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ORIGINAL ARTICLE

Contribution of geoelectrical soundings and pedological wells to the estimation of the tonnage of lateritic gravels of the northern flank of Mount Bangou: implications for road construction

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Abstract

The increasing demands on lateritic gravels in road construction presently make it necessary to quantify the available resources that can be used in road construction. This study aims to estimate the tonnage and to valorize the lateritic gravels of the north flank of Mount Bangou (west Cameroon) in road construction. Interpretation of 48 vertical electrical soundings coupled with 20 pedological wells from five lateritic gravel sites was carried out to determine the thickness of the lateritic gravel level. The thickness of the lateritic gravel level obtained from the geoelectrical soundings is the greatest (8.88–12.45 m) compared to that obtained from the pedological wells (1.23–1.98 m), and thus shows the inadequacy of the pedological wells for the determination of the thickness of the lateritic gravels. Thus, the electrical resistivity method is appropriate to estimate the thickness of the lateritic gravel level. The lateritic gravels studied are characterized by the electrical resistivity curves of type K, HK, Q, QH, KQ, HKH, H, and KH. The medium-thick (8–36 m) and thick (13–44 m) zones are areas of high potential lateritic gravels. The proven reserves of lateritic gravels at the Chenye, Sekakouo, Bamendjou 1, Bamendjou 2, and Bangam sites are, respectively, 3,479,003 t, 1,389,522 t, 5,002,505 t, 839,455 t, and 2,663,105 t and can build, respectively, 53,298 m; 226,167 m; 131,574 m; 778,314 m and 401,068 m of road, either as a subgrade layer or sub-base layer.

Keywords Mount Bangou · Lateritic gravels · Estimation · Proven reserves of lateritic gravels · Geophysical soundings · Pedological wells

Introduction

The mode of communication, the importance of roadways in general, and in particular addressing road infrastructure challenges are important and unavoidable factors for the economic, cultural, and social development of a country or a continent (Combere 2008; Onana et al. 2015). In countries where a particular emphasis is placed on the development of a variety of infrastructure, a considerable increase in the use of the soil resource is increasingly observable. The majority of roads in the tropics are in concretionary lateritic soils (Maignien 1966). Because of the abundance of lateritic gravels in tropical countries, their low exploitation costs, and their ease of exploitation relative to certain crystalline formations (CEBTP 1984; Sikali and Mir-emirati 1986; Meïssa 1993; Bagarre 1990), they are of obvious interest in road construction. They constitute almost 100% of the sub-base layers and 60–70% of the base layers of roadways in the intertropical zone, more specifically in developing countries (Tockol 1993).

Furthermore, designing roads that avoid, reduce and, as a last resort, compensate for environmental impacts and integrate the constraints and challenges of the operator are part of the sustainable development strategy. Natural aggregates, the second raw material consumed, are made from rock, which is a non-renewable source (Bizriche et al. 2012). The manufacturing process of these aggregates is dependent on fossil fuels. Thus, aware of the dependence of fossil fuels on the industrial manufacturing process of aggregates widely used in road construction around the world, the use of soil materials in road embankments is a very interesting alternative in an environment perpetually plagued by climate change.

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Laterites show great typological diversity in the intertropical zone in general and in Cameroon in particular. Thus, lateritic gravels, lateritic cuirass, lateritic carapaces, and lateritic fines are encountered in Cameroon (Sikali and Mir-emérati 1986; Mbumbia et al. 2000; Hyoumbi Tchumgouelieu et al. 2018) and cover about 70% of the area of Cameroon (Sikali and Mir-emérati 1986). Previous work has been conducted by Manefouet (2016) on the weathering and geotechnical characterization of lateritic clays and gravels of the lower zone of the southern slope of the Bambouto mountains, by Sikali and Mir-emarati (1986); Ekodeck 1984; Nzabakurikiza et al. (2012); Onana et al. (2015); Takala and Mbessa (2018); Hyoumbi Tchungouelieu et al. (2017), and Ngo'o Ze et al. (2019) on their use in road construction. Thus, depending on their geotechnical properties closely related to their origin (parent rocks), altitude, vegetation, and climate, they are used either as a base layer, sub-base layer, or as a subgrade layer (Sikali and Mir-emérati 1986). Nevertheless, the systematic use of laterites as construction materials is beginning to make them a scarce resource in some parts of Africa (Bohi 2008). This "scarce resource" status has resulted in the necessity of quantifying the available and usable resources in civil engineering construction (Bohi 2008), given the necessity for developing countries to build an accurate database of their soil resources. Similarly, serene and equitable exploitation of lateritic gravels requires knowledge of the resource and its quantity. In addition to the geotechnical characteristics and the cost of exploitation of lateritic gravels, the knowledge of their tonnage is crucial for their exploitation.

The most commonly used method of estimating geo-material tonnage is that which takes into account the surface area, specific gravity, and thickness of the geo-material. However, the spatial heterogeneity and great thickness of lateritic soils, as well as the presence of indurated levels (Tardy 1997) do not facilitate the realization of pedological wells until the wall of the lower gravelly level is encountered. In addition, the exploration of geo-resources faces major environmental challenges. Deep geological exploration activities generate various levels of environmental and biodiversity impacts, including the local destruction of associated ecosystems and the perturbation of the environment and biological diversity. Furthermore, drilling or excavation may create potential conduits or communication to groundwater resources that should be protected. In such a context, geoelectrical soundings, non-intrusive and capable of simultaneously investigating a large volume of soil (Rey 2005) coupled with pedological wells constitute an interesting alternative. Their rapid implementation and relatively low cost for soundings can allow a more reliable determination of the thickness of the soil layers, and eventually a more reliable estimation of the tonnage of lateritic gravels. This study aims to determine the tonnage of lateritic gravels on the northern flank of Mount Bangou and their use in road construction using an approach based on geophysical surveys coupled with soil wells.

Geographic and geological setting

The northern flank of Mount Bangou is located in the west Cameroon region, straddling the Kong-Khi and High Plateaus departments. It is positioned in the localities of Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam. Mount Bangou, was built up during the Eocene and is the oldest dated volcano in the Cameroon Volcanic Line (CVL) (Fosso et al. 2005). It is located between 5°28′1.23"N and 5°15′51.83"N latitude and between 10°31′33.6" and 10°14′14.25"E longitude and belongs to the west Cameroon highlands. It covers an area of 354 km^2 (Fig. 1). Altitudes in the area vary from 990 m to 2045 m with an average of 1,518 m. The climate is humid tropical, tempered by altitude (Nono et al. 2009) and sub-equatorial (Olivry 1986) with an average annual rainfall of 1741 mm and 1674 mm, the temperature gradient varying from 20.3 to 23.0 °C (Sighomnou 2004; Nono et al. 2009) and from 20.0 to 23.5 °C for the sites in the Kong-khi and High Plateaus departments, respectively.

The study area is marked by volcanic, plutonic, and metamorphic rocks. The volcanic rocks include aphyric basalts, tuffs, sub-aphyric basalts, porphyritic basalts, rhyolites, quartz-trachyte and rhyolites, rhyolite-aegirine plus or minus arfvedsonite and plutonic rocks as porphyroid granite and syntectonic granite, granite with amphibole and/or biotite, granite with aegirine plus or minus eckermannite-arfvedsonite, undifferentiated granito-gneiss, syenodiorite and quartz-syenodiorite. The metamorphic rocks consist of orthogneiss with mega feldspar, medium-grained orthogneiss, and undifferentiated metamorphic gneiss (Fosso et al. 2005; Kuepou et al. 2006; Nono et al. 2009; Kwékam et al. 2010) (Fig. 1). Extensive weathering of the rocks in this region has resulted in huge lateritic soil volumes. The highlands of western Cameroon are occupied by red and brown ferralitic (lateritic) soils, hydromorphic soils, and soils that are not well developed (Segalen 1967). The lateritic gravels of the northern flank of Mount Bangou are developed on aphyric basalts (Fig. 1).

Materials and methods

Field data acquisition

The field investigation consisted of prospecting the gravelly formations in the study area and selecting representative sites and these sampling site data are shown in Fig. 2.

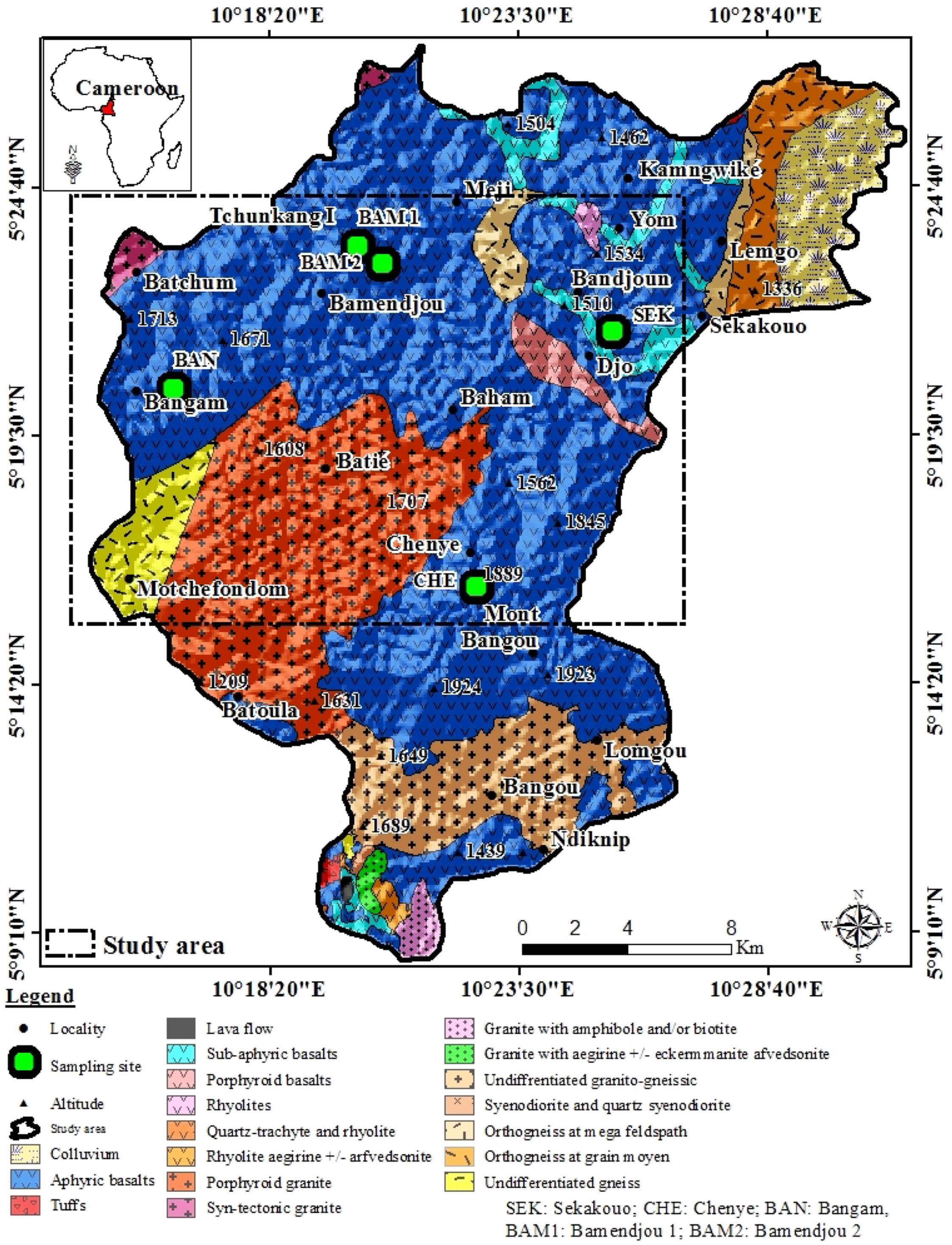


Fig. 1 Geological map of the study area; modified from Fosso et al. (2005); Kuepou et al. (2006); Nono et al. (2009); Kwekam et al. (2010)

The sites of Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam were selected for this work. Altitude levels guided the selection of representative sites, as many studies have shown the influence of altitude levels on soil distribution in the landscape (Leumbe et al. 2005, Tematio 2005, Hyoumbi Tchumgouelieu et al. 2017, Hyoumbi Tchumgouelieu et al. 2018). The fieldwork also consisted of the implementation of pedological wells and the collection of samples for physical–mechanical analyses. The pedological wells were implanted about the topo-sequential method.

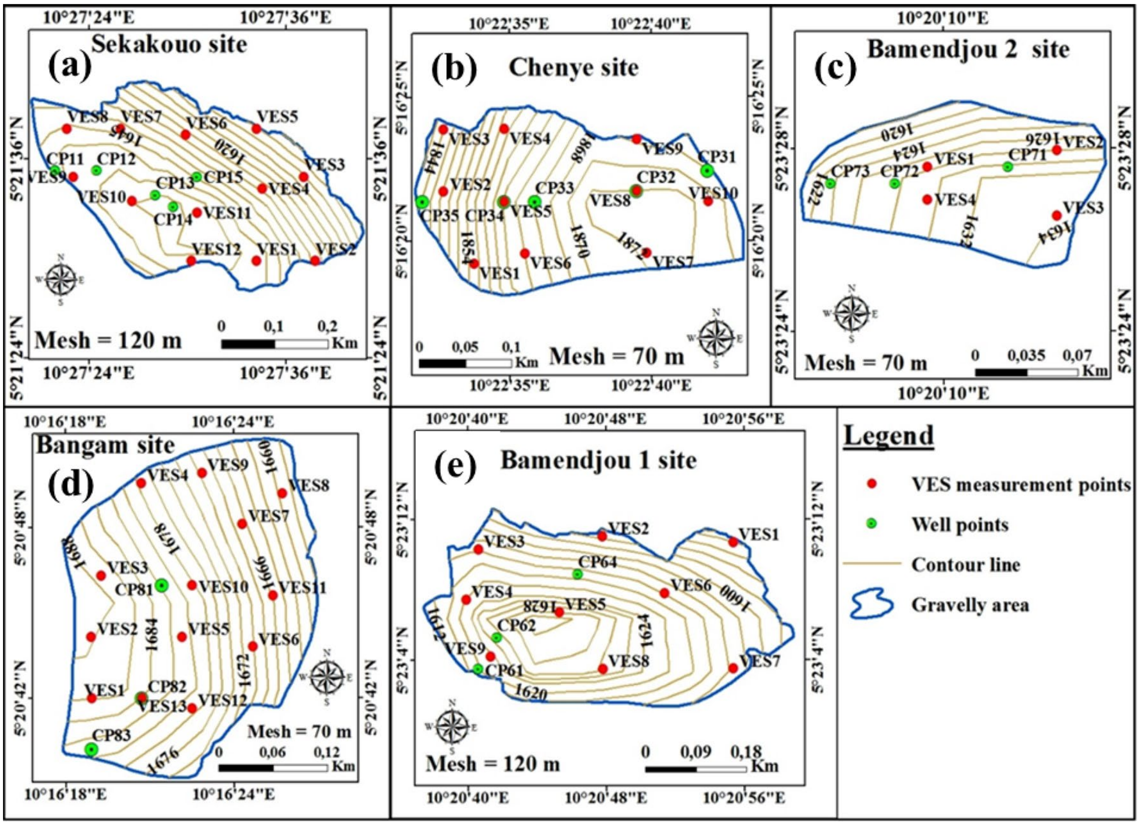


Fig. 2 Sampling map of the studied sites, **a** Sekakouo, **b** Chenye, **c** Bamendjou 1, **d** Bamendjou 2, **e** Bangan

They were located at the top, on the slope, and at the foot of the gravelly zone of each site. Twenty pedological wells were constructed on all five sites studied. Soil profiles were described through the soil pits concerning the Maignien (1980) method of morpho-structural soil description in the field. The Munsell code was used to determine the color of the soil volumes in the soil profiles. The perimeter coordinates of the gravelly zone at each gravel site were surveyed in the field using a Garmin 30 × Global Positioning System (GPS) terminal with the surface tracing option of this GPS.

Geo-electrical data and interpretation

Geo-electrical data were acquired at the separate lateritic gravel sites (Fig. 2). The vertical electrical soundings of the Schlumberger type were carried out with the Lippmann 4-point light 10 W resistivity meter at the node of each previously established mesh (or sampling distribution). The mesh was established beforehand on each gravel site following a very specific spacing to cover the entire site studied (Fig. 2). Forty-eight vertical electrical soundings (VES) were carried out on all five sites.

The electrical device used in the geophysical investigation was that of Schlumberger. The center of the device, called the tracing point or station, remains fixed, and the current injection electrodes (A and B) are progressively moved away from the center of the device (station). The electrodes M and N remain fixed for a series of measurements corresponding to a certain number of separations of A and B and then are moved apart generally taking into account the relationship 4 < AB / MN < 20 (Fig. 3).

Since the current is known, the potential can be measured and the apparent resistivity can be calculated using Eq. (1).

$$\rho a = \frac{\pi \Delta V}{I}\left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MM}{2}\right)^2}{MN}\right] \quad (1)$$

where ρa: apparent resistivity; AB: current electrode spacing in meters; ΔV: potential difference in volts, MN: potential electrode spacing in meters; I: current intensity in Ampere; π = 22/7.

In these analyses, the maximum extent of AB/2 was 100 m. The electrical method aims to determine the physico-electrical properties of the soil or subsoil (conductivity, resistivity and resistance) through the electrical

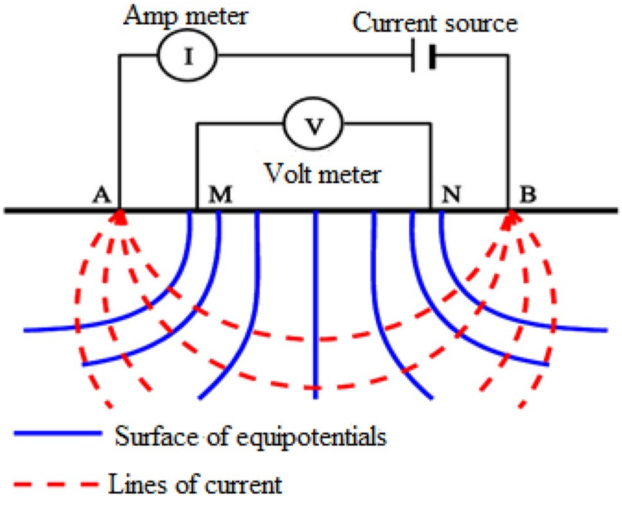


Fig. 3 Schlumberger device (Fauchard and Mériaux, 2004)

soundings, which led to the evaluation of the layout of the ground layers and the determination of the thickness of the ground layers.

The electrical resistivity curves were interpreted automatically using geoelectrical joint inversion software (jointem). The preliminary interpretation of the VES curves was carried out based on the studies of Telford et al. (1990), Koussoubé et al. (2003), Singh and Stephen (2004), and Gouet et al. (2020). These inversions were used to average the apparent resistivities of each geoelectrical sounding point to determine the average thickness of the gravelly levels.

Tonnage estimation

The tonnage of each lateritic gravel site was evaluated by taking into account the average thickness of the lateritic gravel level, the total surface area of the gravelly zone, and the specific weight of the lateritic gravel at each site studied. Twenty sampling wells were drilled at varying depths, depending on the thickness of the lateritic gravel level (B-horizon). The total area of the gravelly zone at each site was determined using global mapper software, after surveying the GPS coordinates of their perimeters in the field. The 1D inversions of the VES were used to establish the geoelectrical sections and to determine the thicknesses of the lateritic gravel level at the study sites. Thickness values from the 1D inversions were corroborated with thicknesses from the soil wells. The product of the volume and specific gravity yields the tonnage of the material investigated (Kouakou et al. 2017). The specific gravity was determined in accordance with the NF P94-054 standard. Thus, knowing the total surface of each gravelly zone, the average thickness of the lateritic gravel level, and the gravel unit-specific gravity, the tonnage of lateritic gravels of each site was determined through Eq. 2.

$$T = A \times E \times \gamma s \tag{2}$$

where T is tonnage in t; A is the total area in m^2; E is the thickness of gravelly level in m, γs is specific gravity in t/m^3.

Quantification in pavement layers

The choice of the type of pavement structure (e.g., flexible pavements; semi-rigid pavements; rigid pavements) is guided by the technical aspect included in the technical specifications, the economic aspect (cost of the project), and the availability of usable material deposits. Moreover, the knowledge of the tonnage of lateritic gravels usable is decisive to their exploitability. It also allows better planning of the backfilling or reprofiling of roads. The thickness of the subgrade layer, the sub-base layer, and the base layer is generally about 30 cm (CEBTP, 1984). The structure of pavement is more or less similar to a three-dimensional geometric shape. In rural areas, the average width of the roadway ways is 2 × 3.50 m, and the shoulders are generally 2 × 2 m according to CEBTP (1984). Thus, the total width of a pavement layer is equivalent to 11.5 m. According to Sikali and Mir-emirati (1986), one m^2 of raw material corresponds to about 0.75 m^3 compacted in a given pavement. The volume of lateritic gravel for 1 km of pavement was calculated with reference to Eq. (3).

$$\mathrm{V\ (1\ km) = L \times l \times h} \tag{3}$$

$$Q = \frac{1000m \times A \times E}{0.75(\mathrm{L \times l \times h})} \tag{4}$$

where L × l × h = volume of a pavement layer, L is the length, l is the width, and h is the height of the pavement layer concerned, A is the total area in m^2; E is the thickness of the gravelly level in m, γs is the specific weight in t/m^3, Q in Eq. 4 yields the total number of meters of road that can be constructed with mined lateritic materials.

Results

Thickness of the gravelly lateritic level from the pedological wells

Twenty manual pedological wells were dug at all five study sites. Table 1 summarizes the thickness values of the lateritic gravel level obtained from the pedological wells of the studied sites. Figure 4 shows the typical profiles observed on the different lateritic gravel sites studied.

Table 1 Thicknesses of the lateritic gravel level were obtained from the pedological wells of the studied sites

Sites	Code	Position	Roof-wall (cm)	E (m)	Max	Min	Mean	Sd	Altitude (m)	Area (m^2)
SEK	CP11	B	0–73	0.73	2.4	0.73	1.23	0.69	1661	143,509
	CP12	V	0–122	1.22					1668	
	CP13	V	16–120	1.04					1679	
	CP14	S	10–250	2.40					1685	
	CP15	V	19–94	0.75					1665	
CHE	CP31	B	13–63	0.50	2.95	0.5	1.45	0.97	1865	51,786
	CP32	V	10–130	1.20					1873	
	CP33	V	20–200	1.80					1867	
	CP34	S	35–330	2.95					1859	
	CP35	V	07–85	0.78					1836	
BAM1	CP61	S	5–303	2.98	2.98	0.97	1.92	1.01	1643	16,126
	CP62	V	86–223	0.97					1635	
	CP63	B	10–190	1.80					1645	
BAM2	CP71	B	40–67	0.27	5.07	0.27	3.285	2.08	1604	157,462
	CP72	V	40–433	3.93					1627	
	CP73	S	26–533	5.07					1638	
	CP74	V	68–455	3.87					1625	
BAN	CP81	S	30–102	1.20	4.02	0.8	2.01	1.76	1688	78,519
	CP82	V	0–80	0.80					1671	
	CP83	B	18–420	4.02					1665	

SEK Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou 1 site; *BAM2* Bamendjou 2 site, *BAN* Bangam site, *S* Well drilled at the top of the gravelly zone, *E* Thickness of the lateritic gravel, *V* Well drilled on the slope of the gravelly zone, *B* Well drilled at the bottom of the gravelly zone, *Sd* Standard deviation, *Max* Maximum, *Min* Minimum

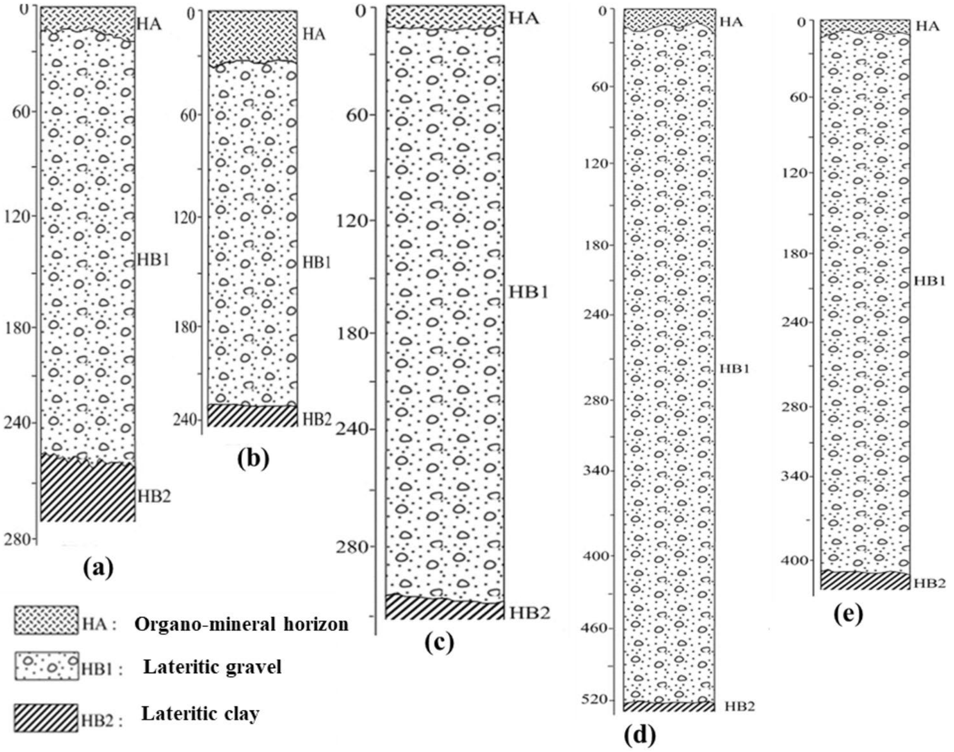


Fig. 4 Typical soil profile of the five sites, **a** Sekakouo site; **b** Chenye site, **c** Bamendjou 1 site, **d** Bamendjou 2 site and **e** Bangam site

The soil profile of the northern flank of Mount Bangou includes three pedological levels (Fig. 4). They are of the ABC type of soil horizons. From top to bottom, the first level (10–86 cm) corresponds to the light red organo-mineral level and is a fine pedoturbated soil with a silty, silty-clay, and silty-sandy texture. The structure is lumpy and contains many rootlets (Fig. 4).

The second level (72–387 cm) is the lateritic gravel level with a predominantly light red, silty-clay, silty-sandy, silty, silty-sandy-clay, and silty-sandy fine soil for the Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam soil profiles respectively. The structure is predominantly gravelly and contains abundant millimeter to multi-centimeter-sized gravel (20–73%). The lateritic gravel level crops out in some localities (Fig. 4).

The third horizon is the lateritic clay level with a clayey texture and polyhedral structure (Fig. 4).

Sekakouo site

Five pedological wells were drilled at this site: three wells were drilled on the slope, one well at the foot of the gravelly zone, and one well at the top. The thickness of the lateritic gravel level at the Sekakouo site varied from 0.73 to 2.40 m. The highest value corresponds to well CP14 at the top of the gravelly zone and the lowest to well CP11 at the bottom of the gravelly zone. The mean value of the thickness of the lateritic gravel level for these five wells is 1.23 m with a standard deviation of 0.69. The total area of the gravelly zone is 143,509 m^2.

Chenye site

Five soil wells were drilled at this site: two wells were drilled on the slope, two wells at the base of the gravelly zone, and one well at the top. Thickness values of the lateritic gravel level at the Chenye site range from 0.50 to 2.95 m. The highest value corresponds to well CP34 at the top of the gravelly zone and the lowest to well CP31 at the bottom of the gravelly zone. The mean value of the thickness of the lateritic gravel level for these five wells is 1.45 m with a standard deviation of 0.97. The total area of the gravelly zone is 51,786 m^2.

Bamendjou 1 site

Three pedological wells were drilled at this site: one well was drilled on the slope, another well at the foot of the gravelly zone, and one well at the top. The thickness of the lateritic gravel level at the Bamendjou 1 site varies from 0.97 to 2.98 m. The highest value corresponds to well CP61 at the top of the gravelly zone and the lowest to well CP62 at the bottom of the gravelly zone. The average value of the thickness of the lateritic gravel level for the five soil wells is 1.93 m with a standard deviation of 1.02. The total surface area of the gravelly zone is 16,126 m^2.

Bamendjou 2 site

Four soil wells were drilled at this site: two wells were drilled on the slope, one well at the foot of the gravelly area, and one well at the top. The thicknesses of the lateritic gravel level at the Bamendjou 2 site vary from 0.27 to 5.07 m. The highest value corresponds to well CP73 at the top of the gravelly zone and the lowest to well CP71 at the bottom of the gravelly zone. The mean value for these five wells is 3.285 m with a standard deviation of 2.08. The mean value for these five wells is 1.23 m for a standard deviation of 0.69. The total area of the gravelly zone is 157,462 m^2.

Bangam site

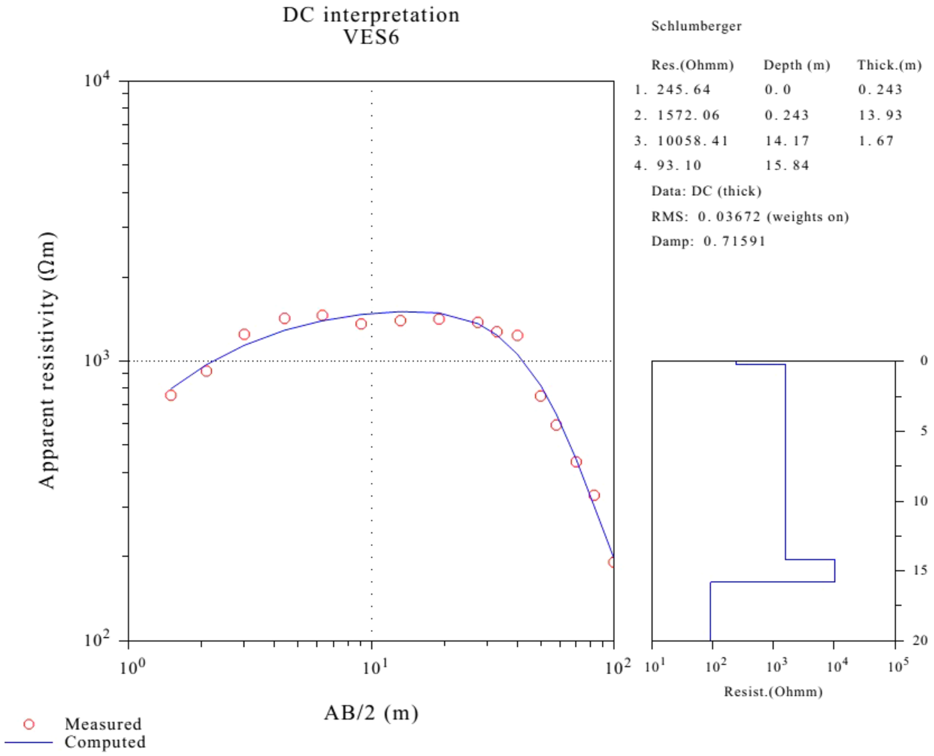
Three pedologic wells were drilled at this site: one well was drilled on the slope, two wells were drilled at the foot of the gravelly zone, and one well was drilled at the top. Thickness values of the lateritic gravel level at the Bangam site range from 0.08 to 4.02 m. The highest value corresponds to well CP83 at the top of the gravelly zone and the lowest to well CP82 at the bottom of the gravelly zone. The mean value for these five wells is 2.01 m with a standard deviation of 1.76. The total area of the gravelly zone is 78,519 m^2.

1D inversion

Modeling of data from forty-eight (48) VES carried out on all five sites shows the existence of eight (08) models of electrical resistivity curves (K, HK, Q, QH, KQ, HKH, H, and KH) materializing the layout of geological layers and their electrical variation based on studies by Telford et al. (1990), Koussoubé et al. (2003), Singh and Stephen (2004) and Gouet et al. (2020) (Figs. 5, 6, 7, 8, 9, 10, 11, 12). This typological multiplicity of resistivity curves confirms the structural heterogeneity of the lateritic soils of the North Slope of Mount Bangou.

The SEV curves were compared with the soil profiles and the geological history of the region to better reconstruct the litho-pedological sections. Thus, at the geo-environmental level, the lateritic gravels studied here developed on subaphyric basalts (Fig. 1) (Fosso et al. 2005; Kuepou et al. 2006; Nono et al. 2009; Kwékam et al. 2010) resting on a granitoid and gneiss bedrock, probably of Pan-African age (Fosso et al. 2005). The long period (44.7 to 43.1 ± 1 Ma) of weathering of these rocks resulted in great thicknesses of lateritic formations (Fosso et al. 2005). They formed in an environment where elevations range from 990 to 2045 m and on slopes ranging from seven to 36%. The soil profiles

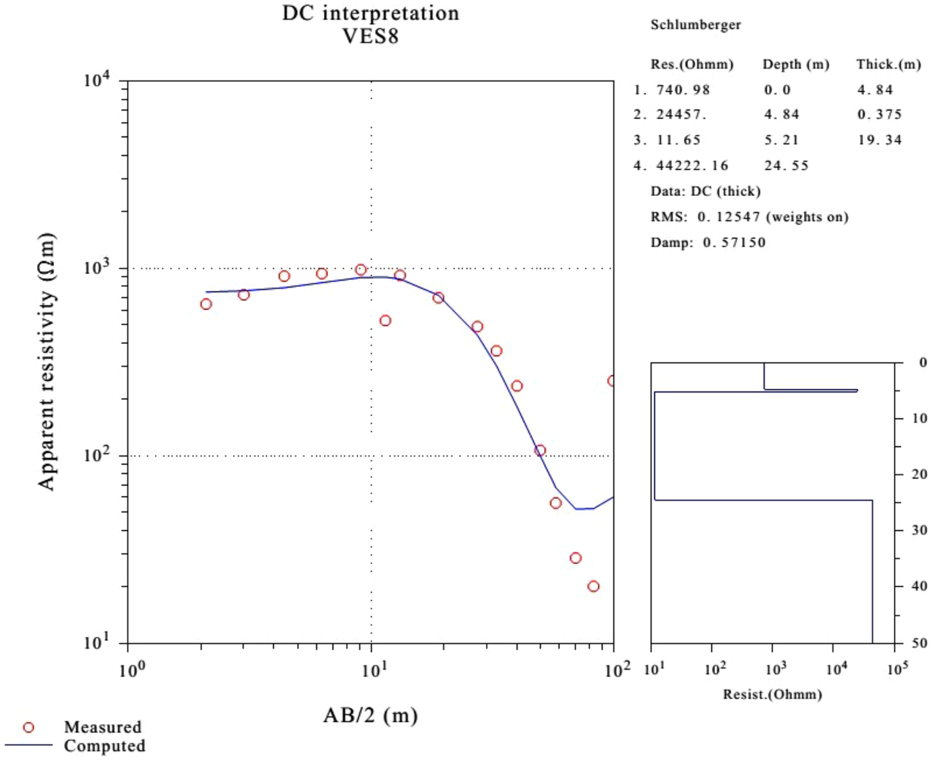
Fig. 5 Typical geo-electric curve type K



	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	245. 64	0. 0	0. 243
2.	1572. 06	0. 243	13. 93
3.	10058. 41	14. 17	1. 67
4.	93. 10	15. 84	

Data: DC (thick)
RMS: 0. 03672 (weights on)
Damp: 0. 71591

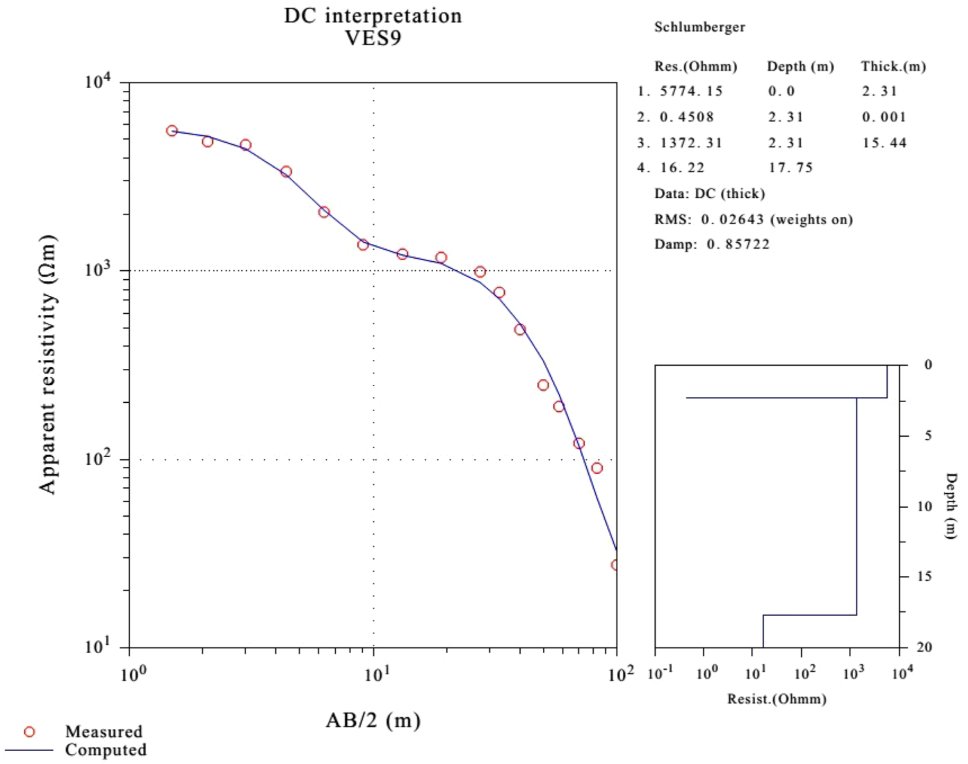
Fig. 6 Typical geo-electric curve type KH



	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	740. 98	0. 0	4. 84
2.	24457.	4. 84	0. 375
3.	11. 65	5. 21	19. 34
4.	44222. 16	24. 55	

Data: DC (thick)
RMS: 0. 12547 (weights on)
Damp: 0. 57150

of the sites studied showed an organized structuring into an organo-mineral horizon, a thick lateritic gravel level, and a lateritic clay level structured in successive strata. The organo-mineral horizon is absent in some areas of the study sites. The succession of soil volumes along the litho-pedological logs from the VES showed the same structuring

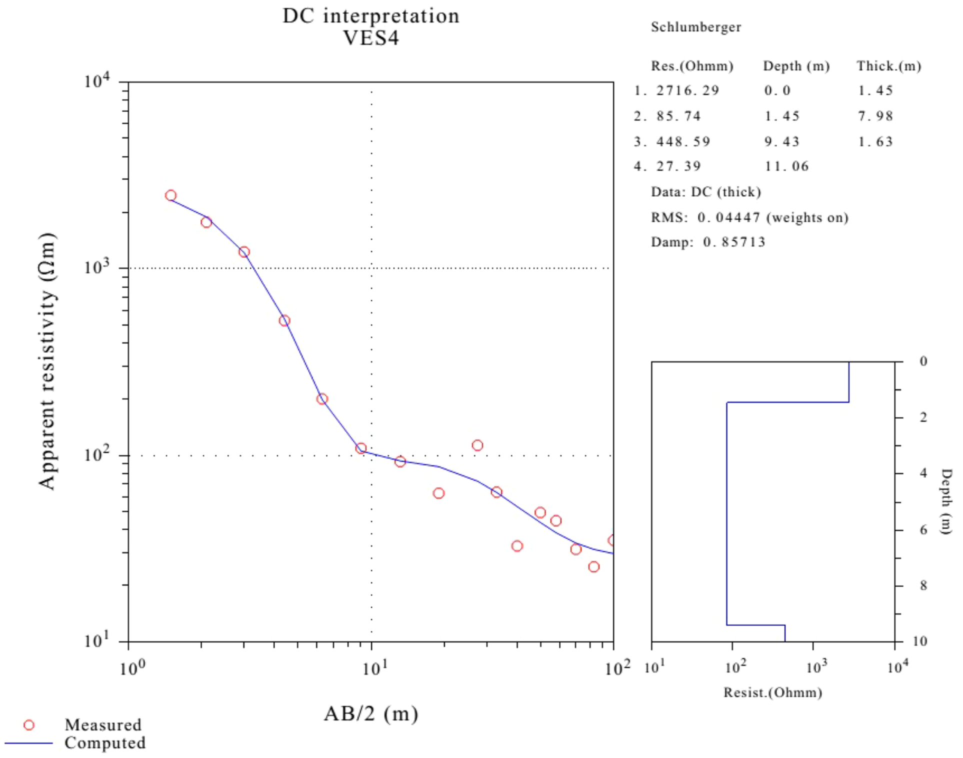


Schlumberger

	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	5774.15	0.0	2.31
2.	0.4508	2.31	0.001
3.	1372.31	2.31	15.44
4.	16.22	17.75	

Data: DC (thick)
RMS: 0.02643 (weights on)
Damp: 0.85722

Fig. 7 Typical geo-electric curve type HK



Schlumberger

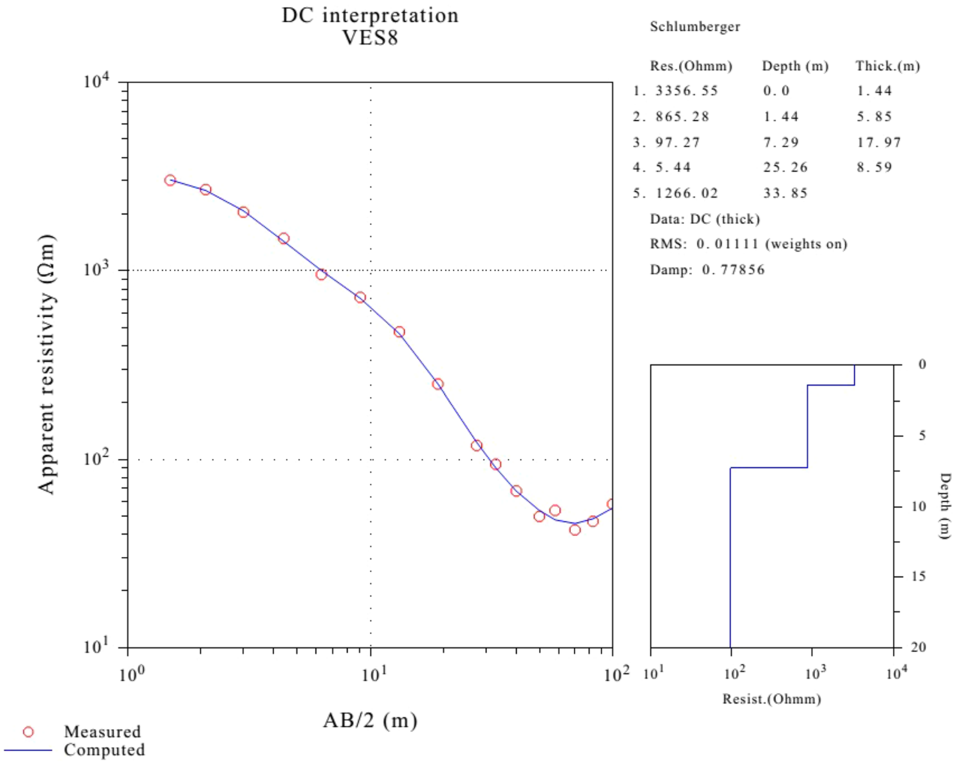
	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	2716.29	0.0	1.45
2.	85.74	1.45	7.98
3.	448.59	9.43	1.63
4.	27.39	11.06	

Data: DC (thick)
RMS: 0.04447 (weights on)
Damp: 0.85713

Fig. 8 Typical geo-electric curve type H

as observed in the soil pits (the lateritic gravel level is surmounted in areas by the organo-mineral horizon and rests on the lateritic clay level) except that the VES investigated deeper and found formations that the soil pits did not. In general, the VES showed that the subsurface of the study area is made up of: the organo-mineral horizon, lateritic

Fig. 9 Typical geo-electric curve type QH



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   Res.(Ohmm)   Depth (m)   Thick.(m)
1. 3356.55      0.0         1.44
2. 865.28       1.44        5.85
3. 97.27        7.29        17.97
4. 5.44         25.26       8.59
5. 1266.02      33.85
   Data: DC (thick)
   RMS: 0.01111 (weights on)
   Damp: 0.77856
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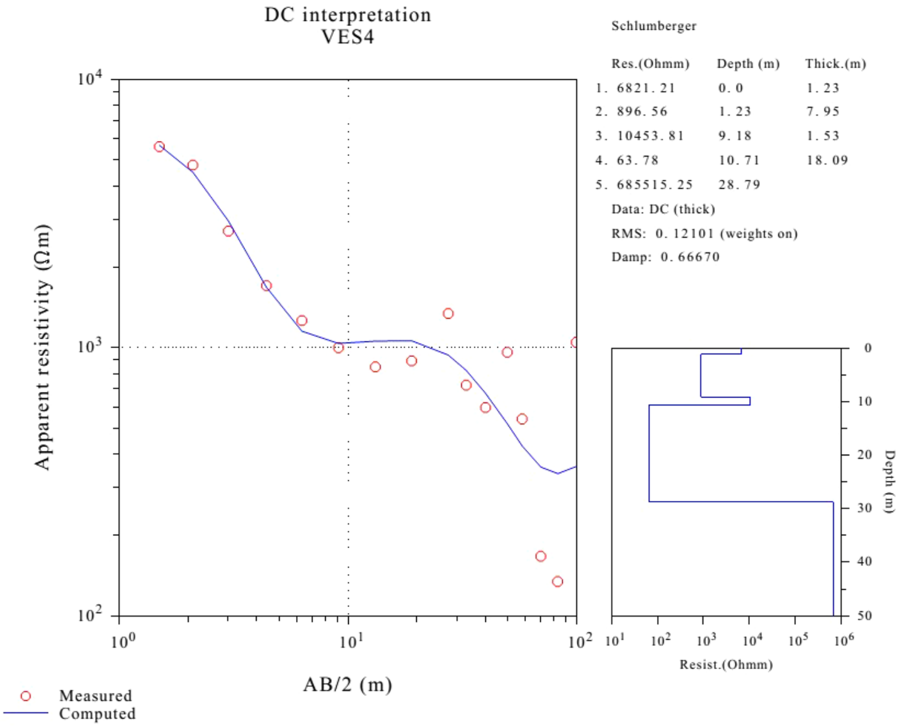
Fig. 10 Typical geo-electric curve type HKH



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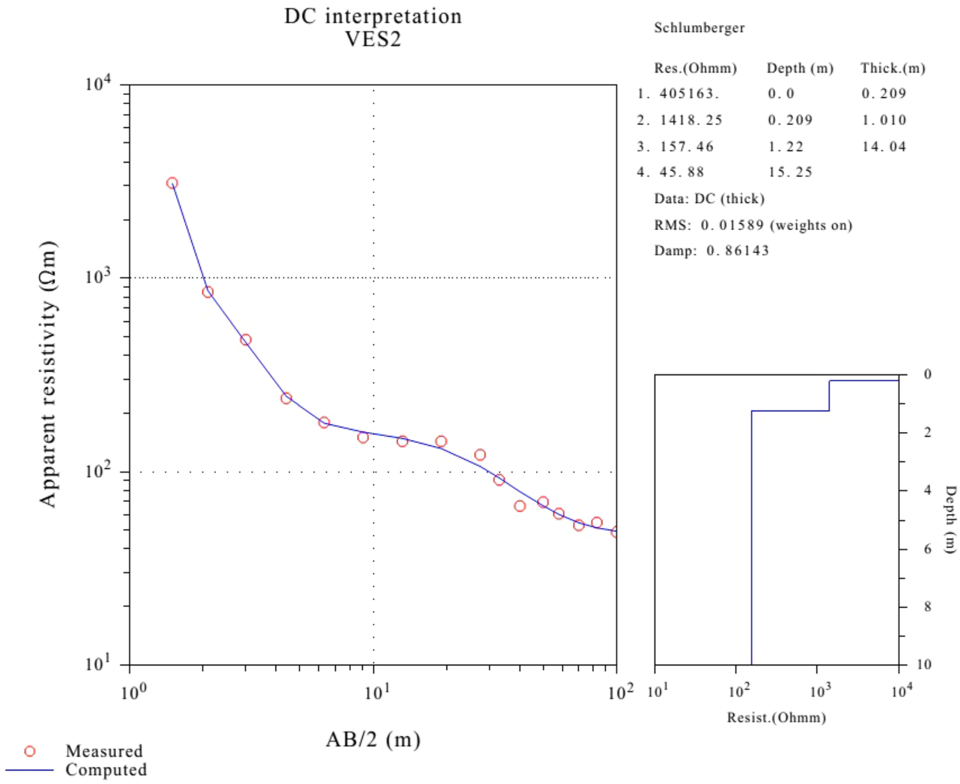
   Res.(Ohmm)   Depth (m)   Thick.(m)
1. 6821.21      0.0         1.23
2. 896.56       1.23        7.95
3. 10453.81     9.18        1.53
4. 63.78        10.71       18.09
5. 685515.25    28.79
   Data: DC (thick)
   RMS: 0.12101 (weights on)
   Damp: 0.66670
```

gravel, lateritic cuirass, lateritic clay, more or less cracked basalt, the aquifer, and the granite-gneissic basement. The resistivities of the lateritic gravel level range from 100 to 10,000 Ω.m.

Sekakouo site

The one-dimensional inversion (1D) of the vertical electrical soundings (VES) made at the Sekakouo site (SEK) shows

Fig. 11 Typical geo-electric curve type Q



Schlumberger

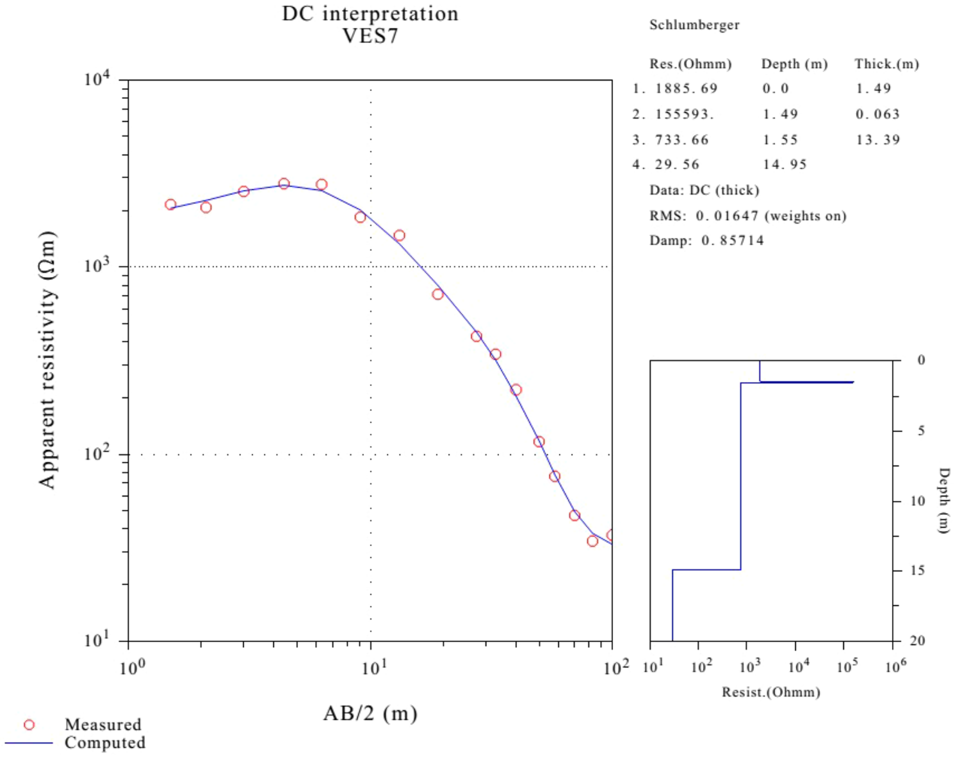
	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	405163.	0. 0	0. 209
2.	1418. 25	0. 209	1. 010
3.	157. 46	1. 22	14. 04
4.	45. 88	15. 25	

Data: DC (thick)

RMS: 0. 01589 (weights on)

Damp: 0. 86143

Fig. 12 Typical geo-electric curve type KQ



Schlumberger

	Res.(Ohmm)	Depth (m)	Thick.(m)
1.	1885. 69	0. 0	1. 49
2.	155593.	1. 49	0. 063
3.	733. 66	1. 55	13. 39
4.	29. 56	14. 95	

Data: DC (thick)

RMS: 0. 01647 (weights on)

Damp: 0. 85714

the existence of electrical resistivity curves of types K, Q, QH, HK, and H. The QH- and H-type resistivity curves predominate and the K-type curves are the least common at this site. The number of layers varies from four to five. The litho-pedological section of the VES at the Sekakouo site consists of lateritic gravel, lateritic cuirass, lateritic clay, aquifer, and granite-gneissic basement. Thicknesses of the lateritic gravel level vary from 1.45 to 18.66 m with a mean of 8.88 m and a standard deviation of 5.33 (Table 2). The greatest thickness is obtained at the VES1 sounding point and the least at the VES4 sounding point (Fig. 13).

Chenye site

The Chenye site (CHE) is characterized by KH-, Q-, QH-, HK-, and H-type electrical resistivity curves. The H- and KH-type curves are the least encountered at this site. The number of layers varies from four to five. The organo-mineral horizon, lateritic gravel, lateritic cuirass, aquifer, and lateritic clay characterize the litho-pedology of the Bamendjou 1 site. The average thickness of the lateritic gravel level is 10.32 m with a standard deviation of 3.80. They vary from 5.32 to 15.60 m (Table 3). The highest thickness is observable at the VES1 sounding point and the lowest at the VES3 sounding point (Fig. 14).

Bamendjou 1 site

The Bamendjou 1 site (BAM1) is characterized by K, Q, and HK electrical resistivity curves. The number of layers varies from four to five. Lateritic gravel, lateritic cuirass, aquifer, lateritic clay, and fresh (i.e., unweathered) rock characterize the litho-pedology of the Bamendjou 1 site. The average thickness of the lateritic gravel level is 11.68 m with a standard deviation of 8.01. They vary from 0.39 to 23.52 m (Table 4). The greatest thickness is observable at the VES3 sounding point and the lowest at the VES1 sounding point (Fig. 15).

Bamendjou 2 site

The Bamendjou 2 site (BAM2) is characterized by K, HKH, and H-type electrical curves. The H-type electrical curves predominate. This site is the only one to admit HKH-type electrical resistivity curves. Overall, the number of layers is four. The litho-pedological section of the VES at the Bamendjou 2 site consists of lateritic gravel, lateritic cuirass, lateritic clay, fresh rock, aquifer, basalt, and granite-gneissic basement. The thicknesses of the lateritic gravel level vary from 0.8 to 47.38 m. The greatest thickness is observable at the VES1 sounding point and the lowest is obtained at the VES3 sounding point (Fig. 16). The average thickness is 19.28 m with a standard deviation of 20.28 (Table 5).

Bangam site

The electrical resistivity curves of types KH, Q, KQ, HK, and H characterize the Bangam site (BAN). This site is dominated by Q-type electrical resistivity curves and KQ-type curves are the least encountered. The number of layers varies from four to five. The litho-pedological section of the VES at the Bangam site consists of lateritic gravel, lateritic cuirass, fresh rock fragments, fresh rock, lateritic clay, aquifer, basalt, and granite-gneissic basement. The thicknesses of the lateritic gravel level vary from 1.49 to 26.64 m. The greatest thickness is observable at test point VES2 and the lowest at test point VES7 (Fig. 17). The average thickness is 12.07 m with a standard deviation of 6.61 (Table 6).

Thickness maps of the lateritic gravel level

The thickness (isopach) maps of the lateritic gravel level were constructed solely from the thickness data from the geoelectrical surveys. These maps show three distinct thickness zones: thin zone, medium-thick zone, and thick zone.

Sekakouo site

Figure 18a shows the thickness distribution of the gravelly level at the Sekakouo site. The thin zones are observed to the NW and NE of the gravelly zone and have thicknesses between one and eight m. The medium thickness zones (eight to 13 m) are the most encountered and define a band that extends from the east to the north and SW. The thicker zones cover the SE and have thicknesses between 13 and 19 m.

Chenye site

The thickness of the lateritic gravels at the Chenye site is shown in (Fig. 18b). The thin zones occupy the east and west of the gravelly zone and range from five to 10 m thick. The medium thickness zones (10–13 m) are the most represented and are encountered in the north, center, and part of the south of the gravelly zone. The thicker zones (13–16 m) are rarer and occupy part of the northern gravelly zone (Fig. 18c).

Bamendjou 1 site

At Bamendjou 1, the thin zone demarcates a band in the NW part of the study area. Thin formations in the form of pockets are also observed to the south and SE of the gravelly zone. Thicknesses of the shallow zone range from three to 13 m. The medium thickness zones (13–20 m) are the most

Table 2 Resistivity values, layer thicknesses, depth, and Sekakouo VES curve models

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve type	Litho-pedological type
VES1	4	1	1435.5	0	1.64	18.66	K	Lateritic gravel
		2	27,331	1.46	0.167			Lateritic cuirass
		3	228.94	1.62	17.02			Lateritic gravel
		4	105.92	18.65				Lateritic clay
VES2	4	1	405,163	0	0.209	15.05	Q	Lateritic Cuirass
		2	1418.25	0.209	1.01			Lateritic gravel
		3	157.46	1.22	14.04			Lateritic gravel
		4	45.88	15.25				Lateritic clay
VES3	4	1	4039.44	0	0.335	3.525	Q	Lateritic gravel
		2	415.34	0.335	3.19			Lateritic gravel
		3	102.31	3.52	6.44			Lateritic clay
		4	18.39	9.97				Basalt
VES4	4	1	2716.29	0	1.45	1.45	HK	Lateritic gravel
		2	85.74	1.45	7.98			Lateritic clay
		3	448.59	9.43	1.63			Aquifer
		4	27.39	11.06				Lateritic clay
VES5	4	1	7597.32	0	1.52	1.52	QH	Lateritic gravel
		2	79.24	1.52	0.61			Lateritic clay
		3	0.0031	2.13	0.001			Basalt
		4	33.84	2.13				Lateritic clay
VES6	5	1	6338	0	1.11	10.80	HK	Lateritic gravel
		2	1813.26	1.11	9.69			Lateritic gravel
		3	14.32	10.8	14.63			Aquifer
		4	1262.06	25.43	13.89			Basalt
		5	14.63	39.32				Aquifer
VES7	4	1	1635.53	0	0.438	6.478	K	Lateritic gravel
		2	4747.67	0.438	6.04			Lateritic gravel
		3	130.57	6.48	0.312			Lateritic gravel
		4	67.82	6.79				Lateritic clay
VES8	5	1	3356.55	0	1.44	7.29	QH	Lateritic gravel
		2	865.28	1.44	5.85			Lateritic gravel
		3	97.27	7.29	17.97			Lateritic clay
		4	5.44	25.26	8.59			Aquifer
		5	1266.02	33.85				Granito-gneissic basement
VES9	4	1	7810.12	0	0.496	9.29	H	Lateritic gravel
		2	1567.25	0.496	8.79			Lateritic gravel
		3	6.65	9.29	1.083			Aquifer
		4	55.67	10.37				Lateritic clay
VES10	4	1	6921.9	0	2.76	10.39	H	Lateritic gravel
		2	325.9	2.76	7.63			Lateritic gravel
		3	1.53	10.39	0.909			Aquifer
		4	203,796.61	11.3				Granito-gneissic basement
VES11	4	1	418,299	0	0.967	8.16	H	Lateritic cuirass
		2	3814.91	0.967	8.16			Lateritic gravel
		3	0.289	9.13	0.046			Aquifer
		4	39,543.01	9.17				Granito-gneissic basement
VES12	4	1	1006.15	0	3.6	13.95	QH	Lateritic gravel
		2	153.97	3.6	10.35			Lateritic gravel
		3	3.22	13.95	10.08			Aquifer
		4	76,555.84	24.03				Granito-gneissic basement

ρ (Ω.m) resistivity, *P (m)* depth, *E (m)* material thickness, *E. Gravel (m)* the thickness of the lateritic gravel, *VES* vertical electrical sounding

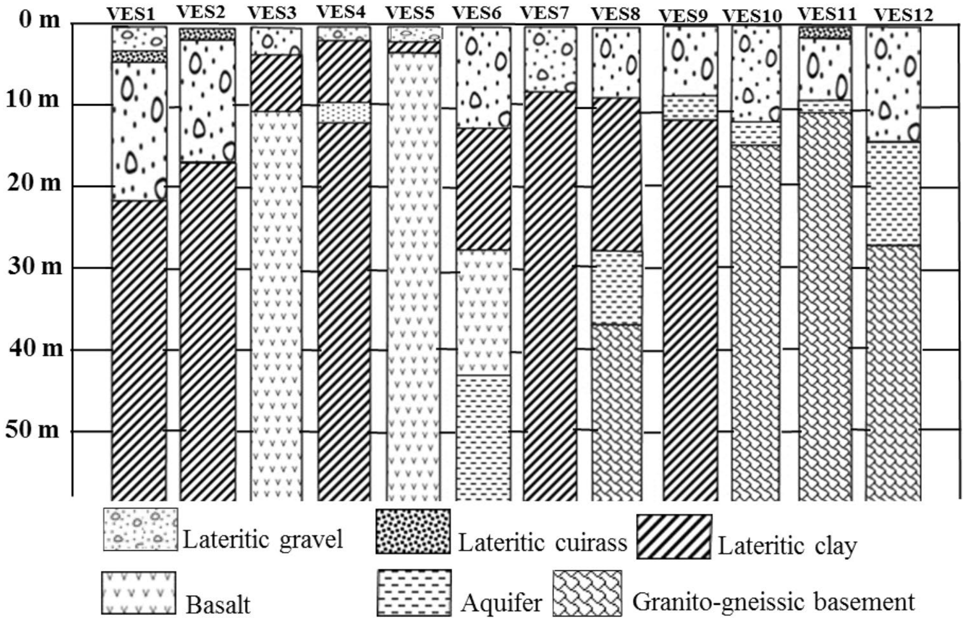


Fig. 13 1D lithology of the Sekakouo vertical electric drill holes

encountered and occupy part of the SW and part of the SE. The thicker zones are present in the NNE and SW and have thicknesses that vary from 20 to 27 m (Fig. 18d).

Bamendjou 2 site

Figure 18e shows the thickness distribution of the lateritic gravel level at the Bamendjou 2 site. The thin areas are the most encountered and are observed at NS of the gravelly zone and have thicknesses between nine and 24 m. The medium thickness zones (24–36 m) occupy the NW of the gravelly zone. The thicker zones are the least encountered and are observed to the NNW. Their thicknesses vary from 36 to 44 m.

Bangam site

The thicknesses of the lateritic gravel level at the Bangam site are shown in (Fig. 18f). The thin domains occupy the SSW, SE, and NNE of the gravelly zone and range in thickness from one to 12 m. The medium thickness domains (12–19 m) are the most represented and are encountered in the central and NW of the gravelly zone. The thicker zones (19–27 m) are less common and occupy the western part of the gravelly zone.

Specific gravity

The specific gravity values (γs) of the lateritic gravel levels of the studied sites range from 2.60 t/m^3 to 2.81 t/m^3. The values 2.73 t/m^3, 2.60 t/m^3, 2.72 t/m^3, 2.70 t/m^3 and 2.81 t/m^3 are noted for the SEK, CHE, BAM1, BAM2 and BAN samples respectively (Table 7). The mean value for the 5 sites is 2.71 t/m^3 with a standard deviation of 0.08.

Estimated tonnage of lateritic gravels studied

The calculation of gravelly volume involves the thickness of the lateritic gravel level and the total surface area of the gravelly zone at the site. The thickness of the lateritic gravel level at the Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam sites were determined from the interpretation of the geoelectrical soundings and the pedological wells. Thus, the volume multiplied by the specific gravity yields the product that provides the tonnage estimates of the material sought for road building (Kouakou et al. 2017).

Site tonnage from determined pedological well thicknesses

The values 481,889 t; 195,233 t; 822,330 t; 143,030 t and 443,483 t are noted for the Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam sites respectively. The tonnage of the sites studied varies from 143,030 t (Bamendjou 2 site) to 822,330 t (Bamendjou 1 site), for an average value of 417,193 t (Table 7).

Tonnage of the sites studied from the thicknesses determined from the geo-electric soundings

Table 7 summarizes the specific gravity, lateritic gravel level thickness, gravelly area, volume, and gravelly tonnage by study site. Overall, the tonnage of the study sites ranges from 839,455 t to 5,002,505 t. The greatest value corresponds to the Bamendjou 1 site and the Sekakouo site

Table 3 Resistivity values, layer thicknesses, depth, and Chenye VES curve models

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve type	Litho-pedological type
VES1	4	1	5000.12	0	1.72	10.47	QH	Lateritic gravel
		2	2268.00	1.72	8.75			Lateritic gravel
		3	18.10	10.47	4.50			Aquifer
		4	65.32	14.96				Lateritic clay
VES2	4	1	9516.70	0	1.51	8.58	QH	Lateritic gravel
		2	3791.15	1.51	7.07			Lateritic gravel
		3	18.60	8.58	11.98			Aquifer
		4	26,309.70	20.55				Fresh rock
VES3	4	1	5421.48	0	2.31	5.42	Q	Lateritic gravel
		2	681.31	2.31	3.11			Lateritic gravel
		3	82.27	5.41	11.33			Lateritic clay
		4	42.91	16.74				Basalt
VES4	4	1	228,469	0	1.61	14.73	H	Lateritic cuirass
		2	568.61	1.61	1.093			Lateritic gravel
		3	1739.41	2.70	13.64			Lateritic gravel
		4	124.94	16.34				Aquifer
VES5	4	1	7825.79	0	3.50	6.15	HK	Lateritic gravel
		2	0.3683	3.50	0.002			Fresh rock fragment
		3	5,347.15	3.50	2.65			Lateritic gravel
		4	73.49	6.15				Lateritic clay
VES6	4	1	103,277	0	1.78	13.66	Q	Lateritic cuirass
		2	2216.82	1.78	6.46			Lateritic gravel
		3	536.95	8.24	7.20			Lateritic gravel
		4	70.63	15.44				Lateritic clay
VES7	4	1	22,129	0	0.219	15.66	Q	Lateritic cuirass
		2	1079.23	0.219	4.23			Lateritic gravel
		3	1,006.07	4.44	11.43			Lateritic gravel
		4	142.65	15.87				Aquifer
VES8	4	1	1998.85	0	3.49	10.81	HK	Lateritic gravel
		2	1,556.42	3.49	4.42			Lateritic gravel
		3	3263.05	7.90	2.90			Lateritic gravel
		4	155.42	10.81				Aquifer
VES9	4	1	9,161.10	0	2.79	12.15	QH	Lateritic gravel
		2	1251.63	2.79	9.36			Lateritic gravel
		3	20.87	12.15	6.48			Lateritic clay
		4	208.34	18.63				Basalt
VES10	4	1	78.62	0	0.344	5.55	KH	Organo-mineral horizon
		2	15,662	0.344	0.647			Lateritic cuirass
		3	248.47	0.991	4.90			Lateritic gravel
		4	1,000,000	5.90				Granito-gneissic basement

ρ (Ω.m) resistivity, *P (m)* depth, *E (m)* thickness, *E. Gravel (m)* the thickness of the lateritic gravel, *VES* vertical electrical sounding

is represented by the lowest value. The values of 3,479,003 t; 1,389,522 t; 5,002,505 t; 839,455 t and 2,663,105 t are noted for the Sekakouo, Chenye, Bamendjou 1, Bamendjou 2 and Bangam sites, respectively. The average value for the five sites is 2,674,718 t (Table 7).

Assessment of the volume of lateritic borrow in pavement layers

According to previous work by Foko Tamba et al. (2022), the lateritic gravels materials of the northern flank of

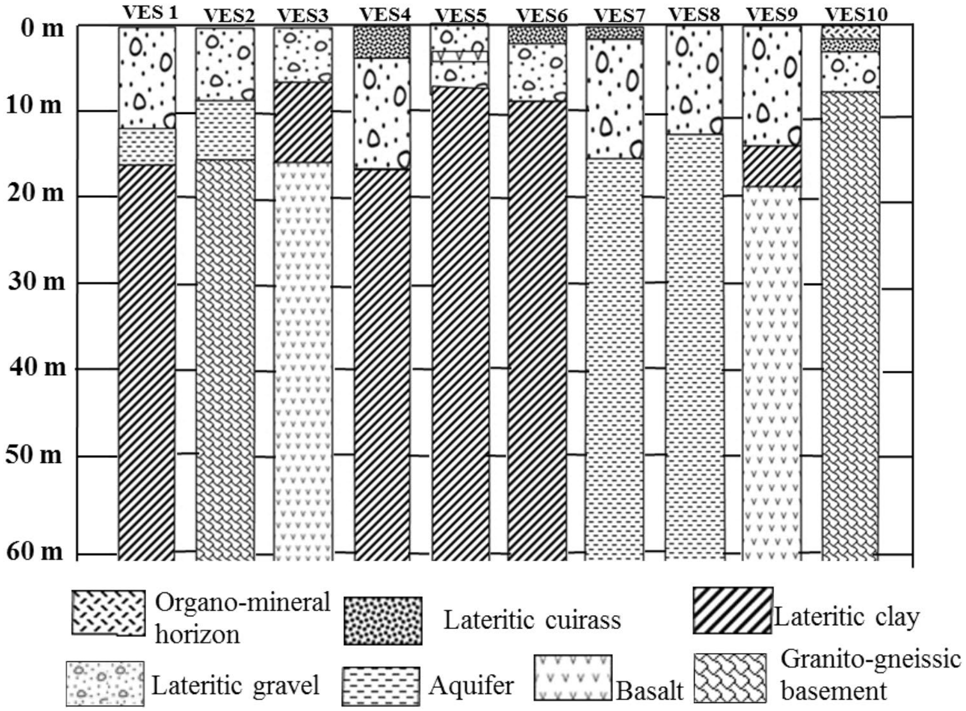


Fig. 14 1D lithology of the Chenye vertical electrical boreholes

Mount Bangou are gravels and silty or clayey sands, and silty soils of subgroups A-2-7 and A-4, respectively, according to the Highway Research Board (HRB) classification; and silty gravels according to the Laboratoire Central des Ponts et Chaussées (LCPC) classification. They can be used naturally in pavement layers, in particular in subgrades for all traffic classes. They can also be used in the sub-base for low traffic levels of class T1 (100–300 vehicles per day), T2 (300–1,000 vehicles per day), and T3 (1000–3000 vehicles per day), except lateritic gravels from the Chenye and Sekakouo sites (CEBTP 1984; Sikali and Mir-emarati 1986). Because of the inadequacy of soil wells for determining the thickness of lateritic gravels, the evaluation of the volume of lateritic materials studied in pavement layers took into account only the quantities of lateritic gravels determined from the geophysical data.

Evaluation in the form layer

In road construction, the installation of a subgrade layer is only necessary when the platform or the upper part of the excavation does not have sufficient bearing capacity. Generally, the form layer is constructed or installed for the purpose of constructing the roadway on a homogeneous platform of good quality. The thickness of the subgrade layer is generally equal to about 30 cm (CEBTP 1984). Thus, the structure of pavement is more or less equivalent to a three-dimensional geometric shape. In rural areas, pavements generally have an average width of 7.50 m plus shoulders of 1.5 m × 2. The volume of lateritic gravel for 1 km of roadway was calculated with reference to Eq. (5).

$$V(1\text{km}) = L \times l \times h \tag{5}$$

where L is the length, l is the width, and h is the height. A.N: For L = 1 000 m, l = 10.5 m, h = 0.3 m. We have:

$$V\ (1\ \text{km}) = 1000 \times 10.5 \times 0.3$$

$$V(1\ \text{km}) = 3150\ \text{m}^3$$

Sikali and Mir-emarati (1986) report that 1 m^2 of raw lateritic gravelly material corresponds to about 0.75 m^3, compacted into a pavement layer. In this context, for 1000 m of road length, approximately 2363 m^3 of material will be used. As a reference, at CEBTP (1984), the gravel from the Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam sites can be used in a form layer.

Sekakouo site

The Sekakouo site shows a proven reserve of 1,274,360 m^3 or a tonnage of 3,479,003 t for an area of 143,509 m^2. Thus, 1,274,360 m^3 can build about 539,298 m of the road in form layer, either 539.298 km.

Chenye site

The proven reserve of the Chenye site is 534,432 m^3 or a tonnage of 1,389,522 t for an area of 51 786 m^2. Therefore,

Table 4 Resistivity values, layer thicknesses, depth, and VES curve models of Bamendjou 1

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve type	Litho-pedological type
VES1	4	1	336.21	0	0.389	26.789	K	Lateritic gravel
		2	29,570	0.389	0.355			Lateritic cuirass
		3	867.83	0.744	26.40			Lateritic gravel
		4	66.94	27.15				Lateritic clay
VES2	4	1	153.32	0	0.415	4.13	K	Lateritic gravel
		2	914.43	0.415	3.71			Lateritic gravel
		3	27,535	4.12	0.471			Lateritic cuirass
		4	97.19	4.59				Lateritic clay
VES3	4	1	87,511,116	0	1.16	23.52	Q	Lateritic cuirass
		2	5815.72	1.16	4.22			Lateritic gravel
		3	841.82	5.38	19.30			Lateritic gravel
		4	205.58	24.68				Basalt
VES4	4	1	3473.22	0	5.88	10.28	HK	Lateritic gravel
		2	223.49	5.88	1.77			Lateritic gravel
		3	8222.10	7.65	2.63			Lateritic gravel
		4	42.01	10.28				Lateritic clay
VES5	4	1	6035.52	0	1.071	3.35	K	Lateritic gravel
		2	18,688	1.071	2.28			Lateritic cuirass
		3	1119.43	3.35	33.19			Lateritic gravel
		4	16.65	36.54				Aquifer
VES6	4	1	245.64	0	0.243	14.17	K	Lateritic gravel
		2	1572.06	0.243	13.93			Lateritic gravel
		3	10,058.41	14.17	1.67			Lateritic cuirass
		4	93.10	15.84				Lateritic clay
VES7	4	1	2462.26	0	3.78	11.25	HK	Lateritic gravel
		2	873.95	3.78	2.10			Lateritic gravel
		3	3100.55	5.88	5.37			Lateritic gravel
		4	55.36	11.25				Lateritic clay
VES8	4	1	5327.89	0	0.900	20.28	K	Lateritic gravel
		2	12,248	0.900	3.10			Lateritic cuirass
		3	1236.17	4.00	19.38			Lateritic gravel
		4	41.76	23.39				Lateritic clay
VES9	4	1	5774.15	0	2.31	17.75	HK	Lateritic gravel
		2	0.4508	2.31	0.001			Basalt
		3	1372.31	2.31	15.44			Lateritic gravel
		4	16.22	17.75				Aquifer

ρ (Ω.m) resistivity, *P (m)* depth, *E (m)* thickness, *E. Gravel (m)* the thickness of the lateritic gravel, *VES* vertical electrical sounding

534,432 m^3 can build approximately 226,167 m of the road in form layer, either 226.167 km.

Bamendjou 1 site

At Bamendjou 1, the proven reserve is 1,839,156 m^3 or a tonnage of 5,002,505 t for an area of 157,462 m^2. Thus, 1,839,156 m^3 of lateritic gravels can build about 778,314 m of the road in form layer, either 778.314 km.

Bamendjou 2 site

The Bamendjou 1 site shows a proven reserve of 310,909 m^3 or a tonnage of 839,455 t for an area of 78,519 m^2. Therefore, 310,909 m^3 can build about 131,574 m of the road in form layer, either 131.574 km.

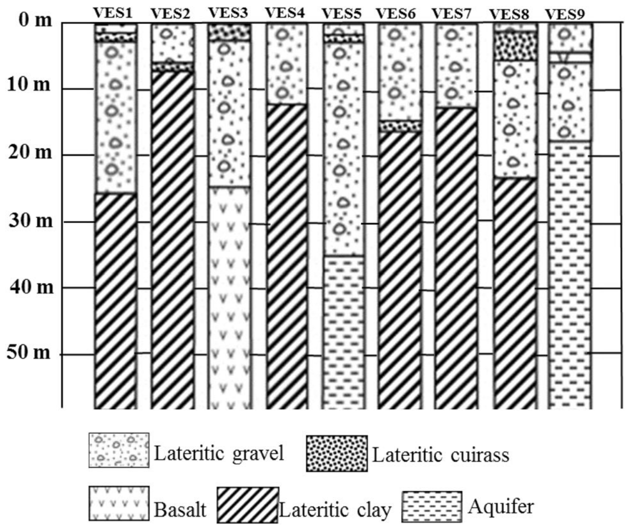


Fig. 15 1D lithology of the vertical electric soundings of Bamendjou 1

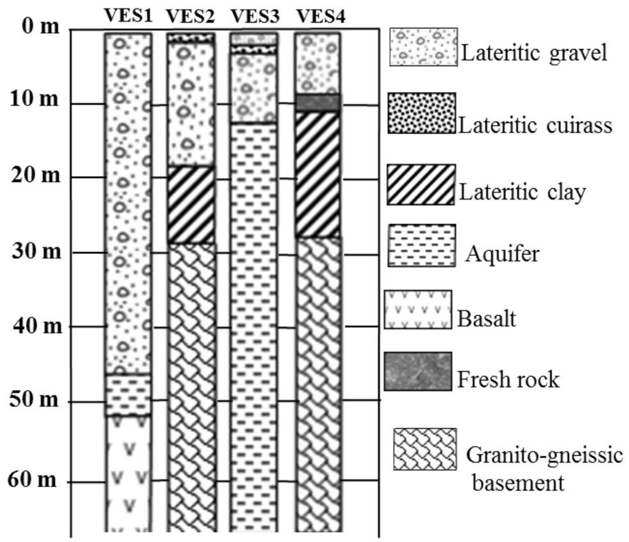


Fig. 16 1D lithology of the vertical electric drillings of Bamendjou 2

Bangam site

The proven reserve of the Bangam site is 947 724 m^3, or a tonnage of 2,663,105 t for an area of 78 519 m^2. Thus, 947,724 m^3 of lateritic gravels can build approximately 401,068 m of the road in form layer, either 401.068 km.

Evaluation in sub-base

According to CEBTP (1984), the sub-base layer must have a maximum thickness of 25 cm and a minimum thickness of 10 cm. Concerning equation (3), the volume of lateritic gravels for the construction of 1 km of pavement was calculated.

A.N: For L = 1 000 m, l = 10.5 m, h = 0.25 m.

$$V = 1000 \times 10.5 \times 0.25$$

$$V = 2625\ m^3$$

For 1000 m of road length, approximately 2625 m^3 of gravelly lateritic materials will be used. In Cameroon, for soil to be eligible as a sub-base, it must have a Californian bearing ratio (CBR) capacity equal to or greater than 30%, although a CBR of 25% can be tolerated for Tl traffic (Sikali and Mir-emarati 1986). Thus, the gravelly lateritic materials of the Bamendjou 1, Bamendjou 2, and Bangam sites can be used as sub-base (CEBTP 1984; Sikali and Mir-emarati 1986).

According to Sikali and Mir-emarati (1986) 1 m^2 of raw lateritic gravelly material corresponds to about 0.75 m^3 compacted in a pavement layer. Thus, 1,96,875 m^3 of lateritic gravel would construct 1 km of pavement.

Bamendjou 1 site

At Bamendjou 1, the proven reserve is 1,839,156 m^3 or a tonnage of 5,002,505 t for an area of 157,462 m^2. Thus, 1,839,156 m^3 can build approximately 934,174 m of the road in sub-base, either 934.174 km.

Bamendjou 2 site

The Bamendjou 1 site shows a proven reserve of 310,909 m^3 or a tonnage of 839,455 t for an area of 78,519 m^2. Therefore, 310,909 m^3 can build about 157,922 m of the road in the sub-base layer, either 157.922 km.

Bangam site

The proven reserve of the Bangam site is 947,724 m^3 or a tonnage of 2,663,105 t for an area of 78,519 m^2. Thus, 947,724 m^3 can build about 481,384 m of the road in the sub-base layer, either 481.384 km.

Discussion

The pedological wells and the interpretation of the vertical electrical soundings revealed relatively thick lateritic gravel levels (weathering set) (~ 35 m) compared to the organo-mineral horizon (pedoturbated set). This disproportion in thickness between the weathering and pedoturbated package is a typical feature of soils in hot and humid regions, such as ferralitic soils, where weathering is generally very intense (Chatelin 1974; Bitom 1988; Tardy 1993; Leumbe et al. 2005). The lateritic gravels on the

Table 5 Resistivity values, layer thicknesses, depth, and VES curve models of Bamendjou 2

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve layer	Type Litho-pédologique
VES1	5	1	2456.74	0	2.39	47.38	H	Lateritic gravel
		2	976.47	2.39	11.63			Lateritic gravel
		3	236.29	14.02	33.36			Lateritic gravel
		4	10.53	47.72	13.36			Aquifer
		5	286.06	61.08				Basalt
VES2	5	1	9463.23	0	2.62	19.76	QH	Lateritic gravel
		2	1467.22	2.62	0.027			Lateritic gravel
		3	1000.97	2.64	17.11			Lateritic gravel
		4	83.27	19.76	9.22			Lateritic clay
		5	990,612.88	28.98				Granito-gneissic basement
VES3	4	1	1580.74	0	0.592	12.36	K	Lateritic gravel
		2	34,742	0.592	0.205			Lateritic cuirass
		3	1257.91	0.798	11.56			Lateritic gravel
		4	0.17	12.36				Aquifer
VES4	4	1	6821.21	0	1.23	9.18	HKH	Lateritic gravel
		2	896.56	1.23	7.95			Lateritic gravel
		3	10,453.81	9.18	1.53			Fresh rock
		4	63.78	10.71	18.09			Lateritic clay
			685,515.25	28.79				Granito-gneissic basement

ρ (Ω.m) resistivity, *P (m)* depth, *E (m)* thickness, *E. Gravel (m)* the thickness of the lateritic gravel, *VES* Vertical Electrical Sounding

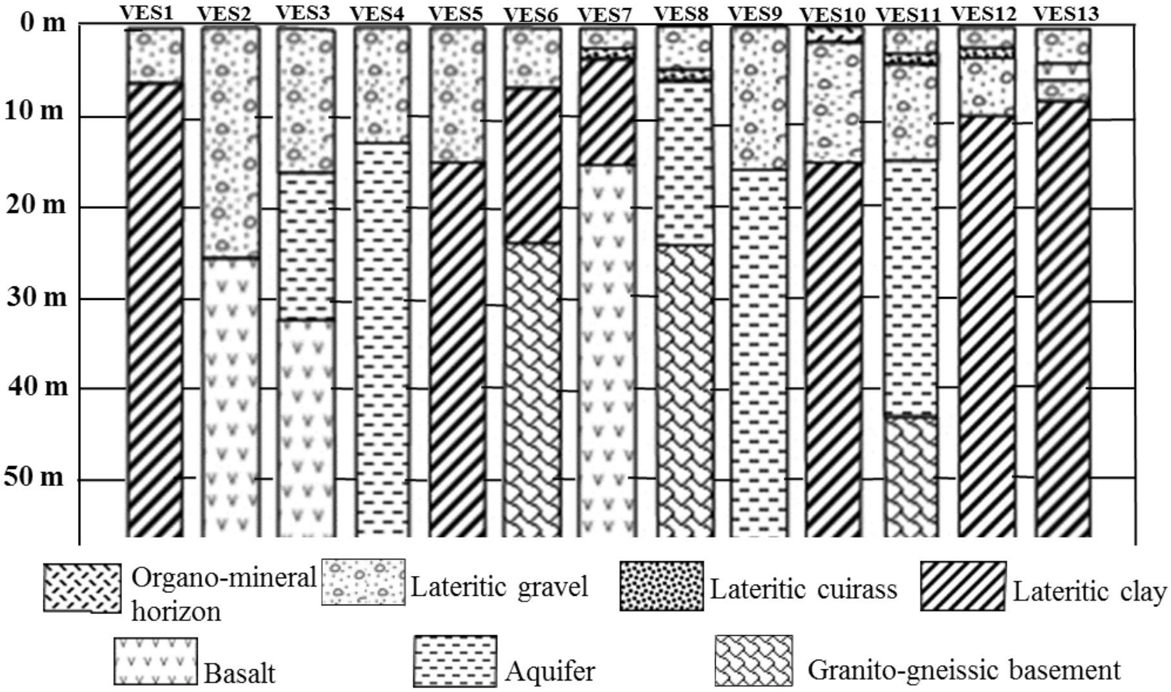


Fig. 17 1D lithology of the Bangam vertical electrical soundings

Table 6 Resistivity values, layer thicknesses, depth and Bangam VES curve models

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve type	Litho-pedological type
VES1	4	1	5306.82	0	3.07	7.47	HK	Lateritic gravel
		2	876.16	3.07	2.58			Lateritic gravel
		3	7883.63	5.65	1.82			Lateritic gravel
		4	123.98	7.47				Lateritic clay
VES2	4	1	1505.46	0	3.28	26.64	Q	Lateritic gravel
		2	827.95	3.28	9.22			Lateritic gravel
		3	208.41	12.51	14.13			Lateritic gravel
		4	51.23	26.64				Basalt
VES3	4	1	4309.47	0	3.90	17.17	QH	Lateritic gravel
		2	1137.63	3.90	13.27			Lateritic gravel
		3	7.60	17.17	13.94			Aquifer
		4	44.36	31.11				Basalt
VES4	4	1	2925.61	0	3.38	12.66	HK	Lateritic gravel
		2	452.15	3.38	2.81			Lateritic gravel
		3	1397.67	6.19	6.47			Lateritic gravel
		4	13.68	12.66				Aquifer
VES5	4	1	5188.30	0	4.63	15.95	Q	Lateritic gravel
		2	2141.37	4.63	0.182			Lateritic gravel
		3	1491.65	4.81	11.14			Lateritic gravel
		4	102.14	15.95				Lateritic clay
VES6	4	1	760.97	0	0.594	7.00	KH	Lateritic gravel
		2	2629.28	0.594	6.41			Lateritic gravel
		3	72.16	7.00	7.83			Lateritic clay
		4	348,847.75	14.83				Fresh rock
VES7	4	1	1885.69	0	1.49	1.49	KQ	Lateritic gravel
		2	155,593	1.49	0.063			Lateritic cuirass
		3	733.66	1.55	13.39			Lateritic clay
		4	29.56	14.95				Basalt
VES8	4	1	740.98	0	4.84	4.84	KH	Lateritic gravel
		2	24,457	4.84	0.375			Lateritic cuirass
		3	11.65	5.21	19.34			Aquifer
		4	44,222.16	24.55				Fresh rock
VES9	4	1	2086.53	0	0.814	16.07	Q	Lateritic gravel
		2	1498.44	0.814	2.09			Lateritic gravel
		3	790.41	2.91	13.16			Lateritic gravel
		4	4.46	16.07				Aquifer
VES10	4	1	6.76	0	0.009	14.75	K	Organo-mineral horizon
		2	6557.69	0.009	0.325			Lateritic gravel
		3	1591.08	0.335	14.42			Lateritic gravel
		4	25.81	14.76				Lateritic clay
VES11	5	1	2579.57	0	1.50	15.27	KH	Lateritic gravel
		2	41,632	1.50	0.311			Lateritic cuirass
		3	681.30	1.81	13.77			Lateritic gravel
		4	3.94	15.58	22.38			Aquifer
		5	8196.76	37.96				Fresh rock
VES12	4	1	1245.89	0	1.001	10.31	K	Lateritic gravel
		2	135,931	1.001	0.039			Lateritic cuirass
		3	1713.78	1.040	9.31			Lateritic gravel
		4	108.31	10.35				Lateritic clay

Table 6 (continued)

VES	Number of layers	N°	ρ (Ω.m)	P (m)	E (m)	E. Gravel (m)	Curve type	Litho-pedological type
VES13	4	1	5719.85	0	4.74	7.34	HK	Lateritic gravel
		2	1.10	4.74	0.005			Basalt
		3	7743.75	4.75	2.60			Lateritic gravel
		4	52.35	7.34				Lateritic clay

ρ (Ω.m) resistivity, *P (m)* depth, *E (m)* thickness, *E. Gravel (m)* the thickness of the lateritic gravel, *VES* vertical electrical sounding

northern flank of Mount Bangou are characterized by a multiplicity of electrical resistivity curve shapes (K, HK, Q, QH, KQ, HKH, H, and KH). The shape of the curves obtained is similar to those identified in the volcanic

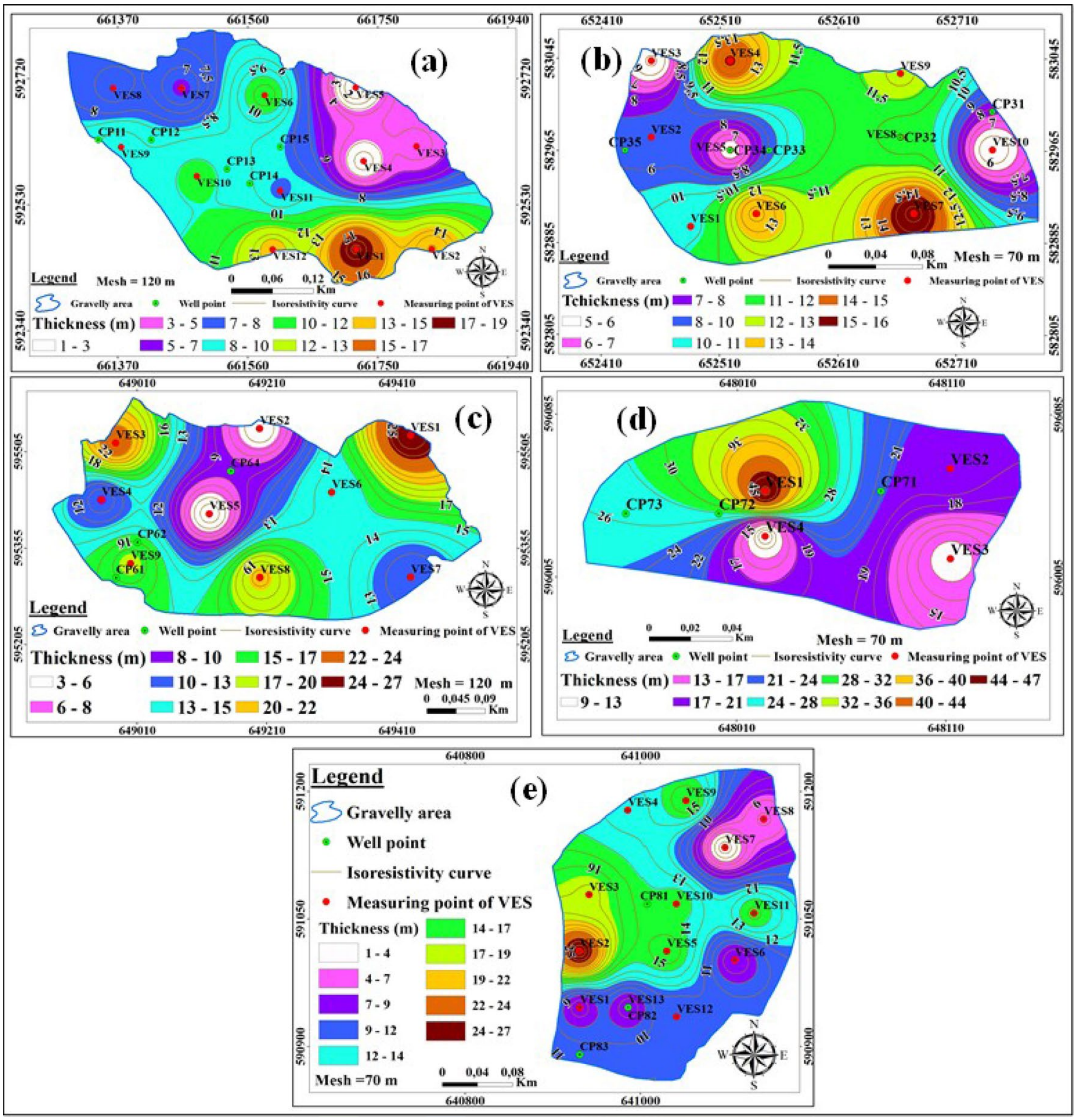


Fig. 18 Isopach maps of gravelly lateritic unit based on VES data base

Table 7 Gravelly tonnage from Sekakouo, Chenye, Bamendjou 1, Bamendjou 2 and Bangam sites

Site	γs (t/m^3)	E$_{geo}$ (m)	E$_{Pu}$ (m)	A (m^2)	V$_{geo}$ (m^3)	V$_{pui}$ (m^3)	T$_{geo}$ (t)	T$_{pu}$ (t)
SEK	2.73	8.88	1.23	143 509	1 274 360	176 516	3 479 003	481 889
CHE	2.6	10.32	1.45	51 786	534 432	75 090	1 389 522	195 233
BAM1	2.72	11.68	1.92	157 462	1 839 156	302 327	5 002 505	822 330
BAM2	2.7	19.28	3.285	16,126	310 909	52,974	839 455	143 030
BAN	2.81	12.07	2.01	78 519	947 724	157 823	2 663 105	443 483
Min	2.60	8.88	1.23	16,126	143 199	52 974	839 455	143 030
Moy	2.71	12.45	1.98	89,480	1 113 673	15 2946	2 674 718	417 193
Max	2.81	19.28	3.29	157,462	3 035 867	302 327	5 002 505	822 330
Sd	0.08	4.02	0.80	Nd	Nd	Nd	Nd	Nd

SEK Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou 1 site, *BAM2* Bamendjou 2 site, *BAN* Bangam site, *Min* Minimum, *Max* Maximum, *γs* specific weight, *Egeo* the average thickness of the lateritic gravel determined from geoelectrical soundings, *EPu* the average thickness of the lateritic gravel determined from wells, *A* surface, *Vgeo* volume from thicknesses of the lateritic gravel from vertical electrical soundings, *Vpui* volume calculated from thicknesses of the lateritic gravel from wells, *Tgeo* tonnage calculated from thicknesses of the lateritic gravel from vertical electrical soundings, *Tpu* tonnage calculated from thicknesses of the lateritic gravel from wells, *Sd* Standard deviation, *Nd* no data

zones of Cameroon by Ananfack Keleko et al (2013) and in the crystalline zones of Cameroon by Njueya Kopa et al (2016). This suggests that the shape of resistivity curves is influenced by topography, individual unit thickness, degree of weathering, and presence or absence of fractures (Njueya Kopa et al 2016) and most importantly, by the arrangement of soil constituents and their spatial arrangement rather than by the nature of the lithology.

The analysis of pedological wells coupled with the VES shows that the structural heterogeneity of the terrain is responsible for the diversity of curve patterns. This observation is coherent with the observations of many authors (Rey 2005; Buvat 2012; Tonang Zebaze et al. 2020). The electrical resistivities and thicknesses of the lateritic gravel level are highly variable from one point of the VES to another of the studied sites and would reflect also the structural heterogeneity of these materials. Tonang Zebaze et al (2020) also noted this structural heterogeneity in the Mbakaou soils of the Adamawa Plateau. This heterogeneity is attributed to variations in the nature and intensity of most processes involved in pedogenesis (Tabbagh et al. 2000; Hovhannissian et al. 2011). The resistivities of the studied gravels range from 130.00 to 9,161.10 Ω.m and conform with the abacuses of Palacky and West (1991) and Marescot (2006), and field observations. These resistivity values show that the gravels at the explored sites are more or less wetted by water. Analysis of the electrical resistivity curves coupled with the soil wells reveals information on both the variation in soil resistivity and the geometric characteristics of the different soil layers located between the surface and the depth of investigation. They are located at various depths. The thickness of the lateritic gravel level obtained from the geoelectrical soundings is the highest (8.88–12.45 m) compared to that obtained from the pedological wells (1.23 to 1.98 m). This shows the inadequacy of pedological wells in determining the thickness of lateritic gravels and this inadequacy would be related to the spatial heterogeneity, the great thickness of lateritic soils, as well as the presence of indurated or well-cemented intervals (Tardy 1997). The analysis of the isopach maps shows areas of low, medium, and high thickness. The zones of medium and high thickness constitute zones of high potential lateritic gravels.

Conclusion

The estimation and valorization of the lateritic gravels of the northern flank of Mount Bangou (west Cameroon) in road construction were carried out on five sites by an approach based on geophysical soundings coupled with data from pedological wells. The soil profiles of this area are of ABC type. The interpretation of 48 vertical electrical soundings coupled with 20 pedological wells made it possible to determine the thickness of the lateritic gravel level. They are characterized by the electrical resistivity curves of types K, HK, Q, QH, KQ, HKH, H, and KH. It was established from this study that electrical resistivity methods are appropriate for estimating the thickness of the lateritic gravel levels. The medium-thick and thicker zones are areas possessing high potential for the formation or development of lateritic gravel material. The proven reserves of lateritic gravels at the Chenye, Sekakouo, Bamendjou 1, Bamendjou 2, and Bangam sites are 3,479,003 t; 1,389,522 t; 5,002,505 t; 839,455 t and 2,663,105 t, respectively. The lateritic gravels of the Chenye, Sekakouo, Bamendjou 1, Bamendjou 2, and Bangam sites can build about 539,298 m; 226,167 m; 131,574 m; 778,314 m and 401,068 m of road, either as a form layer or a sub-base layer. However, the lateritic gravels of the Chenye and Sekakouo sites are not used as sub-base in roadway construction. It is recommended that these lateritic gravels be mined from the thicker areas to best supply the feedstock for road construction in the western part of Cameroon.

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Declarations

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