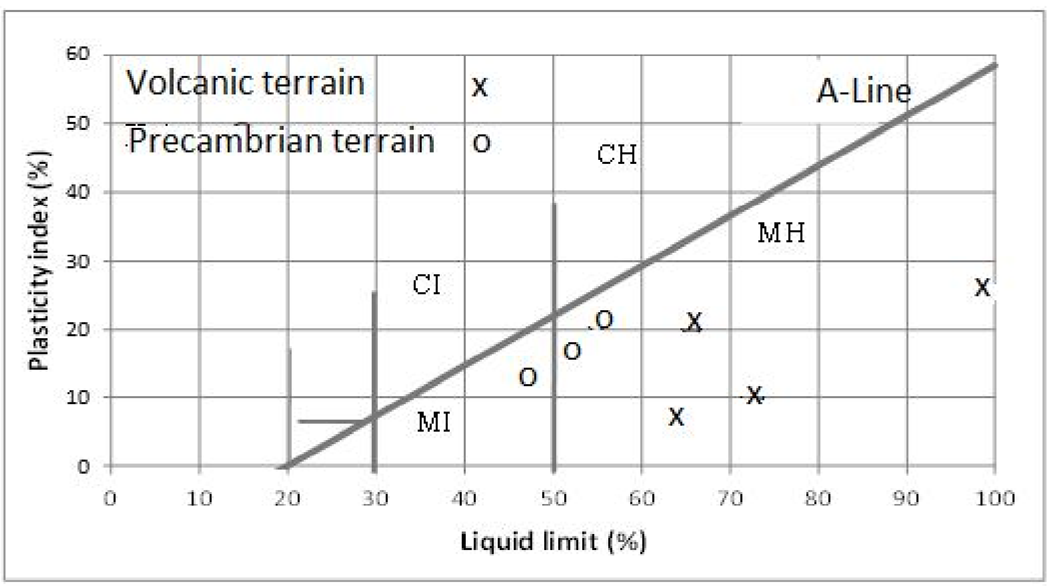
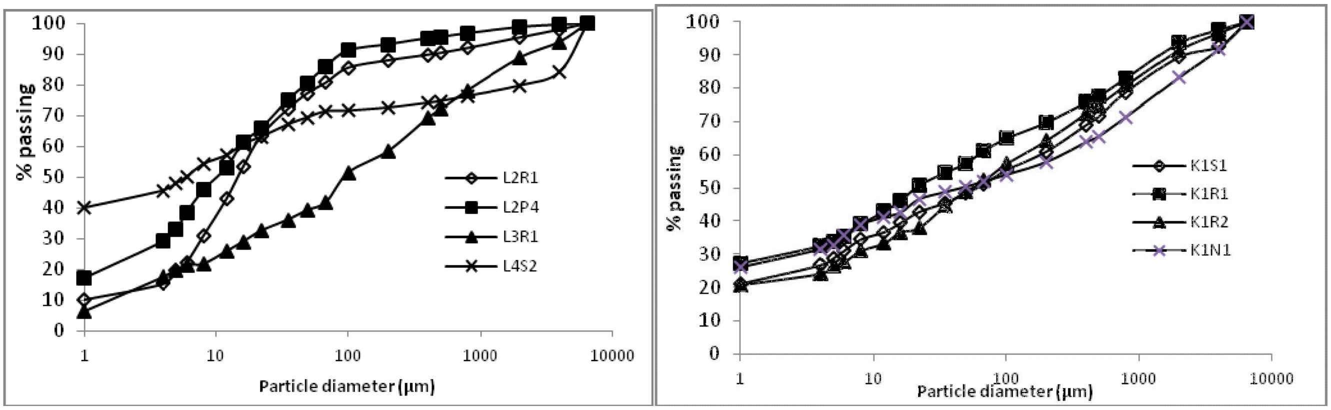


Fig. 4: Classification of Samples using the Plasticity Chart (after Casagrande)

Table 4: Mineralogical composition of volcanic and Precambrian metamorphic terrains

Terrains	Volcanic										Precambrian			
Samples/minerals	L2R1		L2P4		L3R1		L4S2		K1S1		K1R1		K1N1	
	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Mln	3137	32.4	4576	51.2	338	10.5	224	5.8	121	3.0	129	2.7	690	13.8
Cl	1104	11.4	828	9.3	299	9.3	182	4.7	-	-	-	-	-	-
Sdn	1035	10.7	582	6.5	-	-	-	-	139	3.5	-	-	-	-
Qtz	846	8.7	706	7.9	508	15.8	467	12.1	1710	43.0	1990	41.6	229	4.6
Pl	764	7.9	-	-	100	3.1	77	2.0	402	10.1	500	10.5	167	3.3
Sgte	402	4.1	906	10.1	-	-	-	-	-	-	-	-	-	-
Kfs	398	4.1	190	2.1	-	-	-	-	-	-	310	6.5	-	-
Hyt	296	3.1	396	4.4	-	-	-	-	-	-	-	-	-	-
Kln	275	2.8	170	1.9	81	2.5	694	17.9	166	4.2	356	7.4	678	13.5
Zt	262	2.7	131	1.5	-	-	96	2.5	79	2.0	-	-	-	-
Ol	251	2.6	118	1.3	-	-	-	-	-	-	-	-	-	-
Gth	214	2.2	78	0.9	-	-	150	3.9	146	3.7	170	3.6	212	4.2
Mnt	215	2.2	256	2.9	217	6.8	212	5.5	374	9.4	536	11.2	257	5.1
Spt	179	1.8	-	-	114	3.6	167	4.3	182	4.6	283	5.9	177	3.5
Gbt	178	1.8	-	-	1303	40.6	1248	32.2	-	-	143	3.0	144	2.9
Hmt	79	0.8	-	-	-	-	-	-	-	-	-	-	-	-
Bt	58	0.6	-	-	105	3.3	88	2.3	-	-	-	-	252	5.0
Sp	-	-	-	-	95	3.0	100	2.6	-	-	63	1.3	-	-
Cdt	-	-	-	-	46	1.4	53	1.4	-	-	-	-	-	-
Spn	-	-	-	-	-	-	114	2.9	208	5.2	73	1.5	137	2.7
Mvt	-	-	-	-	-	-	-	-	254	6.4	-	-	1880	37.6
Gnt	-	-	-	-	-	-	-	-	197	5.0	-	-	-	-
Srt	-	-	-	-	-	-	-	-	-	-	176	3.7	117	2.3
Hbl	-	-	-	-	-	-	-	-	-	-	54	1.1	-	-
Px	-	-	-	-	-	-	-	-	-	-	-	-	64	1.3

Minerals (Min): **Mnt**: Montmorillonite, **Kln**: Kaolinite, **Cl**: Chlorite, **Gth**: Goethite, **Gbt**: Gibbsite, **Hyt**: Halloysite, **Spn**: Serpentine, **Spt**: Sepiolite, **Sgte**: Sigloite, **Mln**: Microcline, **Kfs**: K-Feldspars, **Pl**: Plagioclase, **Sdn**: Sanidine, **Qtz**: Quartz, **Bt**: Biotite, **Mvt**: Muscovite, **Hbl**: Hornblende, **Zt**: Zeolite, **Ol**: Olivine, **Px**: Pyroxene, **Cdt**: Cordierite, **Sp**: Sulphate, **Srt**: Sericite, **Gnt**: Greenalite, **Hmt**: Haematite



(a) **(b)**

Fig. 5: Particle size distribution for the Alou (a) and Kekem (b) areas

an indication of a high susceptibility to slope failure.

The terrain is dominated by feldspars in general and microcline in particular, probably due to its relative durability. The non-swelling type of clay minerals (chlorite, kaolinite, goethite and gibbsite) dominates the clay fraction, suggesting that the swelling property of some clays is limited by the small montmorillonite proportions in this area. Nevertheless, the fine and loose nature of the soils is a considerable factor, considering the water retention potential, evident in their high water content.

Metamorphic terrain at Kekem

Geotechnical properties of samples from the metamorphic rocks showed a lower water content ranging from 7 to 35 %, with higher bulk densities ranging from 1.14 to 1.52 g/ml. Based on variations in the water content, the soil in this area has a tendency to become extremely dry or brick hard in the absence of water, and readily absorbs a huge quantity of water in the event of rainfall.

Sample K1S1 collected at a depth of more than 1meter below the surface showed a high plasticity index (Figure 4) implying it is rich in clay content and has a high water retention potential. Grain size distribution (Figure 5b) clustered around the same class of soil (Figure 8b), with one sample slightly outside the class. The fine and coarse fractions have almost equal proportions, similar to results obtained by Jeong et al., (2011), thus the lateritic soils are less susceptible to movement.

The samples collected from the scarp, regolith and slide surface (Figure 3c), show the dominance of quartz in K1S1, K1R1 and muscovite in K1N1 respectively, and an abundance of montmorillonite, plagioclase, kaolinite and microcline. The significant proportions of goethite and gibbsite in these samples is indicative of very intense weathering process and high proportions of quartz and muscovite, two resistant minerals indicative of a very intense weathering process (Velde, 1992). This is supported by the deep lateritic profile in this area. The increased proportion of the swelling type of clay (montmorillonite) in this area poses a significant problem to slope stability (Miao et al., 2002). This gives the soil a tendency to become brick hard under prolonged high temperatures, and to readily absorb huge quantities of water when available. Though the compact nature of this soil may render it stable, repeated swelling and drying could render the slope unstable. This increases susceptibility of the slopes to failure during continuous rainfall.

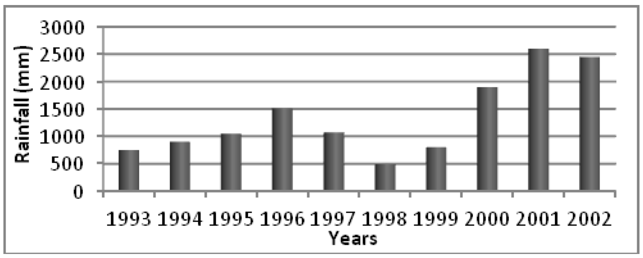
Role of rainfall

Rainfall constitutes a very important factor in landslide occurrences, associated with a vast majority of landslide events all over the globe (Serrano and Jimenez, 2010; Panek et al., 2011). However, rainfall intensity alone cannot be used as a landslide warning signal (Ng and Shi, 1998). Landslides are frequently a combined effect of intense rainfall and wet antecedent soil moisture conditions (Ray, 2004), which is a function of the particle sizes available and clay properties. Rainfall data obtained from the weather station of the Santa Tea Plantation and from Bafoussam were utilised to obtain a picture of rainfall for the area around the Bamboutos caldera and the Kekem area respectively (Fig 6 and 7). The data showed continuously high total annual and total July rainfalls for about 5 years, leading up to 2003 (Fig 6a and b). This indicates a build-up of soil moisture and rising up of the groundwater levels in the soils. Intense and prolonged rainfall in July 2003 coupled with the antecedent moisture conditions rendered the slopes susceptible to the eventual landslide events of 20th July 2003.

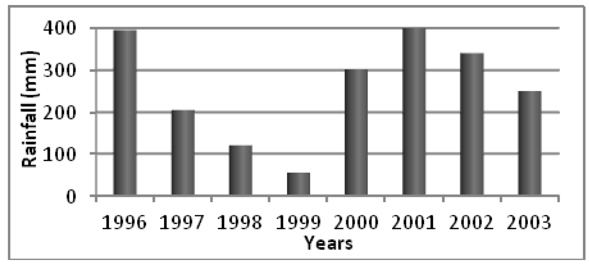
Rainfall data was collected from Bafoussam for a period of 10 years. The total annual rainfall showed an almost uniform high rainfall from 1998 to 2007 (Fig 7a). The total rainfall in October showed a pattern of increasing rainfall cycles with peaks in 1999, 2004 and 2007 (Fig 7b). Such highs are indicative of increase soil moisture content, with a possible implication on the pore water pressure and on the stability of the slopes.

In 2007, the month of October recorded the highest amount of continuous rainfall for 6 days, which was preceded by other rainfall events until the end of the month following the high values recorded from April to September (Fig 7) thereby saturating the soil beyond the limit that can be sustained by the shear strength of the slope and resulting in the landslide disasters. Such prolonged rainfall increases the groundwater level, and alters the pore pressure, reducing the slope safety factor (Hyndman and Brown, 2000;

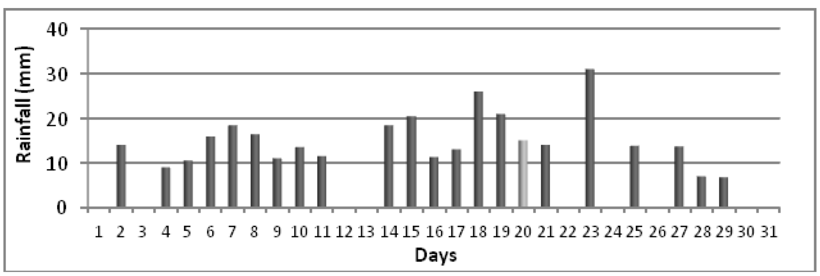
Ayonghe et al., 2004). Considering the fact that both areas have steep slopes with a high degree of weathering which



a) Total annual rainfall from 1993 to 2002

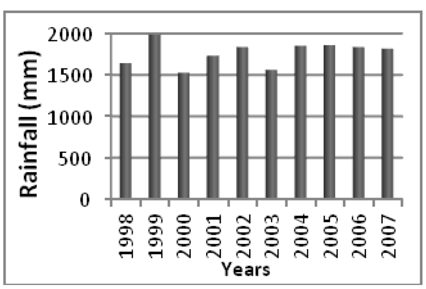


b) Total rainfall in July from 1996 to 2003

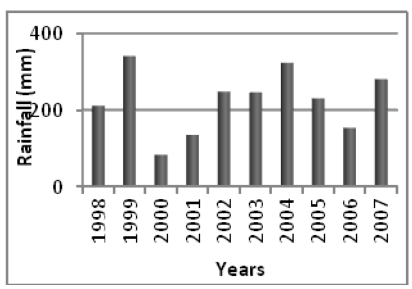


c) Daily rainfall in July 2003 (after Ayonghe and Ntasin, 2008)

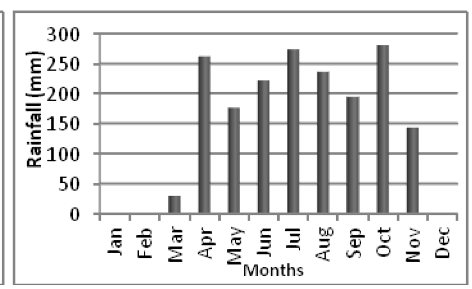
Figure 6: Rainfall data representing the Alou area



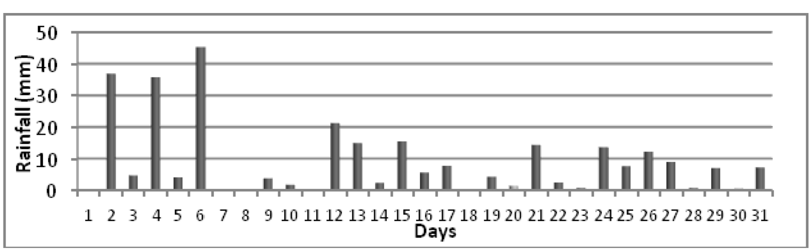
a) Total annual rainfall from 1998-2007



b) Total rainfall in October from 1998-2007



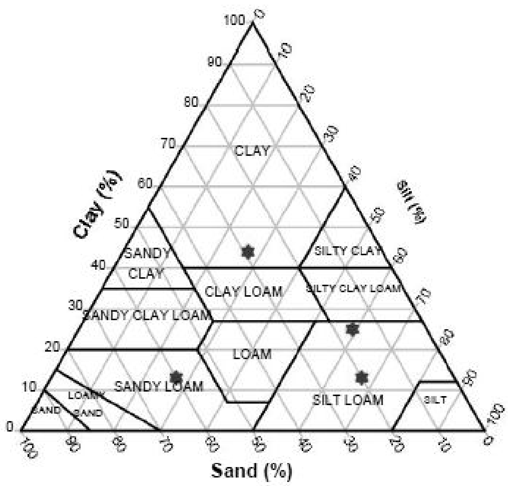
c) Total monthly rainfall for the year 2007



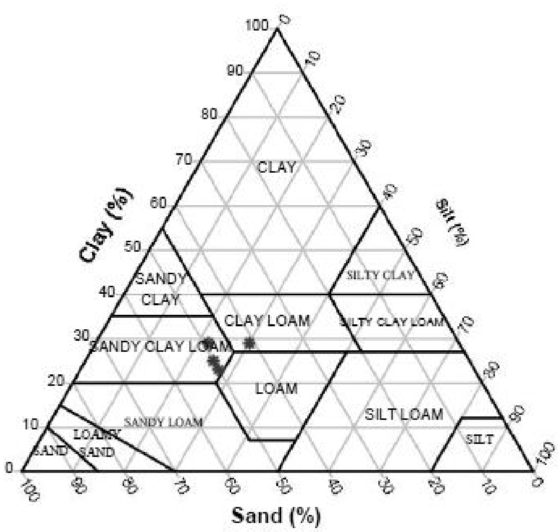
d) Daily rainfall in October 2007

Figure 7: Rainfall data representing the Kekem area

produces fine andisols in the volcanic area and lateritic soils in the metamorphic area, the high and prolonged rainfall is accordingly the major triggering factor in the landslide events of the 20 of July 2003 in the volcanic rocks at Alou and the 20th of October 2007 in the metamorphic rocks at Kekem.



(a)



(b)

Fig.8: Soil classification for (a) Alou (volcanic rocks and (b) Kekem (metamorphic rocks)

Conclusions

Field and laboratory analysis of geotechnical properties of soils from landslide scars within volcanic and metamorphic terrains show significant variations in bulk densities and water content. Grain size analysis indicated a higher proportion of the clay fraction in the metamorphic terrain with an almost equal proportion of the fine and coarse fractions in the metamorphic terrain, while the volcanic terrain showed a lower clay faction with a higher silt fraction.

Clay mineralogy determined from X-ray patterns showed variability in the clay properties of both terrains. Non-swelling type clays characterize the volcanic area whereas the metamorphic area showed significant proportions of the swelling type clays, specifically montmorillonite, which, based on its properties, can render the metamorphic rocks more susceptible to slope instability than the volcanic area.

Results of plasticity measurements reveal similar behaviour of the two terrains, placing them generally under the field of silts of high compressibility, with increases in plasticity indexes with depth, which can be attributed to leaching of the fine fractions down the soil profile.

High and prolonged rainfall is common in both terrains and is seen to be the principal triggering factor of the landslides. However, the elevations of the Bamboutos highlands moderate the temperature to more humid tropical relative to the Kekem area, and provide steeper slopes on which the gravitational pull on the water charged soils rich in montmorillonite clays render the slopes more susceptible to sliding than on the more gentle slopes of the Precambrian rocks at Kekem.

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