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Mineralogical, Geotechnical Characterization and Stability of the Cut Slopes of Widikum and its Surroundings (North-West Cameroon)

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Abstract

The Widikum highlands and its surroundings are located in the North West Region of Cameroon. These five last years, landslides are frequently affecting movement on this portion of the highway. An investigation for understanding the mechanism of these phenomena was recently performed to clarify and to propose suitable remediable solutions. The study included mineralogical and geotechnical characterization of the local soil materials. The X-ray diffraction mineralogical analysis on clay fractions reveals the presence of phyllitic minerals (kaolinite, gibbsite, montmorillonite, illite and biotite). Associated minerals are mainly represented by quartz. Montmorillonite has the small crystal and largest surface which aid in increasing its adsorptive capacity. Clayed minerals can cause swelling and consequently the change or variation of the mechanical characteristics of the materials. The natural water content of weathered products vary from 27 to 47.4% which are close or even lower than the liquid limit included between 59.4 and 71.9%, this justify their unstable character. In addition, the high plasticity index ranges between 17.9 and 29.3% and is indicative of plastic materials thus very sensitive to creep. Moreover, the saturation ratio is very high (60 - 96%) thus attesting to their quasi saturated state. It is advisable to reduce the height of the steps to 2.3m by opting for a bench of 3m and adopting an inclination angle of $\beta = 37.5°$. Building retaining structures as well as eucalyptus and vertiva grass planting is recommended to reduce landslide incidences.

Keywords: Widikum, landslides, highlands, mineralogical characteristics, geotechnical characteristics

1. Introduction

The Cameroon Volcanic Line, direction N30°E and 1600 km long, forms a series of horst and graben, comprising the Bamenda Mountains and it is marked by a succession of volcanic, plutonic and metamorphic formations resting on the crystalline base subject to intensive weathering. Therefore, these are also dominated by three great geomorphological units varying between 250 and 1550 m laid out in successive steps and separated by more marked escarpments (steep slopes greater than 45°) favorable to instabilities. Yet, relatively few scientific data is available on the causes of these instabilities. The main objective of this study is to analyze the stability of Widikum and its surroundings cut slopes by means of the mineralogical and geotechnical studies and to propose suitable remediable solutions. Landslides represent a major threat to human life, constructed facilities, and infrastructure in most mountainous regions of the world (Delmas *et al*. 1987; Lulseged *et al*. 2005; Zangmo *et al*. 2009; Kouayep *et al*. 2009). They are controlled by diversity of factors such as substratum composition, geotechnical parameters of the whole lithological and pedological set up, climatic conditions, geometry and geomorphology of the site (Delmas *et al*. 1987). Very often, human activities are reported to increase slope instability and the likelihood that subsequent rainfall will trigger landslides. Landslides that have so far been recorded have caused a number of damages. In Nepal, in 2015, landslides buried several villages and caused 400 deaths. The case of the slip of Aab Bareek, which occurred on May 02, 2014 in the Badakhchan region in Afghanistan, gives a report of 300 dead and 4000 people displaced. We can also mention that which took place in 1978, 1985, 1986, 1990 and 1998 at Yaoundé, in 1998 at Nkongsamba, and in 2003 at Poli. That of Kekem, on the night of October 20, 2007 killed one person and caused many damages. The investigation of this study is based on the mineralogy and geotechnical characteristics of weathered products in order to infer the causes of landslides in a tropical humid area. For this purpose, a comprehensive set of mineralogical (constituent of weathered products) and geotechnical tests (grain size distribution, Atterberg limits, unit weight and shear strength) were carried out.

2. Location of Study Area and Geological Setting

2.1 Location of Study Area

The study area is situated in the North-West Region of Cameroon. It is located between latitudes 05°49'12" and 05°54'12" of the Northern Hemisphere and longitudes 09°42' 00" to 09°50' 00" East. It comprises the following (figure. 1) villages: Bajem, Befang and Bamben in the North, Widikum in the Center, Diche I in the South, Diche, Denku and Numba in the West and of Tiben and Numben in the East.

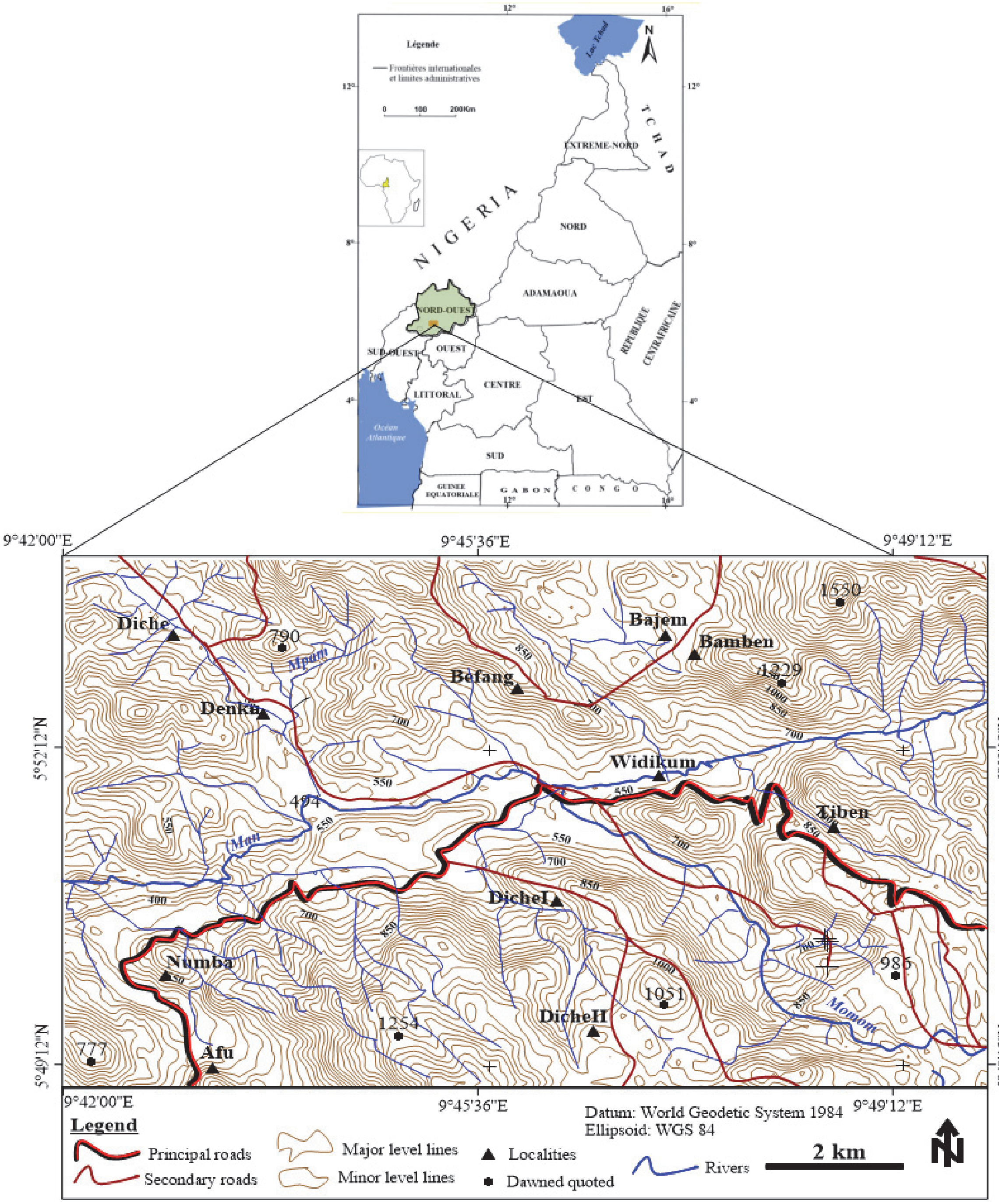

Figure 1. Location of the study area

2.2 Geological Setting

The Widikum environs lies between two climatic zones which are the humid tropical equatorial rainforest climate in the Mamfe basin and the dry savannah climate of the Bamenda highlands frequently affected by landslides. The rainfall records are high with an annual average of 2703.32 mm. These rainfalls have a significant action on the chemical destabilization of the surface and subsurface materials. Moreover, the hydrographical network is sub-dendritic type. Water has a remarkable influence on the weathering and therefore, create structural disequilibrium (erosion and cracks) due to the collapse of huge saturated materials made up of brown aluminous lateritic soils resulting from the volcanic products (old basalts) and plutonic (faded granite) on one hand and gray maroon andosols resulting from the recent volcanic products made up of columnar prims of basalts on other. Furthermore, three great geomorphological units are listed (figure. 2).The low zone (250 – 800 m) is vast and slightly corrugated and marked by a softer relief. The median zone (800 – 1300 m) corresponds to a higher projecting plateau and is marked by the juxtaposition of the morphological characteristics suitable for the low and the high altitude zone. The high altitude zone (1300 m and more) occupy the summit of the study area in which the relief is dominated by interfluves.

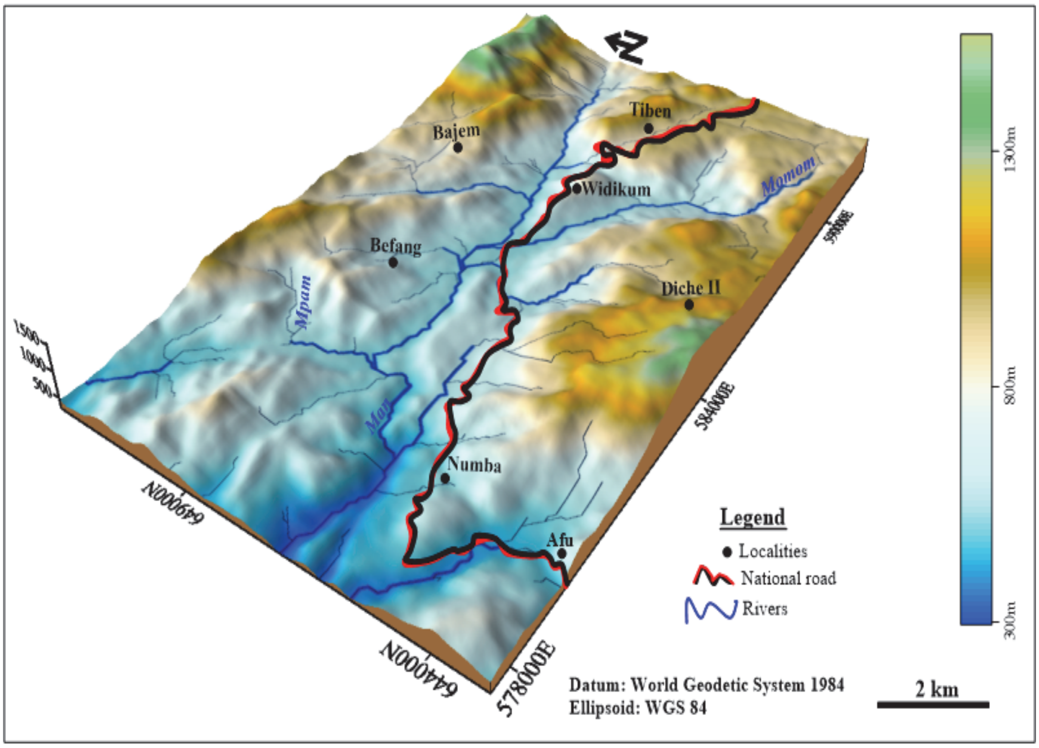

Figure 2. Geomorphological units of the study area

However, the landscape map (figure. 3) presents six different slope classes. The 0 - 7% and 7 - 12% classes represent approximately 27% and correspond to the flat landscapes. These landscapes occupy the base of valleys or depressions and are consequently liable to floods due to the lack of adequate drainage network. The 12 - 18% and 18 - 23% classes, constitutes the undulating landscape and represents a percentage of about 35%. Finally, the 23 - 29% and 29 - 48% of slope classes constutite the bulk, of the slope classes making up 48% of the landscape and which are favorable to landslides and other natural disasters.

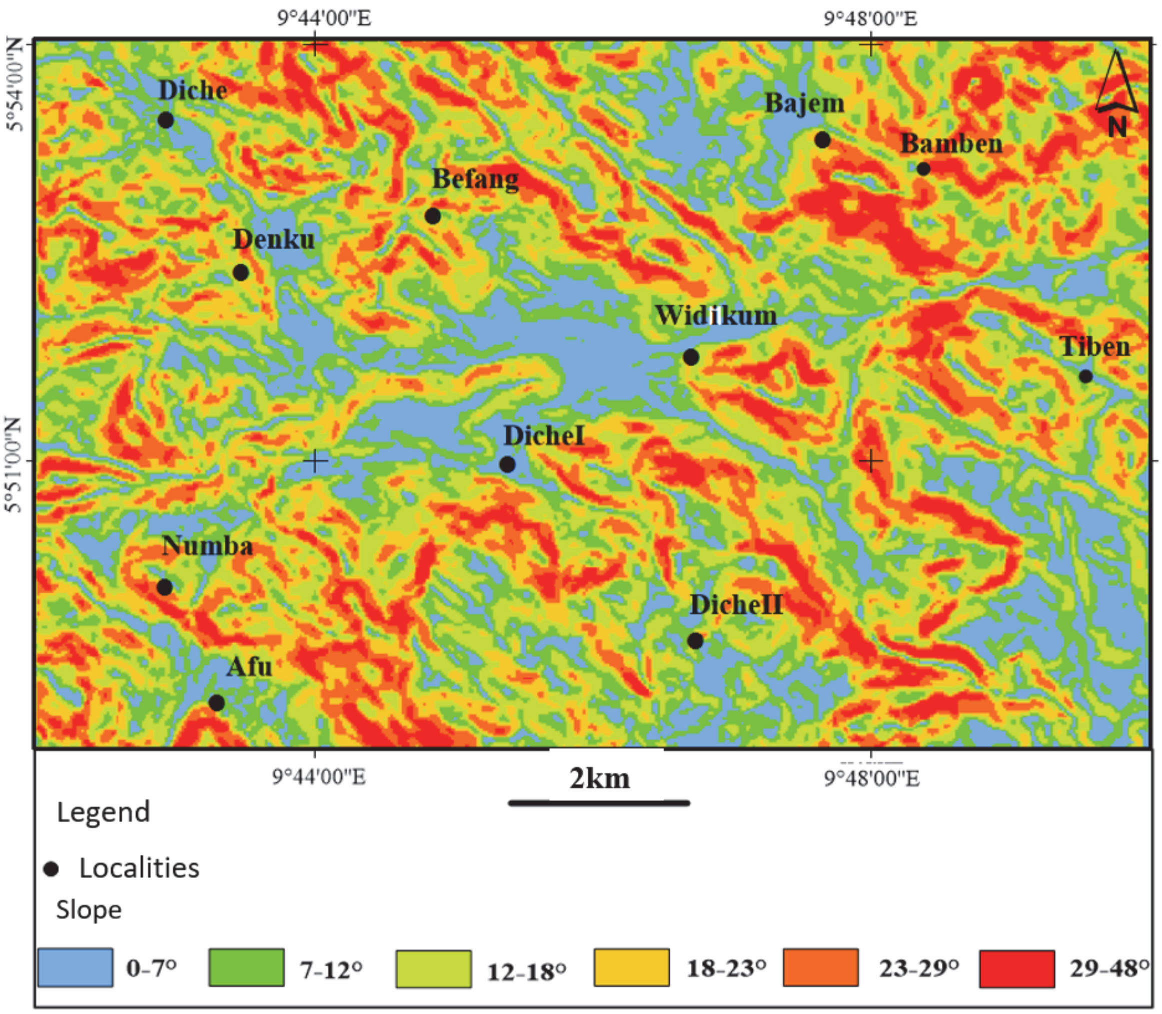

Figure 3. Slope map of the study area

3. Materials and Methods

3.1 Profiling

Soil profiling was carried out on the cut slopes resulting from road construction activities of each of three sites of study area namely Fifty One, Ofen Tiben and Ogwei Tiben. Macroscopic descriptions were performed on each soil profile followed by specimen test collection labeled WD1, WD2, WD3, WD4, WD5, WD6 and WD7 at the upper, median and lower assemblage, for mineralogical and geotechnical analysis. On the whole, seven undisturbed samples were taken using PVC tubes of length 25 cm and of diameter 20 cm. Therefore, WD1 and WD2 represented the upper and lower assemblages specimen respectively from weathered basalt and granite materials of Fifty One. Then, WD3, WD4 and WD5 those coming from the upper, median and lower assemblages of Ofen Tiben weathered granite with phenocristal of feldspar. Finally, WD6 and WD7 are the specimens resulting from the upper and lower assemblage of Ogwei Tiben made up of weathered gneiss with amphibole and biotite.

3.2 Mineralogical Analysis

The mineralogical composition of the materials was studied using X-ray diffractometer. The samples were first heated at 105 °C for 24 hours before being crushed and sieved through an 80µm diameter sieve at the AGEs laboratory of the Department of Geology of University of Liege. The measuring apparatus used was MARK BRUKER diffractometer, using radiation CuKα (5^{th} = 1.518 Å). The scanned angular domain was $5° \leq 2\theta \leq 90°$ with an angular space of 0.020°, within 6 seconds and at an ambiant temperature of 25°C. The apparatus was connected to a computer which directly gave the diffractograms. The different peaks of the diffractograms were determined with the aid of data automatically furnished by the Diffrac+software and controlled manually by ASTM cards.

3.3 Geotechnical Analysis

The geotechnical analysis (natural water content, Atterberg limit, unit weight, triaxial shear strength,) were performed on specimen collected and sealed in plastic bags then transported to the National Civil Engineering Laboratory (LABOGENIE) of Yaounde (Cameroon). The natural water content was determined by drying in an oven at 105°C for 24 hours according to the French Standard Norm NF P 94-050 (1995). However, the liquid limit was determined using the Casagrande method while the plastic limit was identified on the rods of 10 cm length and about 3 mm of thickness according to the French Standard Norm NF P 94-051 (1991). These Atterberg limits were used to determine the plasticity index of the weathered products. Thus, Ip= ω_L - ω_P where Ip is the plasticity index; ω_L the liquid limit and ω_P represents the plastic limit. Moreover, the unit weight was determined using the pycnometer method according to the French Standard Norm NF P 94-054 (1991). The, dry density, porosity, void ratio and the saturation ratio were determined using the relationships between physical characteristics of soils. There are expressed according to the formulas 1, 2, 3 and 4 below.

$$\gamma_d = \frac{\gamma}{1+W} \tag{1}$$

$$n = \frac{\gamma_s - \gamma_d}{\gamma_s} \times 100 \tag{2}$$

$$e = \frac{n}{1-n} \tag{3}$$

and

$$s_r = \frac{w\,\gamma_r}{e\,\gamma_w} \tag{4}$$

respectively where $\boldsymbol{\gamma_d}$ is the unit weight of dry soil, γ the apparent unit weight of soil, $\boldsymbol{\gamma_s}$ the unit weight of solid particles, $\boldsymbol{w}$ a water content, $\boldsymbol{\gamma_w}$ the unit weight of water, $\boldsymbol{\gamma_r}$ the unit weight of soil, $\boldsymbol{e}$ the void ratio and $\boldsymbol{n}$ the porosity. Finally, the unconsolidated and undrained triaxial shear tests were carried out according to French Standard Norm NF P 94-074 (1994) enable to determine the friction angle and the cohesion of weathered products. It was carried out in three stages: sample preparation and installation in a triaxial cell, then saturation and finally shearing of the sample. After shearing of the specimen, respective stress curve τ_{max} = f (σ_{max}) were established from which the friction angle and the cohesion of weathered products were obtained. Finally the critical height step of slopes was determined according to Taylor-Biarez expression in Philipponnat & Hubert (1997) to determine the long term stability of the slopes by means of the formula 5 below.

$$H_{c1} = 2.67\frac{c}{\gamma}\tan\left(45° + \frac{\Phi}{2}\right) \tag{5}$$

If the plateforms limited by a slope is intended to be subjected to a uniformly distributed surchage q, the critical height of each step will be given according to the relation 6 below

$$H_{c2} = 2.67\frac{c}{\gamma}\tan\left(45° + \frac{\Phi}{2}\right) - \frac{2q}{\gamma} \tag{6}$$

where $\boldsymbol{c}$ is the internal cohesion, γ the unit weight of soil, $\boldsymbol{\Phi}$ the friction angle and $\boldsymbol{H_c}$ the critical height respectively.

4. Results

4.1 Outline of Landslide and Soil Profile Characteristics

Three localities namely Fifty One, Ofen Tiben and Ogwei Tiben were affected by landslides. Firstly, the Fifty One locality knew a translational and rotational soil slip (figure. 4a) located between coordinates 05°51'02.7 " North and 09°45'08.2 " East at an altitude of 632 m. Rupture has a width of 8 m, a height of at least 8 m over a length from approximately 10 m. This constitutes a slip material of volume V = 640 m^3. Several factors caused this movement: the nature of the involved rock made up of partially faded basalt, the morphology of the site at the top of a lengthened interfluve with steep slope on granitic base almost completely faded with clay-sandy tendency. In addition, the presence of crack (figure. 4b) due to the water infiltration and finally the presence of water on the walls of the slope (figure. 4c) due to lack of adequate drainage. We can also notice the stratification plan on weathered material (figure 4d).

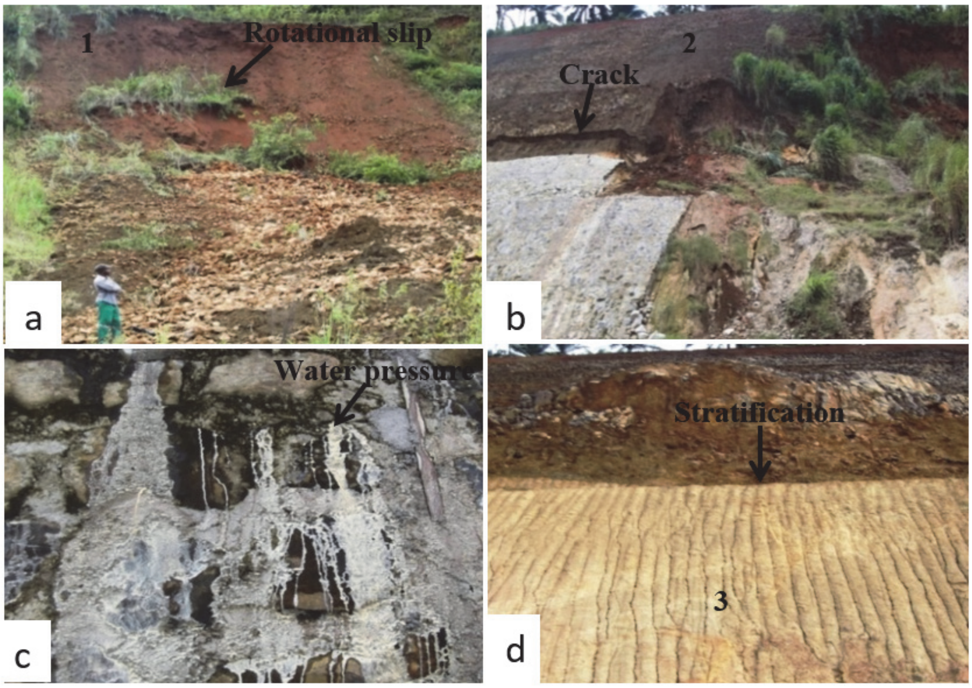

Figure 4. Outline of the Fifty One site. (a): translational and rotational slip. (b): crack. (c): water pressure. (d): stratification on weathered materials. **(1):** dark red to brown gravelly matrix. **(2):** basaltic matrix. **(3):** greyish matrix

Secondly, the translational soil slip which occurred on weathered materials of Ofen Tiben (figure. 5) is located between coordinates 05°51'39.8" North and 09°46'45.1" East, at an altitude of 602 m.This movement is due to several factors: initially, the nature of the bed rock made up of porphyroid granite with biotite, hornblende and phenocristal of feldspar partially faded and presenting many fractures. These materials are on the flank of relatively rounded interfluve with steep slopes combined with their low resistances due to their low compactness. Lastly, the fine grain size materials of clayey consistency, with the permanent presence of water on the surface of the slope constitutes predisposition factors.

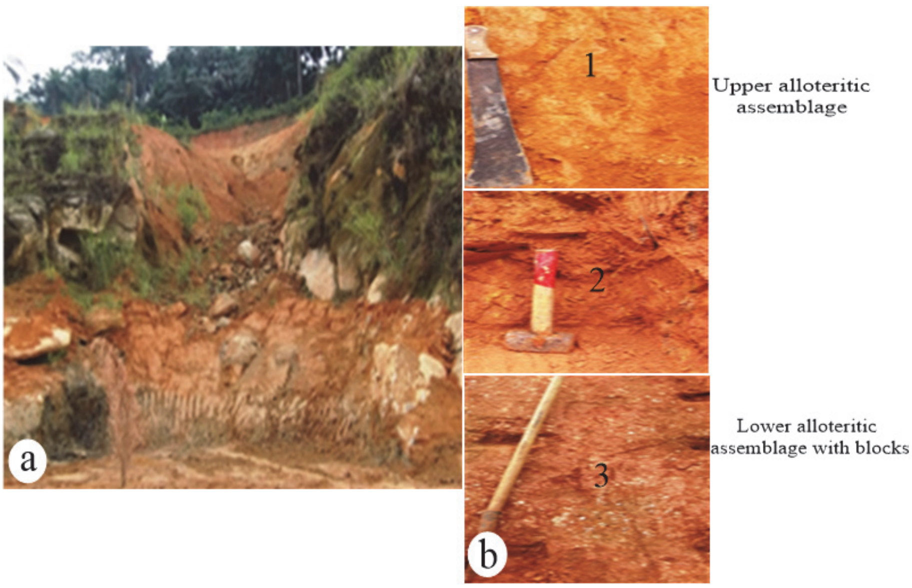

Figure 5. a) Panoramic sight of Ofen Tiben soil slip. b) soil profile **(1):** red yellowish matrix. **(2):** red matrix. **(3):** brown blade matrix

Finally, a translational landslide occurred at Ogwei Tiben site (figure. 6) with coordinates 05°51'49.5" North and 09°47'26.5" East and at an altitude of 618 m. The cut has a width of approximately 6 m, a height of at least 4 m and a length of 7.5 m. Thus, the volume of the slip material is estimated to be 180 m^3. Several factors caused this movement. The nature of the bed rock is made up of gneiss with amphibole and biotite almost completely faded. The geomorphology of the site on the flank of the interfluve consist of abrupt slopes combined with the low cohesion and friction angle of weathered materials due to their heterogeneity with clayey consistency.

Figure 6. Panoramic view of Ogwei Tiben soil slip. **(1):** light gray matrix. **(2):** whitish matrix. **(3):** yellowish red matrix

4.2 Mineralogical Features

The X-ray diffraction mineralogical analysis on weathered materials of Fifty One (figure. 7) reveals that the upper assemblage consists of phyllitic minerals (kaolinite, gibbsite) and associated minerals such as quartz, hematite and goethite. Meanwhile, the lower assemblage consists of phyllitic minerals (kaolinite, illite, muscovite and biotite) and associated minerals such as quartz and hematite.

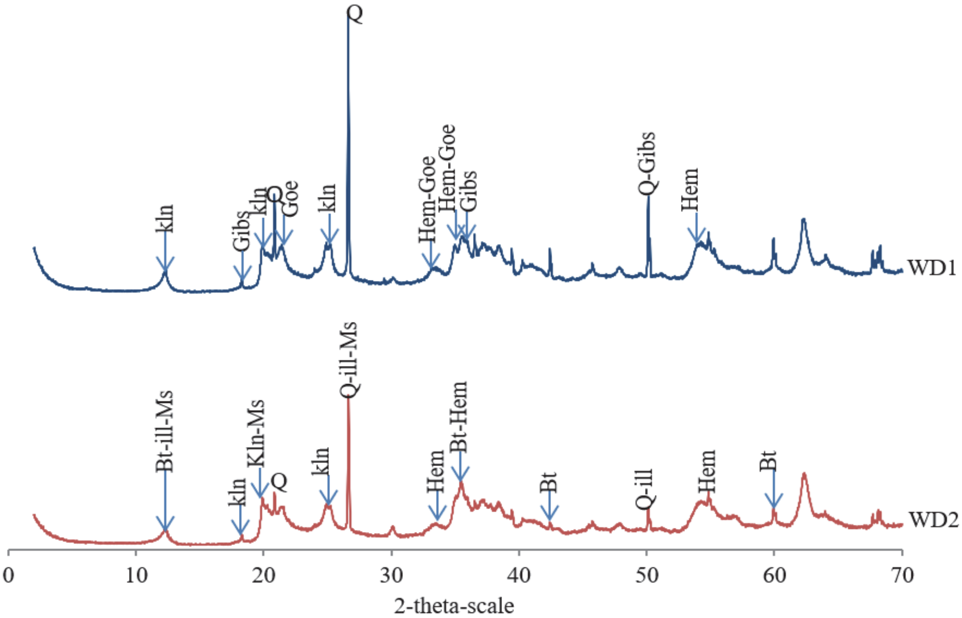

Figure 7. XRD patterns of mineral constituents of Fifty One weathered materials

ill=illite. **Kln**=kaolinite. **Gibs**=gibbsite. **Q**=quartz. **Hem**=hematite. **Bt**=biotite. **Goe**=goethite. **Ms**=muscovite

Furthermore, the X-ray diffraction mineralogical analysis on weathered materials of Ofen Tiben (figure. 8) shows that the upper assemblage consists of phyllitic minerals (kaolinite, gibbsite, biotite and illite) and associated minerals (quartz). Meanwhile, that of median assemblage consist of phyllitic minerals (kaolinite, illite, gibbsite, biotite and montmorillonite) and associated minerals namely quartz. The lower assemblage consists of phyllitic minerals (illite, kaolinite, gibbsite and montmorillonite) and associated minerals (quartz).

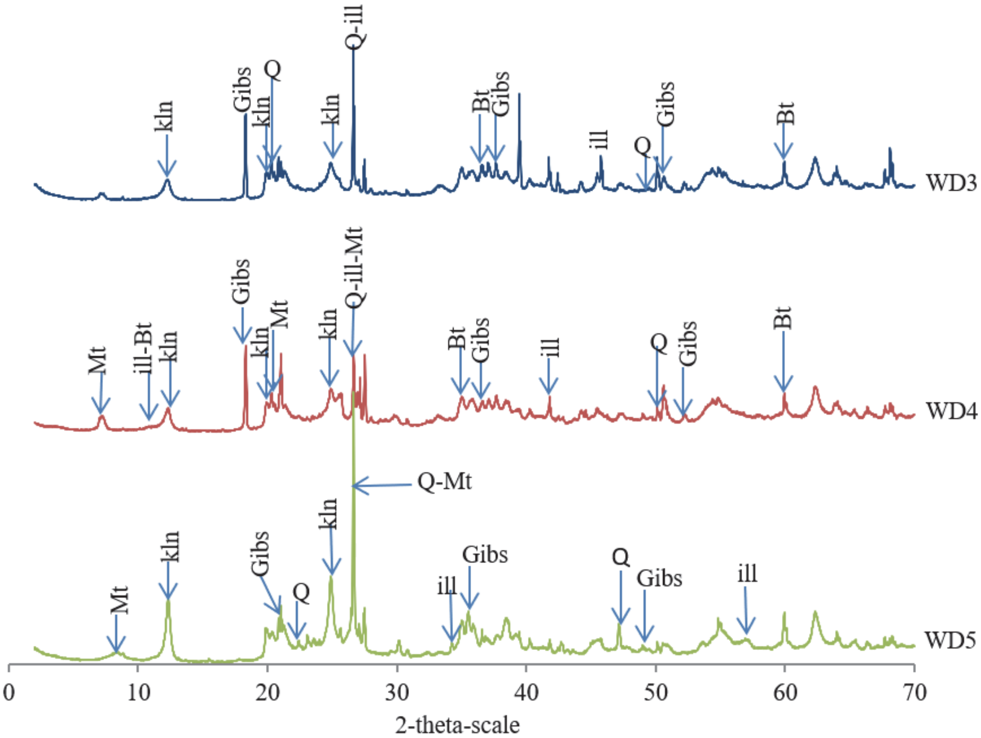

Figure 8. XRD patterns of mineral constituents of Ofen Tiben weathered materials

ill=illite. **Kln**=kaolinite. **Gibs**=gibbsite. **Q**=quartz. **Hem**=hematite. **Mt**=montmorillonite. **Bt**=biotite.

Finally, the X-ray diffraction mineralogical analysis on weathered materials of Ogwei Tiben (figure. 9) indicates that upper assemblage consists of phyllitic minerals (kaolinite, illite, montmorillonite, biotite and muscovite) and associated minerals (goethite and quartz). Meanwhile, the lower assemblage consists of phyllitic minerals (kaolinite, illite, biotite and montmorillonite) and associated minerals (quartz).

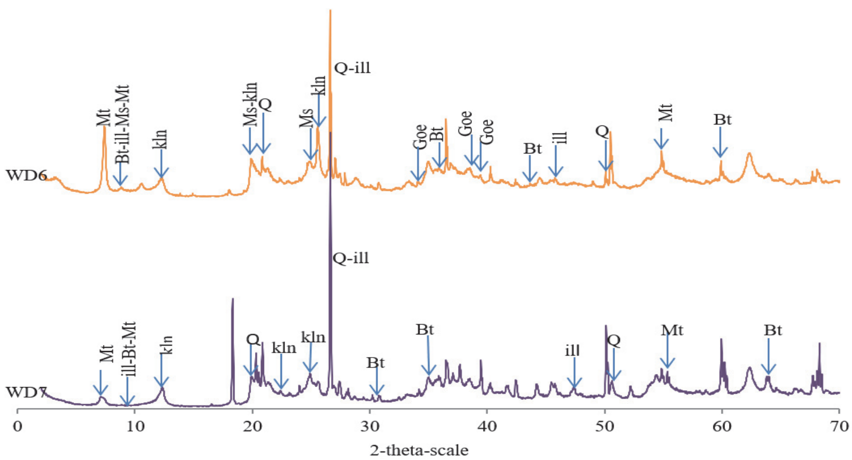

Figure 9. XRD patterns of mineral constituents of Ogwei Tiben weathered materials.

ill=illite. **Kln**=kaolinite. **Gibs**=gibbsite. **Q**=quartz. **Hem**=hematite. **Mt**=montmorillonite. **Bt**=biotite. **Goe**=goethite. **Ms**=muscovite.

The X-ray diffraction mineralogical analysis on weathered materials of Fifty One, Ofen Tiben and Ogwei Tiben are summarized in table 1 below.

Table 1. X-ray diffraction mineralogical composition

Localities		Mineralogical composition	
		Phyllitic minerals	Associated minerals
Fifty One	WD1	Gibs; Kln	Q; Hem; Goe
	WD2	Kln; ill; Bt; Ms	Q
Ofen Tiben	WD3	Gibs; Kln; ill; Bt	Q
	WD4	Gibs; Kln; ill; Mt; Bt	Q
	WD5	Gibs; Kln; ill; Mt	Q
Ogwei Tiben	WD6	Kln; ill; Mt; Ms; Bt	Q; Goe
	WD7	Kln; ill; Mt; Bt	Q

4.3 Geotechnical Characteristics

The geotechnical characteristics on weathered materials of Fifty One, Ofen Tiben and Ogwei Tiben are summarized in table 2 below. These geotechnical characteristics are essential for the slope stability analysis according to Closset &Wojtkowiak (1993).

Table 2. Geotechnical characteristics of Widikum soil and its surroundings

SP	w (%)	w_l	w_p	I_p	n (%)	e (%)	≤80μm (%)	γ (kN/m³)	γ_d (kN/m³)	γ_s (kN/m³)	Sr (%)	Cu (kN/m²)	φ (°)	H_{c1} (m)	H_{c2}
WD1	27.8	59.4	41.5	17.9	43.1	1.24	95	15.2	11.9	26.7	60	10	16.7	**2.3**	**2.3-**
WD2	28.3	64	38.7	25.3	33.8	0.94	61	17.8	13.9	26.9	81	34	16.25	6.8	**0.13q**
WD3	47.4	62.6	44.1	18.5	57	1.32	95	17.0	11.5	26.7	96	16	20.40	5.2	
WD4	46.7	60.6	44.2	16.4	58	1.37	97	16.5	11.3	26.7	90	15	5.68	29.6	
WD5	42.9	63.2	42.7	20.5	56	1.27	78	16.8	11.8	26.7	90	19	9.59	5.1	
WD6	30	71.9	42.5	29.3	33.2	0.95	66	17.7	13.6	26.5	84	30	19.67	6.4	
WD7	27	59.6	39.9	19.7	31.5	0.86	67	18.3	14.3	26.7	86	32	12.59	16.7	

SP = sample. **w=** water content. $\mathbf{w_l}$ = liquid limit. $\mathbf{w_p}$ = plasticity limit. $\mathbf{I_p}$ = plasticity index. **n** = porosity. **e** = void ratio.**γ** = unit weigth. $\boldsymbol{\gamma_d}$ = dry unit weigth. $\boldsymbol{\gamma_s}$ = absolute unit weigth. **Sr** = saturation ratio. **Cu** = internal cohesion. **φ** = friction angle and $\boldsymbol{H_c}$ the critical height.

As seen in this table, the average natural water content varies from 27 to 47.4 %. The liquid limit ranges between 59.4 and 71.9 %. Hence, the plasticity index falls within 17.9 and 29.3 %. The porosity varies between 31.5 to 58 %. The saturation ratio varies from 60 to 96 %. The grain size particles ≤ 80 μm lies between 66 and 97 %.The cohesion ranges between 10 to 34 kN/m². Concerning the friction angle, their values lie between 5.68 to 20.40°.

5. Interpretation and Discussion of Results

5.1 Contribution of the Mineralogical Study

The weathered materials of Widikum and its surroundings are mainly made up of illite and montmorillonite. Montmorillonite has the smallest crystals and largest surface which aid in increasing its adsorptive capacity (Bailey *et al*., 1999). Clayed minerals can cause swelling and consequently the change or variation of the mechanical characteristics of the materials (Pejon *et al.,* 1997).Therefore, the potential of clay swelling depends on the texture and structure of its constituents. Moreover, the presence of a weathered clay formation underneath the sliding horizon can constitute a slip surface whose mechanical characteristics further degenerates in the presence of water and constitutes a destabilization factor (Bureau de Recherches Géologiques et Minières [BRGM], 2009). These phenomena of swelling and shrinkage cause many hazards to civil engineering structures. The study of clay behavior is an important factor which can contribute towards improving the mastery and utilization of these clays and mitigate their undesirable effects on infrastructure founded on it. In the same way, rainfalls constitute the principal triggering factor. Hence, it results in infiltration causing firstly an increase in the water contents, resulting in a decrease of the mechanical resistance of certain clay soils and secondly a rise in the soil water table pitting the aquifers under pressure triggering the detachment of potential unstable soil masses (BRGM, 2009). Generally, when the proportion of the clay particles exceeds 30 %, the weathering materials are regarded as clay (Xiang, 1999). However, the Widikum and its surroundings grain size particles ≤ 80µm lies between 66 and 97 % greater than 35 % thus attesting their clayey character.

5.2 Contribution of the Geotechnical Study

The Widikum locality and its surroundings enjoys an equatorial "Guinean" climate type characterized by the abundance of rainfall (p= 2703.32 mm > 1500 mm/year) (Olivry, 1986). However, water plays a principal role in the slope stability due to their infiltration in weathered products (Philliponnat & Hubert (1997); Flageollet *et al*. 1999; Iverson, 2000; Meisina, 2006; Tofani *et al*. 2006). The natural water content of weathered materials vary between 27 and 47.4 % which are close to or even lower than the liquid limit included between 59.4 and 71.9 % which could justify their unstable character. In addition, an increase in the water content reduces the cohesion of clay materials (Avenard, 1962) and stimulates landslide (Neboit, 1991; Grandjean *et al*. 2006). The poor mechanical characteristics of weathered products are made up of soils susceptible to provoke sliding (Garczynski, 1984). Furthermore, the high plasticity index with values varying between 17.9 and 29.3 % indicates plastic materials and thus very sensitive to creep. The saturation ratio is very high. It comprises between 60 and 96 %. For the majority of samples, the saturation ratio is close to 70 % thus attesting their quasi saturated state. Finally, the weathered products are characterized by a low cohesion ranging between 10 and 34 kN/m^2 and a relatively low friction angle varying between 9.59 and 20.40°.

6. Conclusion and Recommendation

The main purpose of this study was to analyze the stability of Widikum and its surroundings cut slopes by means of the mineralogical and geotechnical studies and to propose suitable remediable solutions. The Fifty One and Ogwei Tiben sites needs some remedial work carried out which entails reducing the slope height and to support it with retaining structures built of basalt hardcores to reduce the effet of slope erosion and also provision should be made for subhorizontal drains to facilitate the drainage of water. The planting of trees especially eucalyptus as well as vertiva grass is recommended at all sites to facilitate the process of evapotranspiration which will render the soil more dried and the roots will also reinforce the soil and thus reduce the incidences of soil slip. Since the least critical height of the steps guarantees more safety and facilitates the execution of the maintenance work, the slope of Ofen Tiben must undergo a height reduction and it's reshaping in steps according to a height of 2.3 m on the basis of data of table 1 when the platforms do not carry a surcharge. Therefore, it is recommended to adopt a bench of 3 m and an inclination of β = 37.5°. However, if the platforms are intended to carry surcharge when executing slope works, the critical height must be calculated using the expression $H_{c2} = 2.3 - 0.13q$. Moreover, if more water still noticed, oozing out the slope surfaces, then it is necessary to carry out gabions works at the base of the slopes made of basalt or granite hardcore with a minimum thickness of 0.8 m.

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