Mineralogy, Geochemistry and Geotechnical Characteristics of Magha Landslides in the Bambouto Caldera, West Cameroon

A.S.L Wouatong[*1], R. Medjo Eko[2], M.A Nankam[2], V. Kamgang Kabeyene Beyala[3], G.E Ekodeck[4]

[1]Department of Earth Sciences, Faculty of Science, University of Dschang, Cameroon
[2,4]Department of Earth Sciences, Faculty of Science, University of Yaoundé I, Cameroon
[3]Higher Teacher Training School, University of Yaoundé I, Cameroon

[*1]aslwouat@yahoo.com; [2]medjoekorobert@yahoo.com; [2]marcoadero@yahoo.fr;
[3]gemkruy@yahoo.fr; [4]gemekodeck@hotmail.fr

***Abstract*-The Magha region located in the Bambouto caldera is a rainy and mountainous spot in Cameroon. Between 1954 and 2003, more than eight disasters due to landslides have been recorded in the area, among which six were catastrophic.**

An investigation for understanding the mechanism of landslide occurrence in that region was recently performed. The study included geomorphological, mineralogical and geotechnical characteristics of the local soil material. Soil profiles examined showed that lenses of sand are found within the soil mass. These lenses are seats of substantial pore water pressure during rainfalls and they contribute to triggering landslides. Specimens collected from soil profiles revealed that the soil material is made of mainly smectite, some kaolinite, halloysite, and illite. It is found that high plasticity and substantial expandability of smectite infer a significant lubricant capacity to the local soils, which decreases the shearing resistance and the safety factor of slopes, and consequently trigger landslides.

Keywords- Magha; Weathering; Saprolite; Smectite; Kaolinite; Landslide

I. INTRODUCTION

Landslides represent a major threat to human life, constructed facilities, and infrastructure in most mountainous regions of the world [5, 16, 35, 14, and 32]. They are controlled by slope gradient, substrate composition and stability, precipitation, hydrogeology, and vegetation. Events that can trigger landslides include earthquakes and high and long lasting rainfall [6 and 22]. Very often, human activities are reported to increase slope instability and the likelihood that subsequent rainfall will trigger landslides. In Northeastern Puerto Rico which is a humid tropical area, an analysis was performed on 173 landslides which occurred in the Luquillo Experimental Forest. It was found that no landslide was related to road before 1936, presumably because roads were rare. However, between 1936 and 1964, 2 percent of all landslides were road related, and between 1964 and 1989, 53 percent were road related [10]. "References [22 and 15] also estimated that landslides in the Luquillo Experimental Forest occurred more often on land associated with agriculture or roads than on land associated with forests".

Within the last three decades, Cameroon has experienced catastrophic mass movements; about thirty known catastrophic landslides have been recorded leading to the loss of some 128 human lives [35]. These include rock fall, landslides and mudflow, both in the rural and urban areas. Examples of these events in urban area occurred in 1978 at Dschang, then in 1989, 1992, 1996, and 2001 [33 and 34]. We can also mention those happened in 1978, 1985, 1986, 1990 and 1998 at Yaoundé, in 1998 at Nkongsamba, and in 2003 at Poli. In rural areas, landslides were registered in 1987at Fossong Wetcheng which is close to Dschang, in1991 at Pinying, in 1993 at Bafaka [17], in 1998 at Awae, in 2003 at Wabane (Magha region) [34], in 2003 at Bana [26 and 14]. All these events have caused serious damage, especially on human lives, houses, agriculture, equipment and different infrastructures. The high density of population in the caldera increases the level of risk evaluated at approximately US$ 3.8 million for patrimony, death of people and destruction of biodiversity [30].

In West Cameroon which is also a humid tropical zone, the Mount Bambouto and its surrounding area are subject to frequent landslides. The loss of human life and land due to landslides is so high that they have already been categorized as the major social problem for that region. No study concerning these natural accidents has not been carried out. Scientific speculation states that geological and geomorphological features of the local soil profile may be the main causes of these landslides according to type of rock and slope. In effect, the local soil is made of volcanic products subject to intensive weathering [23, 30, 18, 32 and 9], which may result in the decrease of soil strength during long lasting rainfall. Yet, no scientific data have been brought forward to back up that feeling.

The main objective of this study is to clarify the mechanism of landslide occurrence in Magha, West Cameroon, particularly in the Bambouto caldera. Unlike previous studies which focused investigations on natural, anthropic or hydrologic causes of landslides in a tropical humid area [6, 10, 22 and 15], this investigation is based on the mineralogy, geochemistry and geotechnical characteristics of a soil to infer the causes of landslides in a tropical humid area. For this purpose, a comprehensive set of mineralogical (constituent of weathering material), geochemical (migration of elements), and geotechnical tests (grain size distribution, Atterberg limits, shear strength and factor of safety) were carried out. The paper first recalls the geology of the region then describes the tests carried out and finally discusses the gathered results.

II. DESCRIPTION OF MAGHA REGION

A. *Outline of Geology and Geomorphology*

The Bambouto Mountains are the third largest volcano set of the Cameroon line after Mount Cameroon and Mount Manengouba. It is a polygenic stratovolcano built between 21 and 4.5 Ma [16]. This volcano lies between the longitudes 9°57' and 10°15'E and the latitudes 5° 27' and 5° 48'N, culminates at Mount Meletan (2740 m) where two great collapse calderas (Figs. 1a and 1b) are encountered [23, 29].

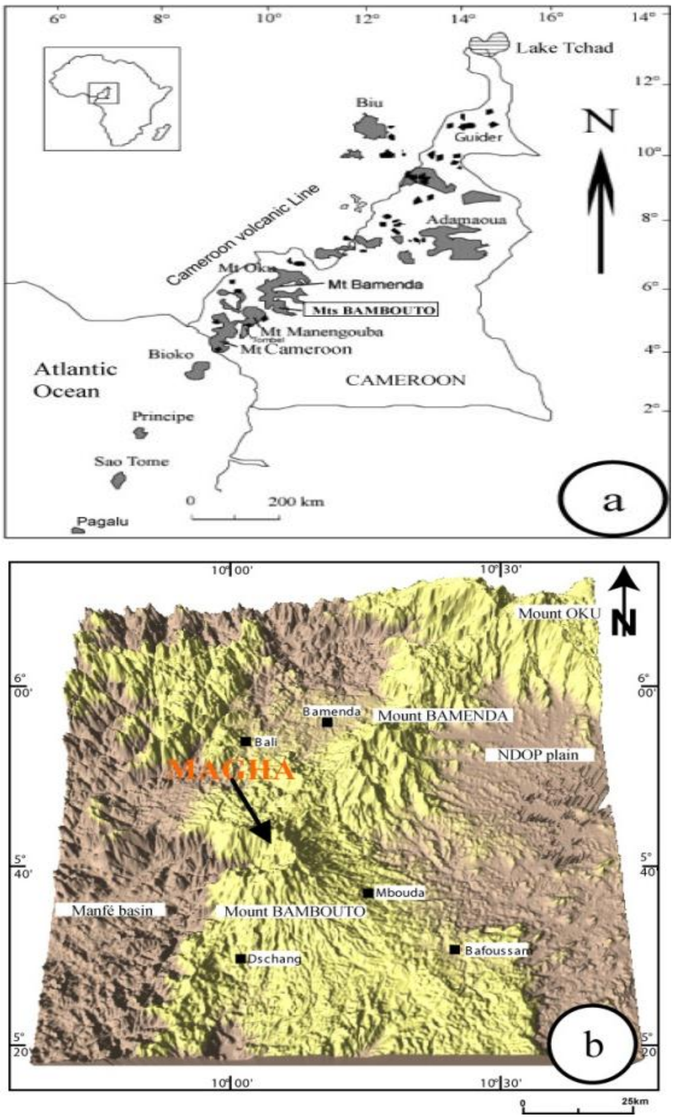


Fig. 1 a) localization of Mount Bambouto in the Cameroon and Magha in the caldera (after [12, 34, 9] Digital elevation model (DEM) of Mount Bambouto

The region has a Cameroonian submountainous type of equatorial climate [25] characterized by heavy rainfall instead of pouring rains in June, July, August and September. The average temperature in the region ranges between 19 and 21 °C. The average rainfall is between 350 and 750mm per year [35]. These rainfalls have a significant action on the chemical destabilization of the surface and subsurface materials it is general statement.

The hydrographical network is dendritic type. Streams have a remarkable influence on the weathering of their beds, and, therefore, create structural disequilibrium (erosion and cracks). By this fact, they can cause the collapse of huge saturated materials. Rainfalls often trigger flooding in certain parts of the caldera, where V-shaped valleys dominate. The vegetal cover consists of grassland (Sporobulus arunlinaria, Pennisetum purpuriun and Imperata cylindrical), mainly close to the caldera rim and the forest in the center of the caldera and along bigger streams. Bushfires and deforestation are means used by local population to clear the vegetation for carrying on agricultural activities.

The distribution of slopes in the region shows that approximately 73% of the caldera is made up of slopes ranging between 11 and 90 °. They are mainly located at the central part of the caldera and towards the caldera rim. Slopes ranging between 2 and 10 °can be easily recognized: they are sporadically distributed in the east and south of the caldera.

Different types of soils are found in that area: they are namely ferralitic red soil on granite, ancient basalt and trachyte, andosolic soil grey and black on recent volcanic rocks (basalt, trachyte and pyroclastic). Their thickness varies between 0.01 m to 0.60 m.

The area where the investigation is conducted is located at Magha inner caldera (Fig. 1b). Due to its unfavorable topographic location, significant parts of local villages are built on steep slopes and volcanic soils. The main volcanic products of the area are derived from basalt, trachyte and phonolite lavas, tuff [31, 19, 18, and 32] and ignimbrites [23 and 9]. They are locally overlain by sedimentary and surface residual formations [28].

Ignimbrites lie directly on the granitic Pan–African basement and have been previously mapped as the basal volcanic complex [3]. They are considered to be the first products of the volcanic activity of the Bambouto Mountain [24]. The ignimbrites occur in discontinuous sheets (Fig. 2) with thickness generally between 30.00 m and 120.00 m. Within the caldera, observations have revealed the presence of tuffs intercalated between trachyte, phonolite and basalt lava flows. The tuffs bear few lithic fragments, with sizes less than 0.80 m. The clasts include trachyte, pumice and granitic basement in a matrix of fine-grained particles.

These pyroclastic materials are widespread in Magha and its surrounding. They are characterized by remarkable weathering and are extensively attacked by water; oxygen, carbon dioxide and organic matter which transform them to saprolite, and the reaction proceeds spontaneously under the local humid tropical climate. These saprolitic materials are not stably emplaced and have a great possibility to move because of their composition and the geomorphologic characteristic of the locality.

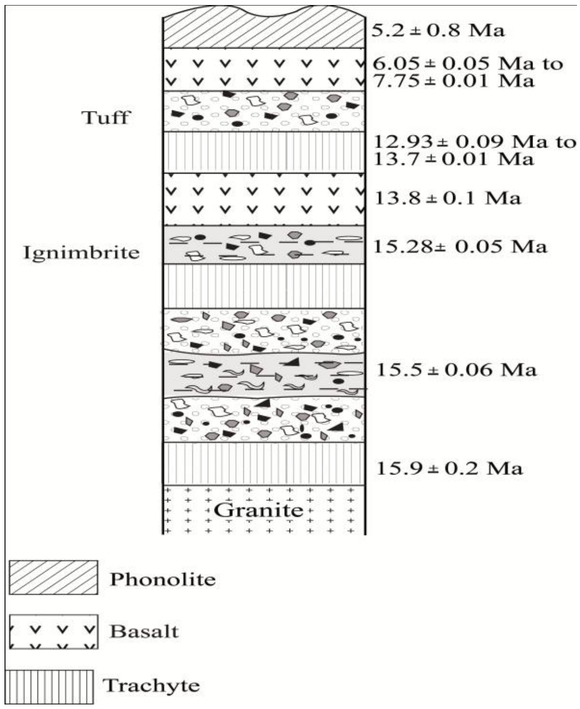


Fig. 2 Stratigraphic section showing the succession of geological formations inside caldera in the Bambouto Mountains (after [20 and 9])

B. Outline of Landslides

Magha Village is vulnerable to landslides and experiences heavy rainfall of 718mm. The first signs of a landslide had been observed in 1954. Since then, the landslides have become regular phenomena which occur every rainy season from July to September. The Magha landslides can be recognized mainly from geomorphological evidence of a deflated steep slope scarps [35, 32] and tension cracks around the head of the landslides as seen in Figs. 3a and 3b.

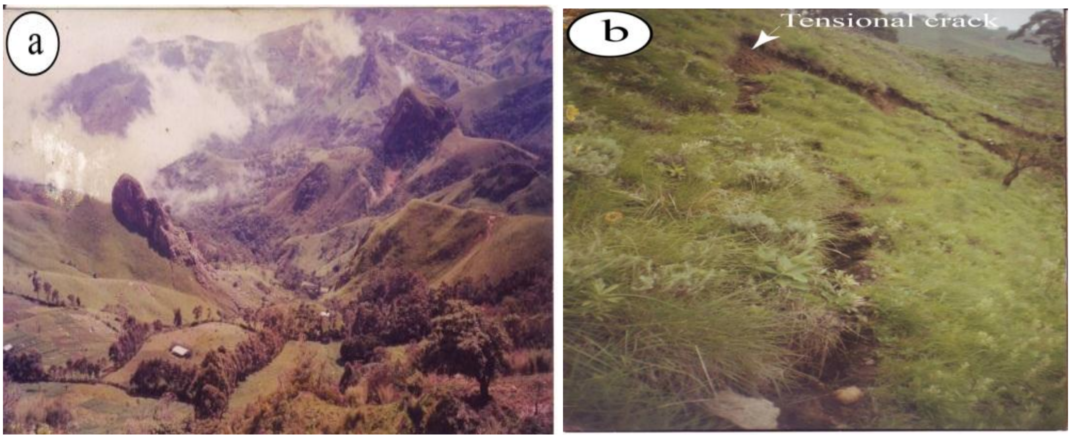


Fig. 3 a) landscape variation and geomorphologic view of Magha area b) tensional crack around the head of landslide

Cracks are generally formed by differential shearing between the moving mass of soil and the inactive one in the landslide area [7]. In August 1997, many landslides occurred due to a heavy rainfall spread over several days. The most important and catastrophic one had a mass of soil displaced on over 5 km on a 70-90 ° slope. Tension cracks observed in the area are considered to be the upper edge of a downward and outward movement of the entire mass of soil that participates in the soil failure (Fig. 3b and Fig. 4).

Fig. 4 Signs of active land sliding

In July 2003, the two catastrophic landslides of Magha took place at coordinates N05° 41’ 39”- E10° 44’ 42” and N05° 40’ 56”- E10° 5’ 22” after heavy and continuous rainfalls. They caused 22 deaths at the locality; many people were injured and infrastructural damages took place. Besides these two major landslides, many landslides were recorded thereafter without serious damages. In the Magha area, more than 30 scars of landslides can be observed. Active zones where landslides occurred present an amphitheatre shape.

Geomorphology of the area (Fig. 3a) displays many sloping zones where landslides are likely to occur as pointed out by [35, 30]. It is observed during landslide occurrence that the root subsides substantially while the tongue bulges with some material flow downward the slide. The mobilized materials are collected in an almost flat area, located at the scarp’s base. At this point the original characteristics of the material are already lost as it has turned into a rather viscous mud, owing to water absorption. The material flows through a narrow and steep discharge to a lower area and valley (Figs. 5a and 5b). The lowest landslide sector corresponds to the main accumulation area.

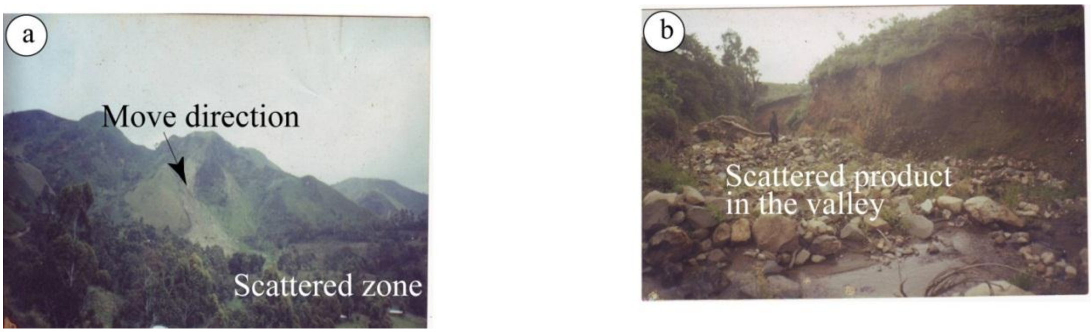


Fig. 5 Morphology of landslide occurring in Magha: a) top of the caldera; b) scattered material in the valley

Rock falls are also common in the caldera. They are usually due to fissures found along the lava flows and along dykes, domes and plugs scattered in the caldera. Water also plays a significant role in this failure when it percolates in the volcanic products through their fissures. When coupled to the weathering process, water lubrication makes detachment of blocks easier.

III. METHODOLOGY

Many samples (13) were collected from saprolitic materials exhibited in cuts achieved during road construction and from soil materials lying in the streams of the valleys (Figs. 6a, 6b). No boring cores were performed. From top to bottom of the soil profile (0.00 – 4.60 m depth), three pedologic sequences were observed.

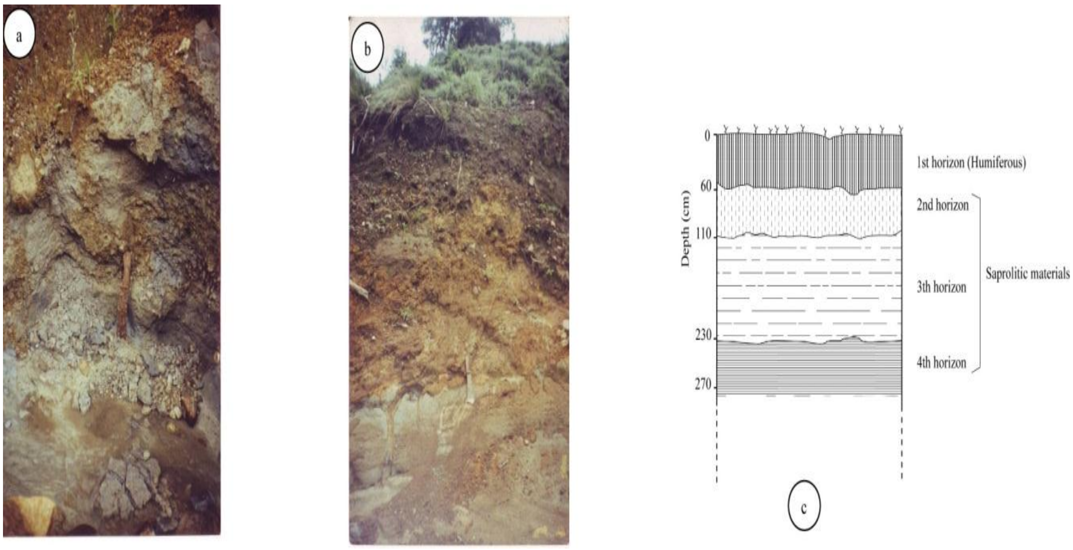


Fig. 6 Saprolitic material: a) around the landslide area; b) inside valley; c) cross section of saprolitic material of Magha

They are as follows:

- (MBG) sequence located on the landslide site at geographic coordinates N ° 05. 41. 21 and E 010. 05. 10. It has 6 horizons numbered 1to instead of through 6 (1, 2 3, 4, 5 and 6). Samples at that sequence were collected at the following depths: No 1 at 1.00 m, No 2 at 1.80 m, No 3 at 2.00 m, No 4 at 2.70 m, No 5 at 3.40 m, and No 6 at 4.60 m.
- (MTR) sequence which is found very close to Magha market at geographic coordinates N 05. 41. 10 and E 010. 05. 22). It has 3 horizons numbered 8 to instead of through 10 (8, 9, and 10). Samples at that sequence were collected at the following depths: No 8 at 1.60 m, No 9 at 2.00 m, and No 10 at 2.40 m.
- (MBA) sequence located on another landslide site at geographic coordinates N05. 41. 14 and E 010. 04. 48. It has 4 horizons numbered 12 to instead of through 15 (12, 13, 14 and 15). Samples at that sequence were collected at the following depths: No 12 at 2.80 m, No 13 at 2.00 m, No 14 at 1.60 m, and No 15 at 1.00 m.

The thickness of horizons varied from the size of a centimeter to that of a meter. From top to bottom of each sequence, the horizons are composed of:

The first horizon is 0.00 to 0.60 m thick; is dark; it is a silty material with a crumbly structure;

The second horizon is 0.20 to 0.70 m thick; it is dark, silty material with a crumbly structure;

The third horizon is 0.60 m to more than 1.00 m thick; its shade is reddish; it is a clayey silty material with many yellow points;

The fourth horizon is 0.30-0.70 m thick; its shade is grey whitish, its consistency is very plastic and it is essentially a clay material (Fig. 6c).

In some profile, one can notice the presence of a grey clay film horizon of 0.01-0.15 m thick.

The materials of July 2003 landslide were moved away and scattered in the lower part area of the valley (Figs. 6a, 6b). The landslide materials are composed only of the weathered pyroclastic and volcanic tuff which are very heterogeneous, slightly moist, of firm consistency, fine grained, very rich in clay fraction and silt, and containing small amounts of sand fraction.

A. X- ray Diffraction

XRD analysis was performed by reflection on both random and oriented powder using an X-ray diffractometer Mac Science - MXP with Ni-filtered Cukα radiation. The samples were treated by wet sieving and sedimentation method. The clay fraction (less than 2 μm) was separated after dis-aggregation in distilled water using ultrasonic wave to identify clay minerals and analyses were made:

- untreated sample;
- treatment with ethylene glycol or formamide;
- heating at 500 ℃ for one hour.

The analytical conditions were an X-ray generator labelled at 18KW, 40.0KV, 100.0mA, with a sample width of 0.02deg. Scanning speed was 8.00degree/min.

The data were recorded between 0° and 60° (2θ).

B. Geochemical Analysis

Chemical analyses were performed by X-ray fluorescence spectrometer XRF RIGAKU 3030 equipped with a W dual anode X-ray tube. Twelve gram of each sample was fused with 6g of 4:1 mix of lithium metaborate and lithium tetraborate, for 20 min at 1100 ℃, with intermittent swirling to ensure thorough mixing. The contents of major element were determined and their values were calculated and expressed in the form of oxides using the rock (name not mentioned) standard of the Geological Survey of Japan.

C. TEM Observation

Three selected samples (No 1, No 6, and No 9) were dehydrated before viewing. The particular micro-morphologies of clay fraction were observed by transmission electron microscope (TEM; JEOL 200CX).

The analyses were performed in 2008 at the Science of Earth and Planetary Materials Laboratory of the Department of Earth and Planetary System Science, Faculty of Science, Hiroshima University (Japan).

D. Geotechnical Parameters

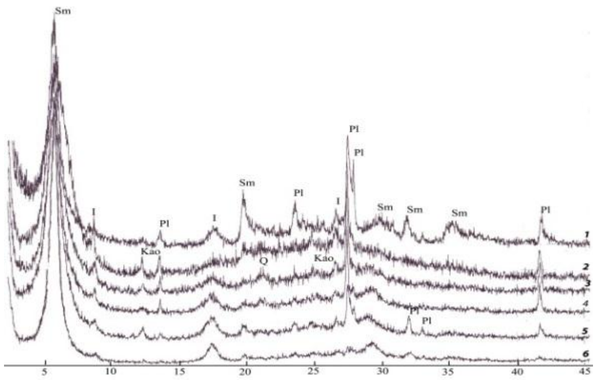
In this study, to check the effects of clay content on the Magha landslide, 5 representative undisturbed soil samples were selected namely No 1, No 3, No 6, No 8, and No 9 for determining geotechnical characteristics which include grain size analysis, consistency of clay and direct shear test.

Grain size analysis was carried out using classical sieve and sedimentation procedures. The grain size distribution was reported accordingly. Atterberg limits were also determined. The physical properties (bulk density, natural water content) were determined using undisturbed soil samples of saprolitic material; the shear strength was also evaluated through a direct shear test (value see result). The slope stability analysis was conducted and the factor of safety (FS) was computed using the Fellenius method. The stability of slope was judged based on the value (see result) of the factor of safety: FS. These geotechnical parameters were determined at the National Civil Engineering Laboratory (LABOGENIE) Yaoundé, Cameroon.

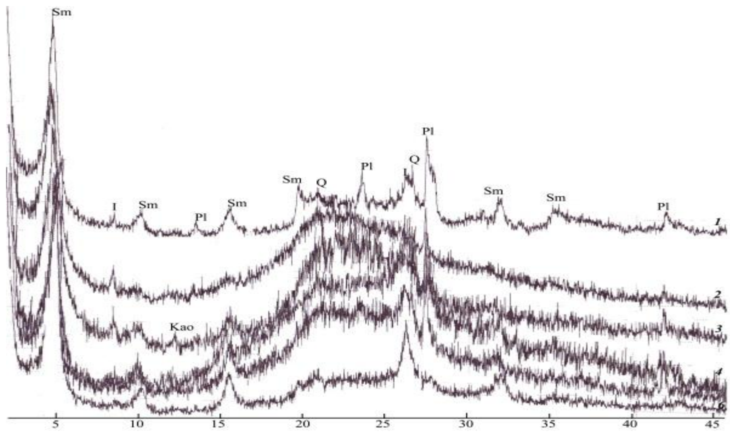
IV. RESULTS

A. Clay Mineralogy and Geochemistry of Weathered and Landslide Materials

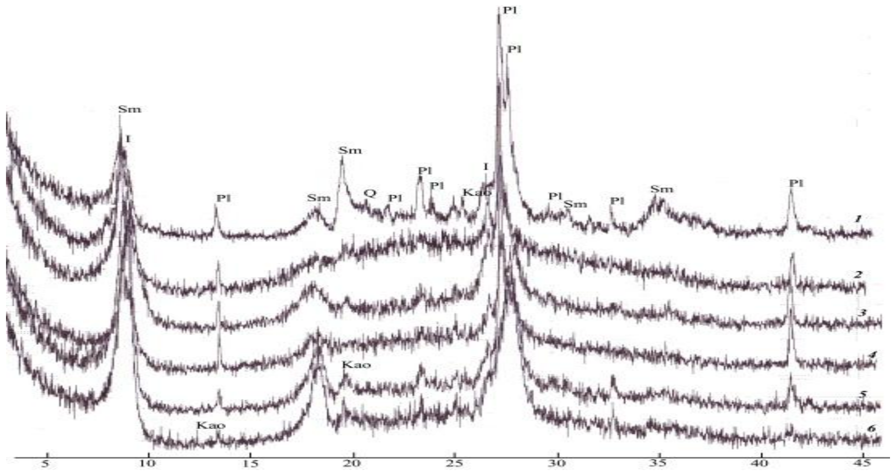
The representative X-ray diffraction (XRD) patterns of the bulk and the clay fraction are illustrated in Fig. 7a. The constituent minerals are feldspar and clay minerals. The 14.60-15.40 Å basal spacing expand to 17.11 Å by ethylene glycol treatment (Fig. 7b) almost completely contracts to 9-10.0Å after heating at 500 ℃ for one hour (Fig. 7c). The results indicate that the 15.38 Å basal spacing is smectite (Sm).



Itensity Lin(counts) 2θ CuKα (a)Untreatment



Itensity Lin(counts) 2θ CuKα (b)Ethylene Glycol

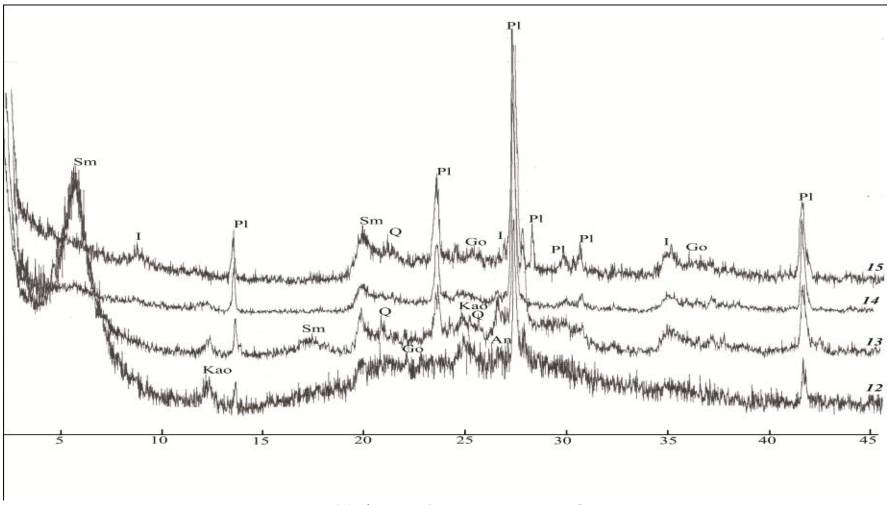


Itensity Lin(counts) 2θ CuKα (c)Heat MBG sample

Fig. 7 X- ray diffraction patterns of saprolitic and landslide materials (MBG: 1, 2, 3, 4, 5, 6), (MTR: 8, 9, 10) XRD, (MBA: 12, 13, 14, 15) of Magha

Sm: smectite; Ch: Chlorite; I: illite; Ha: halloysite; Kao: kaolinite; Gi: gibbsite; Go: goethite; Pl: plagioclase; Q: quartz; An: anatase

Itensity Lin(counts 2θ CuK MTR sample 2θ degree CuK MTR sample



Intensity Lin(counts) 2θ degree CuKα MBA sample Fig. 7 (continue)

The 10.1 Å basal reflections remain unchanged by ethylene glycol treatment. By heating at 500 ℃ for one hour, the intensity of the 10.1Å reflection increases without changing the spacing. Therefore, the 10.1 Å mineral is considered to be mica clay mineral or illite (I). The 7.15 Å and 3.6 Å reflections remain stable at least up to the temperature of 300 ℃ and disappear at 500 ℃ and are thus identified as kaolin minerals (kaolinite: Kao and halloysite: Ha). The 6.48 Å and 3.24 Å basal reflections are identified as plagioclase (Pl). In some samples, one can identify chlorite (Ch) at 13.02 Å, gibbsite (Gi) at 4.84 Å

As seen in Table 1, the saprolitic material is composed mainly of smectite associated with illite occurred mostly at the bottom part of the saprolitic material whereas at the top, the occurrence of halloysite, kaolinite, and gibbsite is observed. Plagioclase is also present whereas quartz, anatase and goethite have been recorded in some samples as trace.

TABLE 1 THE MINERALOGICAL ASSEMBLAGE OF THE SAPROLITIC AND LANDSLIDE MATERIALS OF MAGHA

Samples	Sm	Ch	I	Ha	Kao	Gi	Go	Pl	Q	An
1	●●●							●	○	●
2	●●●		○	○	○			●		●
3	●●●		○		○			●		●
4	●●●		○		○			●		●
5	●●●		○	○				○		●
6	●●●									●
8		○	○	○	●●	○	●			
9	○		○	●●	●	○	●			
10				●●	●					
15	○		●	○	○		○	●	○	●
14	●			○	○			●	○	●
13	●●●			●	●			●	○	●
12	●●●				●		○	●	○	●

●●●, ●●: ABUNDANT, ●: FREQUENT, ○: FEW

Sm: smectite; Ch: Chlorite; I: illite; Ha: halloysite; Kao: kaolinite; Gi: gibbsite; Go: goethite; Pl: plagioclase; Q: quartz; An: anatase

Geochemical composition of saprolitic and landslide materials is reported in Table 2 and the results are also shown graphically in Fig. 8.

TABLE 2 GEOCHEMICAL COMPOSITION OF THE SAPROLITIC AND LANDSLIDE MATERIALS OF MAGHA

Samples	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
1	51.86	1.62	18.35	8.76	0.39	1.51	0.97	1.25	2.01	0.30	12.25	99.27
2	52.10	1.43	19.20	8.55	0.41	1.55	0.95	1.53	2.45	0.23	11.31	99.71
3	52.76	1.39	20.02	8.93	0.46	1.53	0.80	1.67	2.89	0.32	9.10	99.87
4	53.16	1.83	19.55	8.17	0.67	1.67	0.95	2.12	3.13	0.23	8.45	99.93
5	52.34	1.24	17.35	7.64	0.29	1.59	1.65	2.30	2.89	0.37	12.11	99.77
6	45.47	1.38	15.13	6.21	0.20	3.47	5.79	2.53	3.23	0.42	16.09	99.92
8	40.06	0.39	30.45	5.98	0.15	0.21	0.03	0.30	0.54	0.07	20.11	99.29
9	41.70	0.41	30.66	6.92	0.17	0.23	0.04	0.31	0.55	0.08	18.16	99.23
10	43.87	0.23	31.87	3.99	0.02	0.24	0.04	0.23	0.43	0.06	18.77	99.75
15	41.70	2.20	22.49	13.51	0.23	0.58	0.92	1.18	1.75	0.60	14.58	99.12
14	49.01	1.98	23.46	7.53	0.01	0.35	0.39	2.11	2.72	0.35	11.58	99.49
13	56.61	1.42	20.95	3.80	0.03	1.21	0.95	2.23	3.07	0.17	9.79	100.25
12	46.26	2.01	19.94	16.16	0.10	1.16	1.02	0.76	1.27	0.73	10.56	99.97

Silica content varies from 45.47% to 56.61%. According to the profile, SiO2 content decreases. Alumina content varies from 15.15% to 31.87% in the saprolitic and landslide materials. In the sample from MBG, alumina content decreases whereas in the sample from MTR sequence, it increases. These samples show high values (18%-20%) of loss on ignition (LOI). The content of iron varies from 3.8% to 16.16%, but in the studied samples, iron content decreases. Despite low values of MnO (0.01%-0.46%) and CaO (0.04%-1.65%); MgO, Na2O and K2O are important: 0.23% to3.47% of MgO, 0.23% to 2.53% of Na2O and 0.43% to 3.13% of K2O are recorded in the soil samples. One sample (No 6) shows a great amount of CaO (5.79%).

As seen in Fig. 8, the MTR sample tends to Al2O3 summit. This tendency is linked to the presence of kaolinite and halloysite obtained in XRD patterns. The samples from MBG and MBA sequences tend to maintain the alkaline and earth alkaline elements inside profile. This tendency is justified by the presence of remain elements (Ca, Na and K) in the saprolitic materials despite a great leaching. These elements play the role of interfoliar cations inside the 2/1 clay minerals. Our samples show very well the abundance of 2/1 clay minerals through XRD. The mineralogy of the saprolitic and landslide materials shows smectite and illite as clay minerals. The silica/alumina ratio is less than 2, which shows the predominance of the 2/1 clay minerals obtained by XRD patterns. Above tests were carried out on weathered materials from Magha area showing that they contain more smectite than kaolinite.

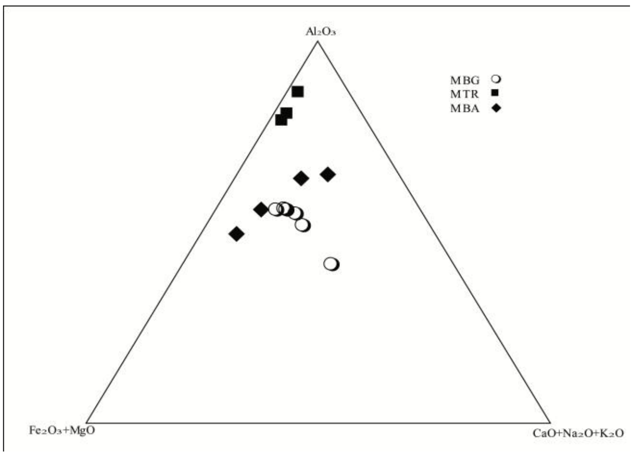


Fig. 8 Ternary diagram showing variation of chemical composition of the landslide materials

B. Transmission Electron Microscope (TEM) Photograph

Transmission electron microscope (TEM) of specimens from the landslide materials shows wide and small particles of smectite with irregular or regular shape (Figs. 9a and 9b). Some specimens show aggregates of kaolinite with hexagonal and pseudo hexagonal shape (Fig. 9c). Smectite particles in a sample are often morphologically non-uniform; they display a variety of habits. The individual crystallites are mostly concentrated in the ≤0.2 micron fraction.

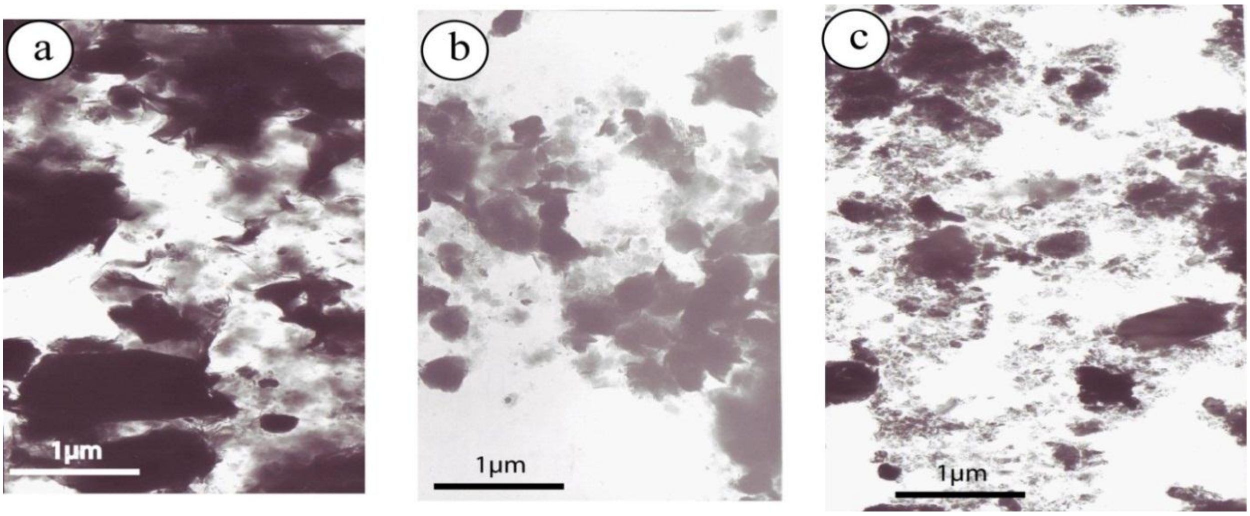


Fig. 9 Ttransmission electron micrographs of landslide materials: a) showing smectite with regular shape particle (sample1); b) showing smectite with irregular shape particle (sample 6); c) showing pseudo hexagonal shape particle

C. Geotechnical Characteristics

1) Hydro-Physical Properties:

Grain size analysis by drying and wetting method reveals that, most of the samples collected from Magha soil profiles are composed of 80% of fine grained and very fine grained particles. The landslide material is largely composed of the weathered pyroclastic and volcanic tuff in clay and silt fraction (70%) (Table 3).

TABLE 3: GRANULOMETRY COMPOSITION OF THE LANDSLIDE MATERIALS

Soil property	1	3	6	8	9
Clay %	56	66	41	56	50
Silt %	22	13	19	9	10
Sand %	20	21	40	34	40
Gravel %	2	0	0	1	0

Using the triangular textural classification, it can be derived that the soil material is clay. According to the grain size distribution curves (Fig. 10); all samples present the same value of uniformity coefficient: it is greater than 2.

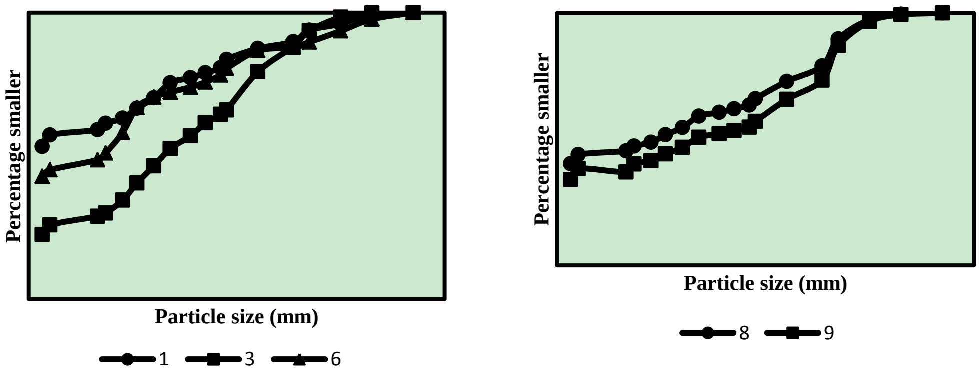


Fig. 10 Granulometric curve of the landslide materials of Magha: a) MBG (1, 3, 6); b) MTR (8, 9)

The geotechnical characteristics of Magha landslide materials are summarized in Table 4.

TABLE 4 GEOTECHNICAL CHARACTERISTICS OF THE LANDSLIDE MATERIALS

Samples	W%	W_l	W_p	I_p	I_c	n%	e	γ_h	γ_s	γ_d	dr	da	Nat sl	Cu	Φ_u °	τ
1	58.10	60.40	43.20	17.20	0.25	29.60	1.21	18.50	26.30	11.19	2.63	1.85	>45 °	0.16	43 °	0.17
3	48.10	66.60	50.30	16.30	1.13	29.20	1.10	18.60	26.30	12.50	2.63	1.86	>45°	0.47	31 °	0.78
6	40.30	66.90	37.60	29.30	0.70	28.80	0.97	18.70	26.30	13.30	2.63	1.87	>45°	0.19	37 °	0.25
8	39.40	54.20	36.20	17.10	0.80	29.27	0.97	18.60	26.30	13.30	2.63	1.86	<70 °	0.47	39 °	0.58
9	40.90	57.10	36.20	20.90	0.70	30.07	1.00	18.60	26.60	13.20	2.66	1.86	<70 °	0.45	41 °	0.30

W% (water content); W_l (liquid limit); W_p (plasticity limit); I_p (plasticity index) ; I_c (consistence index); n% (porosity index); e (void index); γ_h (humid volumic weight); γ_s (dry volumic weight); γ_d (volumic weight); dr (real density); da (apparent density); Nat sl (natural slope); Cu (internal cohesion); Φ_u ° (friction angle); τ (shear strength)

The average natural water content varies from 39% to 58%. These high values are linked to the permanent water content pattern in the landslide zone, the fine grain size of weathered materials and the mineralogical assemblage (smectite, illite and kaolinite) which favour the high water retention capacity.

All the materials tested fall within the range of high plasticity inorganic clay. The liquid limit (Wl) ranges between 54.2 and 66.9%, whereas the plasticity index (Ip) is 16.3%-29.3%, which means that the materials are very plastic. The average unit weight of landslide materials is 18.5 KN/m^3. The density of the soil constituents is 2.63. The consistency index (Ic) ranges between 0.25 and 1, which means the consistency of the materials may be soft, medium or stiff depending on the water content of these clayey materials.

2) Mechanical Test:

Direct shear tests have provided values of internal friction angle $Ø_u$, ranging between 31 and 43 °. Internal angle of friction beyond 35 ° is pretty high values for clay soils. The high values may be explained by the origin of the particle substrate (pyroclastic material) and the presence of granular particles in the samples. The computed safety factor (FS) ranges between 0.90 and 0.97, which is less than the minimum value required for the stability of a slope (1.00). Tension cracks appearing on stable slopes support these low safety factors (Fig. 3b and Fig. 4).

The computed safety factors show that the soil is unstable in the region especially when it is wet because in this condition, its safety factor further decreases.

V. DISCUSSION

A comprehensive geomorphological, mineralogical, and geotechnical investigation is discussed to derive the contribution of parameters involved in the occurrence of landslides. For this purpose, various experimental results are analyzed to ascertain the effective contribution of meaningful factors during occurrence of landslides.

A. Soil Topography

Every mass of soil located beneath a sloping ground surface has a tendency to move downward and outward under the influence of gravity. If this tendency is counteracted by the shearing forces, the slope is stable. Otherwise the slide occurs [24]. Data recorded on site show that the area in which the landslides occurred is very sloppy. Slopes range from 45 ° to 75 °. Such soil topography induces internal forces within the mass soil which render the slope unstable. The computed safety factor carried out during this investigation for evaluating the stability of slopes ranges from 0.97 to 0.90. These values are less than the minimum required for equilibrium of the slopes (1.00). This means that in dry soil conditions, slopes in Magha region are stable because shearing resistance counteracted the downward movement of the mass of soil. When the weather gets wet, the above safety factor decreases, which renders the slopes more unstable. The catastrophic landslides in the Magha region have been recorded during long lasting rainfalls in areas where slopes are steep.

B. Soil Profile

Soil strata are not homogeneous in the Magha region. In effect grain size analysis of Magha soil material showed that sand content ranges from 10 to 30 percent while fine textured material completes the sample material. In addition, soil samples collected at the lower part of the valley after the 2003 landslides were “fine grained soil, very rich in clay fraction and silt, and containing small amounts of sand fraction”. Based on this observation, it can be stated that sand is mixed with fine textured material in the Magha setting. Sand is in the form of sand lenses or pockets since soil strata are not homogeneous. According to [26], sand pockets within clay layers serve as water reservoirs. During wet weather, they become the seat of considerable hydrostatic pressure that tends to cause outward movement of masses in which they are located. As those soil masses move outward, they disintegrate into a mixture of saturated silt, sand, and chunks of clay that flows like a thick viscous liquid. Viscous mud was collected as mobilized materials after the 2003 landslides.

C. Saprolite Mineralogy

The mineralogical composition of samples collected from the MBG sequence where landslide occurred displays smectite with few illite, halloysite and kaolinite. The smectites obtained from Magha saprolitic materials are lamellar aggregates and mossy aggregates as described by [11]. The lamellar aggregates consist of thin discernable smectite films or of minute subhedral platelets. They can be voluminous and porous because of curling and folding of thin films. They can also be compact when thin platelets are associated face-to-face (FF) [4, 29, 28].

Smectites are well-known swelling materials [21]. Swelling minerals such as smectites expand when they become wet. In effect, when they get wet, water enters their crystal structure and increases their volume. They consequently expand. During intensive rainfall, they therefore swell and slopes where they are located become prone to failure. Previous studies involving the role of swelling clay minerals in activating a landslide have shown that even a small amount of swelling clay minerals in soil greatly affects its strength behavior. “Reference [13] highlighted the role of clay minerals in landslide formation and described the effect on velocity in landslide movement”. The presence of swelling minerals in the mobilized materials of the study area greatly supports the occurrence of landslides in the Magha region.

D. Geotechnical Characteristics

It has been observed that liquidity limit of the soil material in Magha ranges from 54.2% to 66.9% while plasticity index ranges from 16% to 29%. These values in the plasticity chart range the local soils in the zone of medium clayey to clayey soils. Result of grain size analysis classifies these saprolotic materials as clay since fine textured materials in soils samples ranges from 70% to 90%. Both soil classification systems lead us to consider the local soils as very plastic clayey materials. It therefore means that the permeability of these materials is very low. In other words, when wet, the materials tend to substantially retain water, which increases their lubricant capacity and consequently decreases the soil shearing resistance. It is observed that the dry shearing resistance of the local soils is not high enough since it ranges from 25 to 50 kPa for the samples tested (Fig. 11).

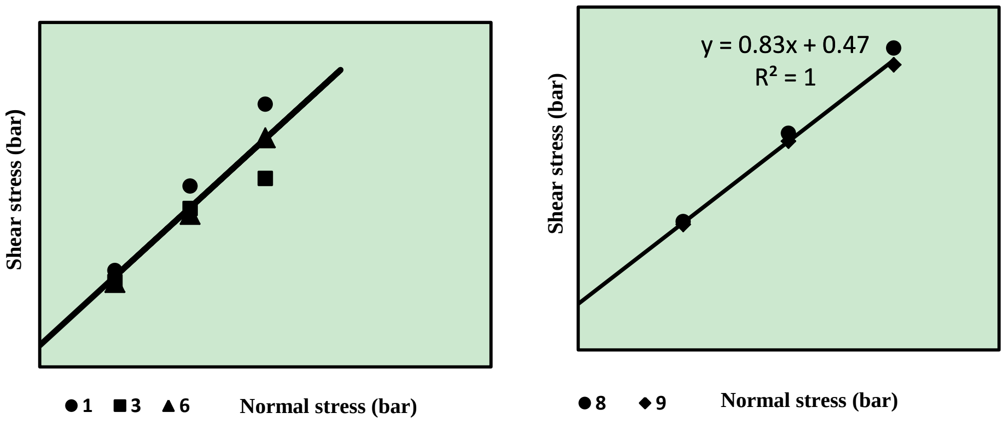


Fig. 11 Shear strength parameters of the landslide materials of Magha: a) MBG (1, 3, 6), τ=0.080σ+0.25, R=0.94; b) MTR (8, 9), τ=0.83σ+0.47, R=0.99

When it decreases as a consequence of wet weather, conditions are set for soil cohesion to become negligible. Additional factors for reduction of cohesion can be mainly attributed to:

- the mineralogy of landslide materials (swelling clay),
- the wet and dry soil cycles linked to the climate change of the area,
- the tension cracks occurrence which favors the quick infiltration of runoff water.

Finally the soil fails as a result of all above mentioned soil characteristics in humid conditions. Landslides of Magha region occurred when the soil was profoundly wet as a consequence of long lasting rainfalls.

VI. PERSPECTIVES

One source of soil instability we mention above is sand lenses that act as water reservoir where pore pressure develops in the soil profiles during wet condition. To alleviate at least the unstability related to this factor, it can be recommended to drain the soils by installing horizontal auger drains. Such drains commonly consist of slotted metal or plastic pipe of about 0.05 m diameter. These drains are given a small downward slope to facilitate the removal of water by gravity. The length of such drains ranges from a few meters to 50 meters. Their spacing depends on local conditions. It was found that several rows of the drains at different elevations are effective [26].

Additional recommendations which can also be set forward for risk alleviation are as follows:

- develop preventive methods of fast evacuation of populations;
- take into account the hazards map in the land use plan;
- develop afforestation;
- avoid deforestation and bushfires;
- improve agropastoral techniques which lead a better management of natural resources.

VII. CONCLUSION

The landslide occurring in the Magha area was investigated mainly from the mineralogical, geochemical and geotechnical viewpoints. The results show that

- the soil is very sloppy with slopes ranging from 45 to 75 °; this geomorphological feature induces internal forces within the mass of soils and renders slopes unstable;
- lenses of sands found in the local soil profiles are the seat of pore water pressure which contributes to trigger landslides;
- landslides materials are mainly composed of smectites which are very plastic and;
- display a substantial expandability; when wet, their high plasticity infers a significant;
- lubricant capacity to the soil , which decreases the shearing resistance and the safety;
- factor of the slopes.

The above factors are mainly those which trigger landslides in the region of Magha, West Cameroon.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude and appreciation to Professor Ryuji Kitagawa of the Department of Earth and Planetary System Science, Hiroshima University, Japan, for his help for analyses, advice and discussion.

REFERENCES

[1] J. I. Branney and P. Kokelaar, "A reappraisal of ignimbrite emplacement: progressive aggradation and changes from particulate to nonparticulate flow during emplacement of high-grade ignimbrite," *Bulletin of Volcanology*, vol. 54, pp. 504-520, 1991.

[2] J. I Branney and P. Kokelaar, "Pyroclastic density currents and the sedimentation of ignimbrites," *Geol. Soc. London Mem.*, vol. 27, p. 152, 2002.

[3] J. C. Dumort, "Carte géologique de reconnaissance du Cameroun à l'échelle 1/500000 feuille de Douala-Ouest et notice explicative. République Fédérale du Cameroun," *Bureau de Recherches Géologiques et Minières, direction des Mines et de la Géologie, Yaoundé-Cameroun*, p. 69, 1968.

[4] D. Eberl, "Clay mineral formation and transformation in rocks and soils," *Phil Trans Royal Soc London A*, vol. 311, pp. 241-257, 1984.

[5] Feng Xia-Ting, J. A. Hudson, Li Shaojum, Zhao Hongbo, Wei Gao Zhang, and Youliang, "Intergrated intelligent methodology for large-scale landslide prevention design," *Inter. Jour. of rock Mechanics and Mining Sciences*, vol. 41, pp. 1-6, 2004.

[6] N. C. Garwood, D. P Janos, and N.V. L. Brokaw, "Earthquake –caused landslides: a major disturbance to tropical forests," *Science*, vol. 205, pp. 997-999, 1979.

[7] F. S. George and L. R. David, "Field investigation, landslide analysis and control," Schuster R L. and Krisel R J. Eds. *spécial raport*, vol. 76, pp. 81-911, 1978.

[8] J. Gouhier, J. Nougier, and D. Nougier, "Contribution à l'étude volcanologique du Cameroun: Ligne du Cameroun," *Ann. Fac. Sci. Univ*. Yaoundé, Cameroun, vol. 17, pp. 3-48, 1974.

[9] M. Gountié Dedzo, A. Nédélec, A. Nono, T. Njanko, E. Font, P. Kamgang, E. Njonfang, and P. Launeau, "Magnetic fabric of the Miocene ignimbrites from West-Cameroon: Implication for pyroclastic flow source and sedimentation," *Journal of Volcanology and Geothermal Research*, vol. 203, pp. 113-132, 2011.

[10] M. R. Guariguata, "Landslides disturbances and forest regeneration in the Luquillo Mountains of Puerto Rico," *J. Ecol.*, vol. 78, pp. 814-832, 1990.

[11] N. Güven, "Smectite. Hydrous phyllosilicates (exclusive of micas)," *Reviews in Mineralogy*," *Mineralogical Society of America*, vol. 19, pp. 497-559, 1988.

[12] A. Kagou Dongmo, "Le mont Manengouba évolution volcanologique caractère magmatologique risque naturels: comparaison avec les monts Bambouto et Bamenda," Thèse Doctorat d'Etat. Université de Yaoundé I., p. 239, 2006.

[13] P. F. Kerr, "The influence of clay minerals on surficial earth movements, Final report," Department of Geology, Columbia University, New York, p. 24, 1972.

[14] S. Kouayep Lawou, R. Medjo Eko, V. Kamgang Kabeyne Beyala, A. S. L. Wouatong, and F. Ngapgeu, "The influence of rainfall on mass movements: The case of Bana, West Cameroon," ISEV2009-*Environmental Vibration: Prediction, Monitoring, Mitigation and Evaluation*, Science Press. Beijing, vol. 1, pp. 822-829, 2009.

[15] M. C Larsen and A. J Torres-Sanchez, “Landslides Triggered by Hurricane Hugo in Eastern Puerto Rico, September 1989,” *Caribbean Journal of Science*, vol. 28, no. 3-4, pp. 113-125, 1992.

[16] Lulseged Ayalew, Hiromitu Yamgishi, Hideaki Marui, and Tkami Kanno, “Landslides in Sado Island of Japan: Part I. Case studies, monitoring techniques and environmental consideration,” *Engineering Geology*, vol. 84, pp. 419-431, 2005.

[17] MNAT/PNUD, “Inventaire, étude et cartographie des zones à risques au Cameroun; Rapport scientifique final du projet MINAT/PNUD CMR/003,” Février, Yaoundé. 1999.

[18] D. C. Nkouathio, A. Kagou Dongmo, J. M. Bardintzeff, P. Wandji, H. Bellon, and A. Poucet, “Evolution of volcanism in graben and horst structures along the Cenozoic Cameroon Line (Africa): implications for tectonic evolution and mantle source composition,” *Miner Petrol*, vol. 94, pp. 287-303, 2008.

[19] J. N’ni and J. B. Nyobé, “Géologie et pétrologie des laves précaldériques des monts Bambouto: Ligne du Cameroun,” *Geochemical Brasil*, vol. 9, pp. 47-59, 1995.

[20] A. Nono, E. Njonfang, A. Kagou Dongmo, D. G. Nkouathio, and F. Tchoua M, “Pyroclastic deposits of the Bambouto volcano (Cameroon Line, Central Africa): evidence of an initial strombolian phase,” *Journal of African Earth Science*, vol. 39, pp. 409-414, 2004.

[21] G. Phillipponnat et B. Hubert, “Fondations et Ouvrages en terre,” Editions Eyrolles, Paris. 1998.

[22] F. N. Scatena and M. C. Larsen, “Physical aspects of Hurricane Hugo in Puerto Rico,” *Biotropica*, vol. 23, pp. 364-372, 1991.

[23] F. Tchoua M, “Découverte d’ignimbrite dans la région de Dschang,” *Annales de la Faculté des Sciences Cameroun*, vol. 2, pp. 77-94, 1968.

[24] F. Tchoua M, “Sur l’existence d’une phase initiale ignimbritique dans le volcanisme des monts Bambouto (Cameroun),” *Compte rendu de l’Académie des Sciences*, Paris, vol. 276, pp. 2863-2866, 1973.

[25] F. Tchoua M, “Contribution à l’étude géologique et pétrographique de quelques volcans de la Ligne du Cameroun (monts Bambouto et Manengouba),” Thèse Doctorat D’Etat Université Clermont Ferrand, France. p. 374, 1974.

[26] K. Terzaghi and R. Peck, “Soil Mechanics in engineering practice,” John Wiley and Sons, New York. 1967.

[27] S.Valet, “Notice explicative des cartes du climat, des paysages agro-géologiques et des propositions d’aptitude à la mise en valeurs des paysages agro-géologiques de l’ouest Cameroun au 1/200000,” *CIRAT-IRAT*, Montpellier, p. 120, 1985.

[28] A. S. L. Wouatong, K. Ryuji, F.Tchoua M, G. E. Ekodeck, and D. Njopwouo, “Clay mineralogy of the landslide in Lembo area, Bana-Bangou district, west province of Cameroon,” *Clay Science Society of Japan*, vol. 12, pp. 293-304, 2004.

[29] P. Yang, “Mineralogical study of landslide in Monden area, southwest Okayama Prefecture, Japan,” *Journal of Science Hiroshima University*, vol. 10, pp. 87-118, 1994.

[30] D. Youmen, “Evolution volcanologique, pétrographique et temporelle de la caldéira des monts Bambouto (Cameroun),” Thèse Doctorat. Université Albrecht. Kiel. Faculté Maths et Sciences Naturelles, France, p. 274, 1994.

[31] D. Youmen, H. U. Schmincke, J. Lissom, and J. Etame, “Données géochronologiques: mise en évidence des différentes phases volcaniques au Miocène dans les monts Bambouto (ligne du Cameroun),” *Development science and technology*, vol. 11, pp. 49-57, 2005.

[32] G. Zangmo T, A Kagou D, D. G. Nkouathio, and P. Wandji, “Typology of natural hazards and assessment of associated risks in the mount Bambouto caldera (Cameroon line, West Cameroon),” *Acta Geological Sinica* (English Edition), vol. 83, no. 5, pp. 1008-1016, 2009.

[33] A. Zogning, “Limbé: une ville de piedmont d’un volcan actif en milieu tropical humide,” *Revue de Géographie*. Alpine n° spécial sur «croissance urbaine et risques naturels, principalement dans les pays envoie développement Tome 4, LXXXII, pp. 77-86, 1994.

[34] A. Zogning, T. Ojuku, and C. Ngouanet, “La catastrophe du 20 juillet 2003 à Magha,” *Scientific report.* MINREST/INC/DRG, p. 68, 2003.

[35] A. Zogning, C. Ngouanet, and O. Tiafack, “The catastrophic geomorphological processes in humid tropical Africa: A case study of the recent landslide disaster in Cameroon,” *Sedimentology Geology*, vol. 199, pp. 13-27, 2007.