

Research Article

The Influence of Climatic, Geological and Hydrodynamic Factors on Slope Stability at Kekem in the West Region of Cameroon

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Abstract

This study focuses on the influence of climatic, geological and hydrodynamic factors on slope stability of Kekem located in the Western Highlands of Cameroon. The methodological approach was based on the analysis of three factors: hydrological, geological and assessment of the hydrodynamic parameters influencing the stability of slopes. The hydrological factors indicate an average annual rainfall of 1,763.04 mm, generating 248.59 mm of runoff and around 402.61 mm of infiltrated water. Geologically, the soils have a high angle of friction at all three elevations, from 25.8 ° at the bottom of the slope to 27.2 ° at mid-slope and 26.2 ° at the top. On the other hand, the cohesion of these soils remains low, varying from 0.325 bar at the bottom of the slope to 0.265 bar at the top and 0.225 bar at mid-slope. Permeability analysis yielded values ranging from 1×10^{-9} to 1×10^{-11} m/s, with an overall porosity of around 55%. These conditions, combined with the morphology of the environment, are the main causes of slope instability in the Kekem district.

Keywords

Climatic, Geological, Hydrodynamic, Factors, Slope Stability, Kekem

1. Introduction

Landslide or slope failure is a major concern worldwide, and is one of the natural phenomena which involves the mass movement of rock mass, or earth down a slope triggered and reactivated by the presence of water and influenced by the soil properties, slope angle and gravity. These mass movements

affect natural slopes, and sometimes re-shapes the earth's relief. The occurrences of slope instabilities present a danger to people, the environment and infrastructure [6, 27]. In tropical environments, high annual rainfall associated with the presence of a marked orographic effects tends to trigger landslides. Since the

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1980s, the mountainous areas of Cameroon have been the focus of interest on landslides, and over the last decade, these mountain environments have recorded such events as landslides and floods [29]. These mass movements are common in humid tropical mountainous areas [30]. Every year, local and international media and humanitarian organizations report several landslides mainly as a result of heavy rainfall. Notable examples include the landslide of December 14, 2022 east of Kinshasa in the Democratic Republic of Congo, reported on the France 24 channel's 8 a.m. news the same day, the November 27, 2022 landslide around the Damas neighborhood in Yaoundé, the October 29, 2019 landslide of Gouatchi é in Bafoussam, the October 20, 2007 landslide in Kekem and the August 24, 2004 landslide in the Abangoh neighborhood in Bamenda, the Kolka event in the Russian Caucasus killed 125 people and the Brenva landslide killed two skiers, the Conchita landslide in California mobilized previous landslide deposits due to intense rainfall, causing 10 deaths and damaging around 30 houses. [1, 12, 14, 15, 23].

Slope instability in humid tropical zones is often linked to high rainfall, the lithological nature and certain hydrodynamic properties which denude the landscape, making it unstable. The increase in the soil's bulk unit weight and the reduction in its cohesion are the factors that favor the instability of the land [4]. Due to the presence of water and the degree of saturation of the surface layer, this will result to a progressive replacement of the air in the soil interstices, and this could have some geo-mechanical consequences. The maximum rainfall values of tropical regions or environments are higher than those from temperate regions [26]. It should be noted that deep soils require a large volume of rainfall to saturate them, resulting in excess hydraulic pressure compared with superficial soils.

Landslide or slope instability have a myriad of origins and can be very dangerous, wreaking havoc to both life and property [7].

In Cameroon, several regions are prone to this problem of

mass movements, notably the West Region. Some towns in West Region of Cameroon, such as Kekem, are prone to intense slope instability. So, even if it is sometimes difficult to detect these mass movements and predict their occurrence, it is possible to limit their consequences by taking preventive measures. In order to reduce and ensure the safety of the environment, it is necessary to carry out a study of the climatic, geological and hydrodynamic factors in areas likely to be affected by mass movements in the city of Kekem.

2. Materials and Methods

2.1. Study Area

Administratively, Kekem is a subdivision in the Haut-Nkam division of the West Region of Cameroon. Geographically, it lies between latitudes 5°06'10" and 5°14'56" North and longitudes 9°57'46" and 10°08'10" East. It stretches along national highway n°5 between Douala and Bafoussam through Bafang. Kekem lies in the transition zone between the Douala coastal plain and the Western Highlands of Cameroon [1]. The city of Kekem has a humid tropical mountain climate with two seasons: a long rainy season of nine months from March to November and a short dry season of three months from December to February [25]. It records a high annual rainfall of (1763.04 mm) and an average annual temperature of 22.05 °C, and is characterized as a high-rainfall zone. The study area belongs to the large coastal plain watershed, and more precisely the Nkam-Dibamba sub-basin, which flows into the Wouri River. The sub-dendritic hydrographic network (Figure 1) is dominated by three rivers (Ngoum, Mwanke and Petit-Nkam), all of which flow into the Nkam from north-east to south-west.

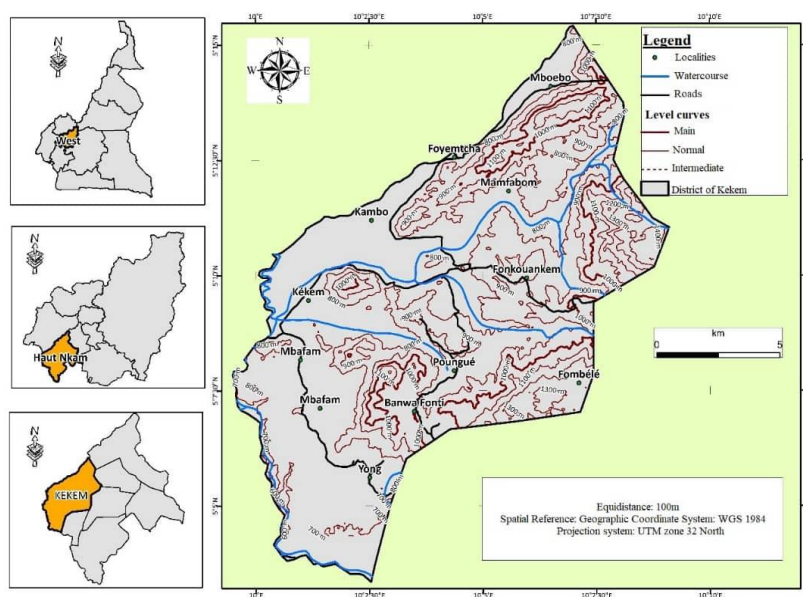


Figure 1. Study area location map.

Geological formations found at Kekem include porphyritic basalts and andesites, undifferentiated gneisses and amphibolites, alluvium, trachytes, anatectites and granitoids consisting of hypersthene granite [24]. The rocks found in the Kekem area is mix of granitic and gneiss materials and this has resulted to

what has been termed the granite-gneissic complex [18]. A distinction is made between oxidic, little evolved and hydro-morphic soils, all of which have undergone the effects of slope rejuvenation through volcanic eruptions and erosion.

Geomorphology of the study area

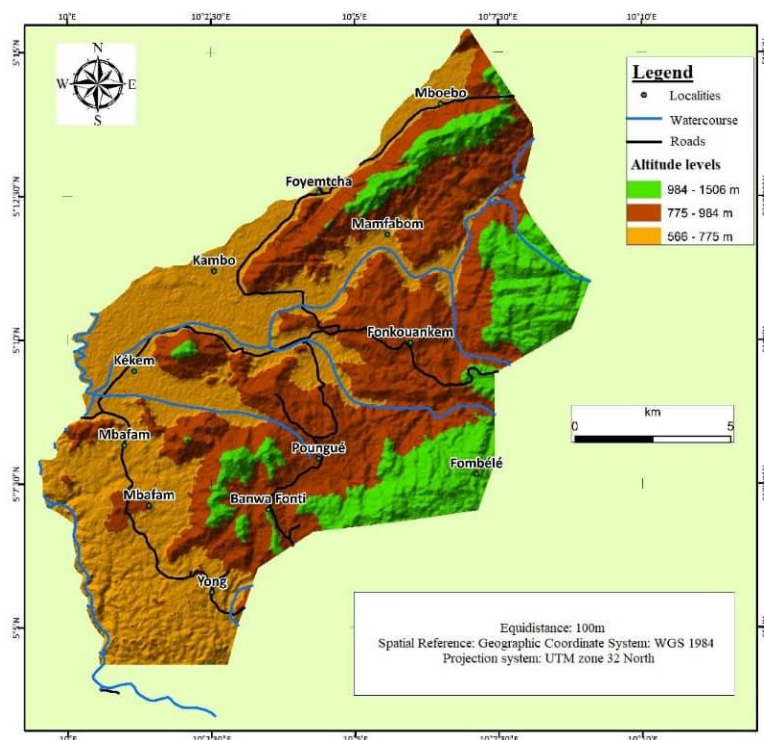


Figure 2. Digital Elevation Model of the study area.

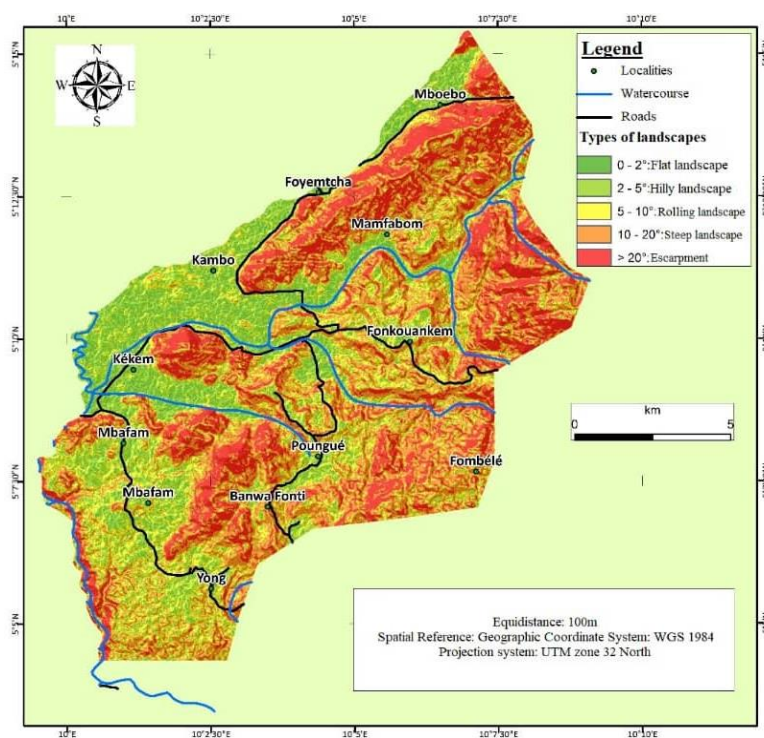


Figure 3. Slope map of the study area.

The morphology of the study area was assessed using the Digital Elevation Model (DEM) and the slope map. The digital elevation model (Figure 2) shows a landscape typical of the Western Highlands, with incised valleys and rounded peaks. The lowlands range in altitude from 566 to 775 m; the midlands range from 775 to 984 m and the upper areas are between 984 and 1506 m in altitude. The slope map of the study area (Figure 3) shows five slope classes corresponding to five morpho-landscape units: flat (0-2 °), hilly (2-5 °), rolling (5-10 °), steep (10-20 °) and very steep (>20 °).

2.2. Assessment of Conditions Conducive to Slope Instability

The fieldwork consisted of several field visits to collect data for the hydrodynamic and geological parameters, which were then analyzed in the laboratory. The analysis was structured in three stages:

The first stage consisted of an analysis of climatic conditions, based essentially on the establishment of a hydrological balance. Generally speaking, for a given period and a given basin, the hydrological balance can be established by the equations (1 and 2) as follows:

$$P + R = E + D + R + DR \quad (1)$$

$$P - E - D = DR \quad (2)$$

Where

P: Precipitation (rain, snow, etc.);

R: Resources from the previous period (groundwater, soil moisture, snow and glaciers);

E: Surface runoff;

D: Evaporation or Evapotranspiration;

DR: Resources available at the end of the period.

The total volume of precipitation over a given period of time between (1999-2020) was evaluated using the arithmetic mean method. This method considers the arithmetic mean of values recorded at several gauge stations over a fixed period of time as the regional average precipitation depth, as shown in equation (3):

$$P = \frac{1}{n} \sum_{i=1}^n P_i \quad (3)$$

With

n: Number of stations;

P_i: Precipitation recorded at station i

Potential evapotranspiration (PET) was estimated using the Thornwaite formula [17]. This was carried out using air temperature values as shown in equations (4, 5 and 6):

$$ETP = 1,6 \left(10^{\frac{t}{5}}\right)^a k \quad (4)$$

$$a = 0,016 I + 0,5 \quad (5)$$

$$I = \sum_{i=1}^{12} i \text{ and } i = \left(\frac{t}{5}\right)^{1,5} \quad (6)$$

ETP: Evapotranspiration in centimeters per month (cm/month);

t: Average monthly temperature in °C;

i: Monthly thermal index;

I: Annual thermal index;

K: Monthly adjustment coefficient.

Using Turc's method, the mean annual actual evapotranspiration of a basin was directly estimated from the annual rainfall (mm) and the mean annual temperature (°C) according to equations (7 and 8):

$$ETR = \frac{P}{\sqrt{0,9 + \frac{P^2}{L^2}}} \quad (7)$$

$$L = 200 + 25t + 0,05t^3 \quad (8)$$

ETR: Actual Evapotranspiration (mm/year);

P: Annual rainfall (mm);

t: Annual temperature (°C).

Runoff (R) was estimated using the Coutagne formula, which uses the rainfall values and catchment area as shown in equation (9):

$$R = (0,164 - 0,00145\sqrt{S}) \times P \quad (9)$$

With

R: runoff in mm;

S: catchment area in km²;

P: annual precipitation in mm

The infiltration was evaluated using the water balance equation of method (2). So, the water balance method is one of the most widely used method for determining infiltrated water as given by (10) [17].

$$I = P - ETR - R - \Delta S \quad (10)$$

With

I: water infiltration (mm);

P: precipitation (mm);

ETR: Actual evapotranspiration (mm);

R: runoff (mm);

S: variation in water stock.

The second step was to carry out four hand-dug pits on the ground slopes with very steep gradients (> 20 °), which are fragile and exposed to the environment. This was carried out using the following tools: a machete, trowel, pick-axe, shovel and auger. The soil material was then macroscopically identified using Maignien's 1980 method for describing soils in the field. The texture was also assessed by rubbing a fresh soil sample between the fingers, and the colors were described using the Munsell code (Munsell Soil-Color Charts 2010). Two types of soil samples (disturbed and undisturbed) were

taken over the entire height of the soil profile according to the different horizons (A, B and BC). So, around 500 g of disturbed samples were taken from each of the soil horizons of each soil profile, after which these were packaged in plastic bags, coded and transported to the laboratory. Upon arrival at the laboratory, the porosity of the soil was determined. The undisturbed soil samples were obtained using metal cylinders of dimensions 3 cm in diameter and of height 5 cm. Both ends of the cylinders were taped with cellophane thereafter waxed, coded and transported to the laboratory for the determination of the, (bulk density and Darcy soil permeability).

The third step was to determine the geological conditions, through field observations and carrying out the shear box analysis (NF P94-071-1). A second set of cores of the undisturbed samples were obtained using PVC (Polyvinylchloride) pipes of dimensions 10 cm in diameter and of height 30 cm. These were taped on both ends, waxed and coded to prevent evaporation of the water contained in the material so as to preserve their condition during transportation to the laboratory. Three soil cores were then taken from the mineral horizon (B) at three different elevations (top of slope, mid-slope and bottom of slope), and were used to determine the shear strength parameters using rectilinear shear box test in the laboratory.

3. Results and Discussion

The results of the analysis of the soil samples obtained from the study area enabled the obtention of the impact of hydrological, geological and hydrodynamic factors on slope instability in the Kekem district.

3.1. Hydrological Conditions of Kekem District

The water balance results obtained in the Kekem district over the period 1999 to 2020 are shown in Table 1.

Table 1. Water balance for Kekem district (1999-2020).

P (mm)	ETP (mm)	ETR (mm)	R (mm)	I (mm)
1763,04	1297,19	1111,84	248,59	402,61

Source: Annual rainfall and temperature report from 1999 to 2020 from the Delegation of Agriculture and Rural Development of Kekem.

The results of the analysis of the actual evapotranspiration (ETR) for the Kekem district was obtained using the Turc method and the estimates of the recharge or infiltration was obtained using the water balance equation approach. It was shown that for an average annual rainfall of 1,763 mm, the amount of water likely to infiltrate was 402 mm, or 23% of the precipitated water. Similar studies carried out in Côte d'Ivoire

at N'zi-Comoé also used the water balance approach [17]. The results of this work showed that for an average of 1155 mm of rainfall per year, the quantity of water likely to infiltrate to recharge aquifers was 105 mm, or 9.15% of the precipitation. The same is true of the rainfall threshold likely to trigger ground movements which varies according to estimates: from 100 mm/24 h to 230 mm, or even 260 mm, compared with what had been established in the Darjeeling area (250 mm/24 h) [9]. The soils in the Kekem district therefore receive water directly from precipitation and are able to accumulate some amount of infiltrated water. This amount of infiltrated water is insignificant to cause mass movement, but over time this accumulation contributes to slope instability. Thus, the effect of precipitation on slope failure mechanisms is essentially governed by the amount of rainwater infiltration into the slope [11]. However, in all the cases so far studied, tropical rainfall plays a predominant role in triggering slope instabilities [13]. The amount of infiltrated water obtained represents 22.84% of annual rainfall in the Kekem district. More often, the volume of infiltrated water into a massif has the effect of increasing the unit weight of the soil, and plays a role in triggering or accelerating a landslide [16]. This value is not very significant, but is one of the factors contributing to the various slope failures that have already occurred at Kekem.

In addition, the water balance method enabled the obtention of a value for the annual water runoff in the Kekem district. This runoff was approximately 248 mm, or 14.10% of the precipitated water. It is evident that runoff perfectly modifies water dynamics on the surface horizons and reduces infiltration [20]. Water falling on saturated surfaces cannot infiltrate, so it becomes surface runoff [3]. This value is not significant enough to directly cause a slope failure. However, this repetitive runoff has gradually evolved over time to create erosions, especially on slopes and embankments. Subsequently, these erosions were at the origin of various modes of slope destruction such as gullies and shear planes, which certainly caused these slope failures in the Kekem district.

3.2. Geological Conditions of Kekem District

The most fragile slopes are mostly developed on fissured formations of gneiss, trachytes and granites. These fissured rocks must have undergone mechanical or, more often, natural degradation. In this case, the most obvious sign of basement fracturing was the presence of discontinuities found in the Kekem district. So, the discontinuities may be natural and reflect on the geological and structural history of the area, or that created by human activities such as excavations of the rock mass [22]. This can also be seen in the dykes, faults and shear zones, which are usually large fractures. Although each fracture has a finite extent and is usually small relative to the mass of the rock, however the interconnection between fractures and sliding surfaces can be formed in the rock mass [2]. These fissures will allow water to infiltrate the rock to a considerable depth, gradually

weakening its stability. Indeed, rock slope instabilities are manifestations of the gravitational displacement of destabilized land masses under the effect of natural or anthropogenic stresses [5]. Thus, the fractured networks have a strong

influence on rock slope stability [31].

It should also be noted that rock weathering is undoubtedly one of the main factors that can have an impact on slope stability.

Table 2. Parameters of the shear test on soils at three altitudes in the Kekem district.

Soil sample	Bottom of slope (566 to 775 m)	Mid-slope (775 to 984 m)	Top of slope (984 to 1506 m)
Internal angle of friction ϕ (°)	25,8	27,2	26,2
Cohesion c (bar)	0,325	0,225	0,265
Factor of safety (FS)	0,632	0,809	0,846

The results of the shear tests carried on the soil samples are presented in Table 2. According to Table 2, the shear stress shows that the high values of the angle of internal friction of the soils obtained in the three altitudinal levels of the Kekem district vary from 25.8° for the bottom of the slope to 27.2° for the mid-slope and 26.2° for the top of the slope. These high values of internal friction angle are relatively close to each other. On the other hand, the cohesion values of these soils are low, ranging from 0.325 bar at the bottom of the slope to 0.265 bar at the top and 0.225 bar at the mid-slope. These findings become more interesting since similar results on ground instability in the Kekem were obtained, where the cohesion values obtained are low (< 0.5 bar) and the angle of friction varying between (15°–22°) [1]. It should be noted that, while the angle of internal friction is higher at mid-slope, soil cohesion is lower at mid-slope. According to the general rule of thumb for the natural angle of a slope, these values are between 25 and 45°, giving them the characteristics of loose soils, and consequently they are all non-cohesive. These loose soils, with very low cohesion values, are inherently unstable. From the results of the low shear values obtained, it is indicative that these soils are unstable and susceptible to landslides at all altitudes. Other studies affirmed that the mechanism of shear failure in fine soils depends not only on the intensity of the forces exerted and the manner in which they are applied to them, but also on the drainage conditions of the pore water [10]. Slope instability (on steep slopes such as the one studied at Kekem can also occur when the soil cover is shallow. Furthermore, the safety factors for all three elevation levels is less than 1, reflecting the instability of these slopes, which are sensitive or vulnerable to slope movements, depending on the equilibrium of the slopes in relation to the theoretical values of the safety factors [8].

3.3. Hydrodynamic Soil Conditions of Kekem District

3.3.1. Profile Characteristics

Characteristic profile of P1

1. Organo-mineral horizon (HA): 0 to 50 cm, grey (5YR5/1), sandy-clay, medium to fine polyhedral structure, not very compact, presence of ant holes, with abundant rootlets and roots, and its boundary with the lower mineral level is undulating and progressive.
2. Mineral horizon (HB): from 50 to 288 cm and more, yellowish-red (5YR4/6), sandy-clayey, medium polyhedral structure, compact, presence of rootlets, ant and termite holes. A boulder is also present in this horizon.

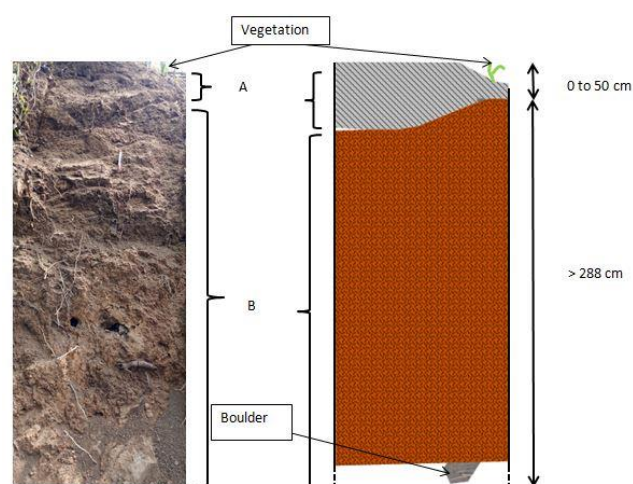


Figure 4. Characteristic profile of ferrallitic soils (P1).

Characteristic profile of P2

1. Organo-mineral horizon (HA): 0 to 60 cm, dark gray (5R3/1), sandy-clay, fine polyhedral structure, very little compaction, presence of ants, rootlets and moderately abundant roots, medium interstitial porosity, its boundary with the lower mineral layer is clear and regular.
2. Mineral horizon (HB): 60 to 135 cm, dark red (5R5/2), sandy-clay, medium to fine polyhedral structure, not very compact, presence of ant holes, rootlets and a few roots, low interstitial porosity, its boundary with the

lower mineral layer is undulating and progressive.

3. Transition horizon (BC): from 135 to 280 cm and more, reddish in color (5R5/4), sandy-clayey, medium polyhedral structure and compact.

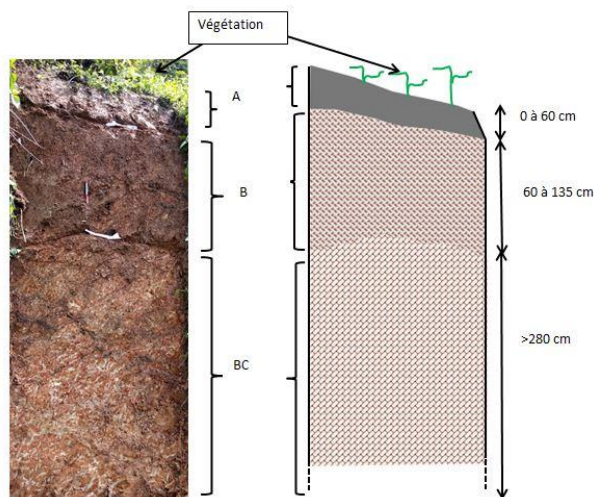


Figure 5. Characteristic profile of ferrallitic soils (P2).

Characteristic profile of P3

1. Organo-mineral horizon (HA): 0 to 30 cm, light gray-brown color (10YR6/2), clay-sandy, with medium to fine polyhedral structure, which are loose and having the presence of ant holes, rootlets and abundant roots, with a clear and regular boundary with the lower mineral layer.
2. Mineral horizon (HB): from 30 to 103 cm, brownish yellow color (10R6/8), sandy-clayey, with medium to fine polyhedral structure, which are loose and having the presence of very few rootlets and ant holes, with medium interstitial porosity and its boundary with the lower mineral layer is undulating and progressive.
3. Transitional horizon (HBC): from 103 to 200 cm and more, yellow in color (10YR7/6), sandy-clayey, with a

medium to fine polyhedral compact structure.

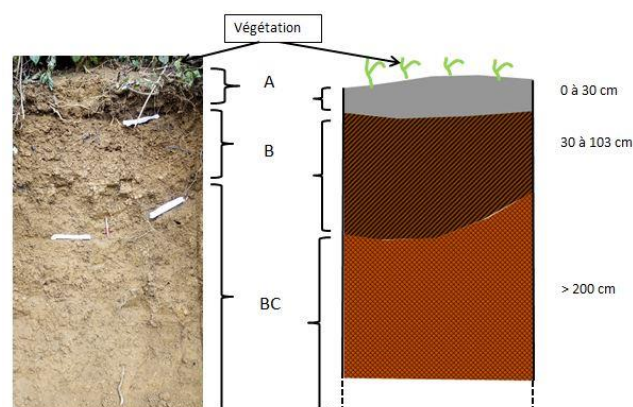


Figure 6. Characteristic profile of ferrallitic soils (P3).

An observation of profile P1 was made which only presents two horizons (A and BC). Meanwhile, observations of the two other profiles (P2 and P3) present three horizons (A, B and BC). Profile P2 shows white areas and spots at the level of horizon BC, but on the other hand the two other profiles do not present these white spots and areas. The texture of the different horizons A, B and BC of these three profiles (P1, P2 and P3) are all identical (sandy-clay). The same is true for their structure (polyhedral). The BC horizon appears on all these three profiles and the thickness of the different A horizons does not attain 100 cm. Biological activity is more developed on the surface horizons than at depths in all these profiles.

3.3.2. Hydrodynamic Parameters of Soils

The permeability and porosity data obtained after laboratory analysis are shown in Table 3. These parameters are grouped according to their values with regards to their horizon and profile as shown in Table 3.

Table 3. Permeability (*k*) and Porosity (*n*) of soils.

Profile	Horizon	Height (cm)	Permeability <i>k</i> (m/s)	Porosity <i>n</i> (%)
P1	A	50	3.10^{-9}	49,96
	BC	238	4.10^{-9}	50,00
P2	A	60	$3,9.10^{-10}$	51,8
	B	75	$3,6.10^{-11}$	56,17
	BC	145	$2,7.10^{-11}$	49,02
P3	A	30	2.10^{-11}	62,83
	B	73	7.10^{-11}	61,13
	BC	97	4.10^{-10}	52,94

From Table 3, it can be seen that the soil porosities obtained are high both in the surface horizons and at depths within the horizons. As such, the porosities vary from 49.96% in the surface horizons to 62.83% within the deeper horizons. Substantially similar results to this work were obtained, where the overall porosity varied between 39 and 50% [32]. Consequently, when the primary porosity of the basement is low, the flow of fluids occurs mainly in the fractures [19]. The soils described in the Kekem district have overall very low permeability values in the horizons. This remark is made at the level of the evolution of permeabilities according to the HA, HB and HBC horizons (Table 3). Furthermore, the surface horizons-A, which contain fine soil particles together with some appreciable amount of organic matter content facilitate the infiltration of water. In addition, this very low permeability of the horizons is explained by their clayey-sandy textures which are expansive in nature and results in a shrinking characteristic in the dry season and swelling in the rainy season. To this, the plant cover must be added, which for these soils it is almost bare, favoring erosion which rather degrades the soil and thus makes it dense. This is similar to the case where the water retention is greater in the upper parts of the profiles and considerably lower in the lower layers [28]. Also, a similar conclusion can be drawn where the surficial samples have a better permeability than deep ones in accordance with their texture [21]. Indeed, an increase in the apparent density leads to a decrease in permeability, a situation which affects the circulation and infiltration of water. These values vary overall from 3×10^{-9} to 2×10^{-11} m/s. Considering their permeability coefficients these soils belong to the class of impermeable soils and behave similar to peats or organic soils given their very low permeability values [33]. These low permeabilities shows that rainwater will tend to accumulate on the surface or runoff on a sloping surface. It is noted that these impermeable soils, located at the levels of very steep slopes ($> 20^\circ$) could be cause of the majority of the instabilities of the slopes identified in the study area. The more impermeable a soil is, the more it is sensitive to landslides and especially as the soil material is made up of fine particles as it with the case of soils in the Kekem area.

4. Conclusion

The humid tropical mountainous areas are liable to experience several incidences of landslides or slope instability due to their climates, their geological nature but more especially the hydrodynamic properties of the soil.

The hydrological analysis shows that the Kekem district is a tropical climate environment and with an appreciable amount of rainfall during the rainy season. The runoff water is very small compared to the amount of infiltrated water and it is approximately a quarter of the precipitated water. The results of the shear testing reveal that the soils of this studied site have a high friction angle as obtained from each of the

three altitudinal levels, i.e. the bottom of the slope the mid-slope and the top of the slope. On the other hand, the cohesion in these soils are low and varies from the bottom of the slope, to the mid slope and finally to the top of the slope. Finally, the evaluation of the hydrodynamic parameters showed that the Kekem soils are impermeable and from a geotechnical point of view they are qualified as unstable soils. Furthermore, the porosity showed that these soils have overall a high porosity at all horizons. Thus, these studied conditions associated with the topography significantly influence the instabilities of the slopes in the Kekem district. This is explained by the fact that the origin of the triggering of a mass movement is rarely unique, but rather the consequence of an association of passive and active factors.

Author Contributions

Leroy Ngadji Fotso: Conceptualization, Data curation, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing

Valentine Yato Katta: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing

Roger Njila Ntankouo: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Temgoua Emile: Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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