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Influence of Physical Properties on the Mechanical Behavior of Foundation Soils: Case of Soils from Fokoué-Centre

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Abstract

Soil investigation prior to construction is a crucial step to ensure the stability and durability of foundations. This study aims to analyze the influence of physical properties on the mechanical behavior of foundation-bearing soils in the Fokoué-Centre area, Western Cameroon. To achieve this objective, soil samples were collected at depths between 50 and 80 cm, followed by dynamic penetrometer testing up to approximately 640 cm to determine dynamic resistance. A Principal Component Analysis (PCA) was then conducted to explore the various physico-mechanical parameters obtained, including ω, ρs, % fines, ωL, ωP, IP, n, and σall. The GTR classification system categorizes the studied soils into three subgroups: i) A3 – low-density clayey-silty soils with high moisture content and abundant fine fraction; ii) A2 – silty-sandy fine soils with moderate water and fine content; and iii) B6 – denser silty gravelly soils with low water and fine content. Mechanically, the soils present allowable bearing pressures ranging from 0.12 to 1.07 bars in clayey soils, 0.77 to 2.3 bars in fine sandy soils, 2.5 to 5.2 bars in lateritic gravelly soils, and over 5.84 bars in cuirass layers. Correlation analysis reveals a significant influence of water content (ω), specific gravity (ρs), fine fraction percentage (% fines), and porosity (n) on the allowable bearing pressure (σall), whereas consistency parameters such as ωL, ωP, and IP appear to have minimal effect. This finding indicates that the mechanical behavior alone should not be the sole criterion for ensuring the stability and durability of structures, particularly those built on Fokoué soils.

Keywords

Physical Properties, Mechanical Behavior, Foundation Soils, Fokoué

1. Introduction

Foundation systems are essential structures that transfer loads from buildings and infrastructures to the underlying soil and subsoil layers. Understanding the characteristics of bearing soils, including their composition, texture, and mechanical behavior, is critical to ensuring the stability and durability of foundation systems (Manefouet, 2016; Demanou Messe, 2022). Moreover, poor foundations often cause more concern than any other structural deficiency. It is generally just as easy to build a good foundation as it is a bad one, hence the necessity of knowing the properties of the soil on which a structure is built (Jacquard & Boutet, 2016). In this context, it is essential to understand the influence of physical properties on the mechanical behavior of soils—such as strength or bearing capacity—to guarantee the stability of foundations (Peter, 2006; Chetti, 2021).

However, soils are complex and heterogeneous materials, and their mechanical behavior can be influenced by numerous factors, including organic matter content, groundwater level and its temporal variation, sensitivity to hydric changes (e.g., permeability and porosity, moisture content, Atterberg limits or methylene blue value, possible mineralogical analysis), as well as the configuration of the foundation type (Jusoh & Osman, 2017). Difficulties in characterizing the physical properties of soils and predicting their mechanical behavior can lead to design and construction errors, which may compromise the stability and longevity of engineering structures.

Numerous studies have addressed the relationships between soil characteristics, particularly between physical and electrical properties (Cosenza et al., 2006; Charlery et al., 2006; Jusoh & Osman, 2017), mechanical and electrical properties (Demanou Messe, 2022; Demanou Messe et al., 2022; Nouwa Ngouateu et al., 2024), and mineralogical and/or geochemical and geotechnical properties (Zagalo et al., 2017). However, the influence of physical properties on mechanical behavior remains insufficiently addressed. Zagalo et al. (2017) established correlations between geotechnical soil properties but in different geological contexts.

Within this framework, accounting for the impact of physical characteristics during soil investigation is essential to improving the design and construction of civil engineering works. The aim of this study is to identify the most influential physical properties affecting the mechanical behavior of soils in general—and specifically in the Fokoué region—in order to develop more accurate characterization and predictive methodologies.

2. Natural Setting of the Study Area

The study area, located in the Fokoué subdivision (Western Cameroon) (**Figure 1**), is characterized by varied geomorphology, including mountains and hills that dominate the landscape, with altitudes reaching up to 1800 meters. The regional geology consists of volcanic rocks overlying a granito-gneissic basement (Kwekam, 2005; Njanko et al., 2010; Fozing et al., 2019; Delor et al., 2021), which has been shaped by tectonic and erosional processes over millions of years.

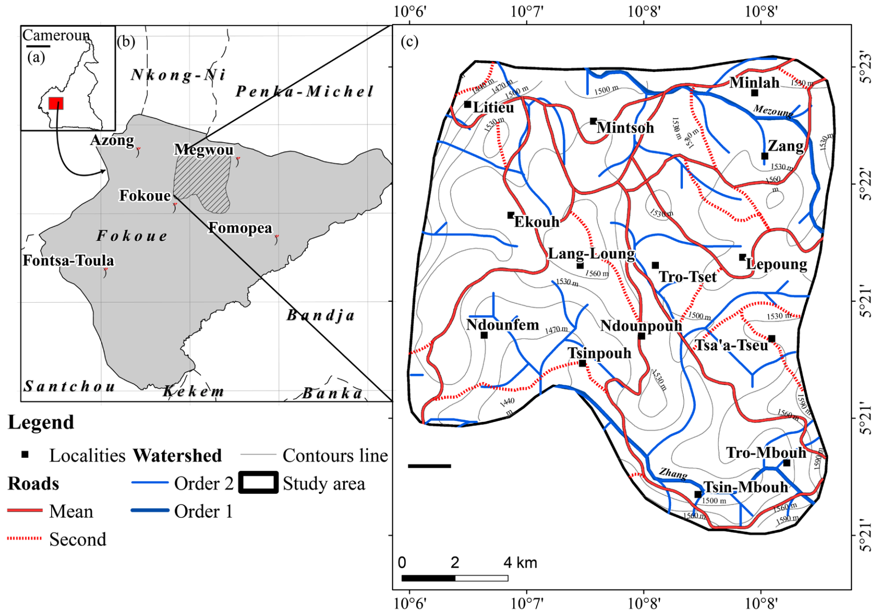

Figure 1. Geographic location: (a) Cameroon, (b) Fokoué District, (c) Study area.

The climate in the study area is tropical, with high temperatures (average of 20.4˚C) and abundant rainfall (1782.3 mm/year) (IRAD de Dschang, 2005-2016). The hydrographic network is marked by several watercourses, including the Zhang and Mezoung rivers, which traverse the study zone.

The soils found in the Fokoué subdivision, and more specifically in the area under study, are derived from various parent rocks. These soils are predominantly ferralitic and ferruginous resulting from prolonged weathering and evolution of the alteration products of these rocks.

3. Methodology of the Study

3.1. Geotechnical Testing

A field campaign was essential for material identification using the Maignien (1980) method. Three main soil types were identified: lateritic gravelly soils, fine sandy soils with varying clay content, and fine clayey soils.

Regardless of the intended use of the soil, it is crucial to understand its nature, composition, and particle size distribution (Manefouet, 2016; Boutahir, 2018). A total of thirty disturbed soil samples were collected using manual auger drilling (targeted sampling strategy—STM) and transported to the laboratory for physical characterization.

The natural water content of the studied soils was determined using the successive weighing method before and after drying at 105˚C, in accordance with standard NF P 94-050 (1995). The specific gravity of the soil grains was determined using a pycnometer, following standard NF P 94–054 (1991). The consistency of the soils was assessed based on the Atterberg limits. The liquid limit (ωL) was determined using the Casagrande apparatus, and the plastic limit (ωP) was obtained using the rolling method. These Atterberg limits were measured following standard NF P 94-051 (1993), and the plasticity index (IP) was calculated as the difference between ωL and ωP. Particle size distribution was performed by dry sieving after washing, according to the procedures of standard NF P 94-056 (1996). The void ratio and porosity were calculated using established relationships among the various physical characteristics of the soils.

3.2. *In Situ* Geotechnical Testing

In this study, a light dynamic penetrometer with constant energy was used as the geotechnical investigation tool, in compliance with EN ISO 22476-2 (2005). The light dynamic penetrometer test is a soil investigation method that evaluates the terrain and provides a characteristic soil parameter (Afnor, 1990). This test allows a qualitative assessment of the resistance of the traversed layers.

The dynamic resistance to failure Qd (kg/cm^2) at the penetrometer tip is expressed using the Dutch formula:

$$Qd = \frac{M^2 \times H \times g}{A \times e} \times \frac{1}{M + M'} \tag{1}$$

$$e = h/N \tag{2}$$

where:

Qd : tip resistance (MPa or kg/cm^2);

M: hammer mass (kg);

H: drop height of the hammer (m);

g: gravitational acceleration (m/s^2);

M': mass of the struck components (kg);

A: cross-sectional area of the tip (m^2);

e: penetration per blow (m);

N: number of blows;

h: total penetration depth (m).

The allowable stress σ all of the foundation soils under the Service ability Limit State (SLS) was specifically assessed using the following formula (Sanglerat, 1965):

$$\sigma_{adm} = \frac{Q_d}{s} \tag{3}$$

where *s* is the safety factor.

The safety factor used to derive allowable stress from dynamic resistance is 20, which incorporates a global safety factor of 3 and a reduction coefficient of 6.6 (Zagalo et al., 2017).

3.3. Principal Component Analysis (PCA)

The geotechnical parameters measured both *in situ* and in the laboratory display substantial variability, which can lead to uncertainties in selecting representative values and in the accuracy of final geotechnical calculations (Saporta & Niang, 2003). This approach relies on examining the relationships between the measured parameters in order to highlight the influence of physical properties on the dynamic resistance of soils—a critical factor in structural design.

PCA graphically displays the differences and/or similarities among samples subjected to selected analytical conditions (Cordella, 2010; Annad & Lefkir, 2022). Samples with similar characteristics cluster together to form more or less distinct aggregates. In this work, the XLSTAT 2018 software was used to generate graphical representations and data matrices.

4. Results and Discussion

The results of the physical and mechanical analyses (**Table 1**) show variations in parameters from one soil sample to another.

Table 1. Summary of the geotechnical characteristics of the studied soils.

	Physical properties								GTR Classification	Mechanical parameter
Samples	Water content (%)	ρs (g/cm³)	Percentage of fines (% fines)	ωL (%)	ωP (%)	IP (%)	Void ratio (e)	Porosity (n)	Subclasses	Allowable stress σadm (bar)
ES01	24.02	2.76	55.03	73.08	50.75	22.05	0.66	40	A2	0.89
ES02	46.77	2.62	82.35	53.4	38.18	15.18	1.23	55	A2	0.2
ES03	13.61	3.15	23.33	58	32.051	25.94	0.43	30	B6	1.57
ES04	27.21	2.71	66.4	56	36.39	19.6	0.74	42	A2	0.77
ES05	43.56	2.53	80.25	63	32.56	30.437	1.10	52	A3	0.25
ES06	25.79	2.76	51.1	75.25	55.71	20.59	0.71	42	A2	0.63
ES07	46.96	2.57	85.42	63.2	31.19	32.01	1.21	55	A3	0.31
ES08	14.65	3.28	5.54	62.6	40.06	22.5	0.48	32	B6	2.45
ES09	23.19	2.79	59.4	64	44.573	19.43	0.65	39	A2	0.47
ES10	45.06	2.67	88.79	75.9	43.67	32.23	1.20	55	A3	0.3
ES11	14.58	2.85	10.4	44.4	26.11	18.29	0.42	29	B6	1.25
ES12	22.81	2.74	41.08	71.4	47.22	24.18	0.63	38	A2	0.79
ES13	21.56	2.88	58.57	62	39.1	22.89	0.62	38	A2	1.14
ES14	25.58	2.73	51.76	61.2	45.8	15.39	0.70	41	A2	0.46
ES15	21.72	2.73	69.15	64.04	43.4	20.65	0.59	37	A2	0.75
ES16	26.88	2.68	51	85.8	49.7	36.13	0.72	42	A2	0.63
ES17	14.58	2.85	3.51	55	37.71	17.31	0.42	29	B6	1.51
ES18	31.38	3.03	17.32	55	39	16.39	0.95	49	B6	1.32
ES19	30.3	3.21	18.93	48.4	41.7	12.17	0.97	49	B6	0.63
ES20	12.32	3.12	7.32	53.8	43.5	10.27	0.38	28	B6	3.37
ES21	28.05	3.07	10.3	53.8	40	13.06	0.86	46	B6	1.1
ES22	48.8	2.71	90.5	61.52	34.4	27.12	1.32	57	A3	0.44

Continued

ES23	15.74	2.99	9.01	61.2	41.6	19.62	0.47	32	B6	4.11
ES24	37.37	2.55	87.74	68.85	40.2	28.6	0.95	49	A3	0.36
ES25	45.7	2.61	95.8	66.1	40.1	26.02	1.19	54	A3	0.34
ES26	36.35	2.85	82.1	65	38.3	26.7	1.04	51	A3	0.78
ES27	53.13	2.55	95.05	76.6	49.9	26.6	1.36	58	A3	0.15
ES28	30.76	2.96	75.15	74.3	47.6	26.7	0.91	48	A3	0.92
ES29	37.76	2.85	7.5	64.4	41.1	23.35	1.08	52	B6	1.13
ES30	24.3	2.74	64.2	53.2	37.2	16	0.67	40	A2	1.23

Descriptive statistics

Variables	Observations	Minimum	Maximum	Mean	Standard deviation
water content (%)	30	12.32	53.13	29.68	11.93
ρ_s (g/cm^3)	30	2.53	3.280	2.82	0.20
(% fines)	30	3.51	95.800	51.47	32.14
ωL (%)	30	44.40	85.800	63.02	9.29
ωP (%)	30	26.11	55.710	40.96	6.41
IP (%)	30	10.27	36.13	22.25	6.37
e	30	0.38	1.36	0.82	0.3
n	30	28	58	44	0.09
σ_{all} (bar)	30	0.15	4.11	1.01	0.90

4.1. Physico-Mechanical Characterization of Soils

4.1.1. Physical Parameters

Overall, the physical parameters studied across the various soil types show considerable variability. According to the GTR (2000) classification system, the soils are subdivided into three subcategories: fine clayey soils (A3), silty-sandy fine soils (A2), and clayey or silty lateritic gravel soils (B6).

The natural water content ranges between 12.61% (on gravels materials) and 53.13% (on fines materials), with an average of 29.92%. The standard deviation and the coefficient of variation are 8.7 and 0.29, respectively. This variation in the water content of the samples can be explained by the role of the fine fraction in retaining water in the soil, and by the influence of the environment. Indeed, materials with low water content are proportionally coarser in grain size. An average value for natural water content in fine clayey soils is lower than the 48% reported by Ananfouet Djeufack (2012) in fine basaltic soils of Dschang and the 59.95% observed in the fine soils of Mouraye, Chad by Zagalo et al. (2017). However, it is comparable to the values obtained by Ngapgue et al. (2008) in the fine soils of Bafoussam. The low water content (14.25%) is observed on some gravelly materials (ES03, ES08, ES11, ES17, ES20 and ES23) and for others, it is higher, at 31.87%

(ES18, ES19, ES21 and ES29). The value of 14.25% is close to the 12.50% obtained by Aboubakar et al. (2025) on gravelly soils in Ngaoundal. These observations show that climatic and morphological conditions could also explain these variations in water content, with average annual precipitation of 1782.3 mm/year and altitudes of up to 1800 m.

The specific gravity ρs of the materials ranges from 2.53 to 3.21 g/cm^3, with an average value of 2.81 g/cm^3. The data dispersion appears low, with a coefficient of variation of 0.06. The specific gravity values (2.53 - 3.21 g/cm^3) indicate that these materials have good to excellent performance in road construction (Nwaiwu et al., 2006; Paige-Green et al., 2015), except for the samples (ES02, ES05, ES07 and ES10) with values <2.60 g/cm^3. This average value is close to those obtained by Onana et al. (2017) (2.69 and 2.81g/cm^3) and Nzabakurikiza et al. (2016) (average ρs = 2.81 g/cm^3) on gravelly materials. The high specific weight values would be linked to the pre-presence of ferromagnesian minerals and silica as observed by Manefouet (2016) on soils in the area. This observation confirms the findings of Nzabakurikiza et al. (2016), who believe that a high specific gravity ρs value is due to the presence of iron. Since void ratio is directly related to the porosity, any increase in one will lead to an increase in the other. Consequently, the porosity of these soils varies from 28 to 58, with an average of 44, indicating that these soils are moderately porous overall. The standard deviation and the coefficient of variation are 0.08 and 0.18, respectively. The void ratio value is significantly lower (0.82) than the 1.38 reported by Zagalo et al. (2017), and the values ranging from 7 to 14 observed by Rutledge (1944), which represent extreme cases of materials with very high void ratios. These findings suggest that the soils analyzed in this study may exhibit relatively low compressibility.

With respect to particle size distribution, gravels, sands, and particles smaller than 0.08 mm (silts and clays) are present in the samples (**Figure 2(a)**). Gravel content varies between 0% and 72.94%, with an average of 24.06%; sand content ranges from 1.73% to 44.46% (mean: 21.62%); and fine particles range from 3.51% to 98.5%, with an average of 52.28%. The high proportion of coarse elements in the materials studied testifies to their extensive lateritization, with the presence of cuirasses in places. This percentage-age is close to the 74% obtained by Manefouet (2016) on gravelly soils developed on basalt, indicating that these soils were formed under the same geo-morphological conditions as those studied.

The Atterberg limits reveal liquid limit values (ωL) ranging from 44.4% to 85.8% (mean: 63.01%), plastic limit values (ωP) from 26.11% to 55.71% (mean: 40.96%), and plasticity index values (IP) ranging from 10.27% to 36.13%, with an average of 22.25%. The plotting of IP and ωL values on the Casagrande plasticity chart (1948) indicates that the analyzed soil samples consist mainly of plastic to highly plastic silts, with the exception of samples ES11 (low plasticity clay) and ES19 (low plasticity silt) (**Figure 2(b)**). The studied materials are clayey and highly plastic materials according to Casagrande plasticity chart. This high degree of plasticity and clayiness is due to the high kaolinite content.

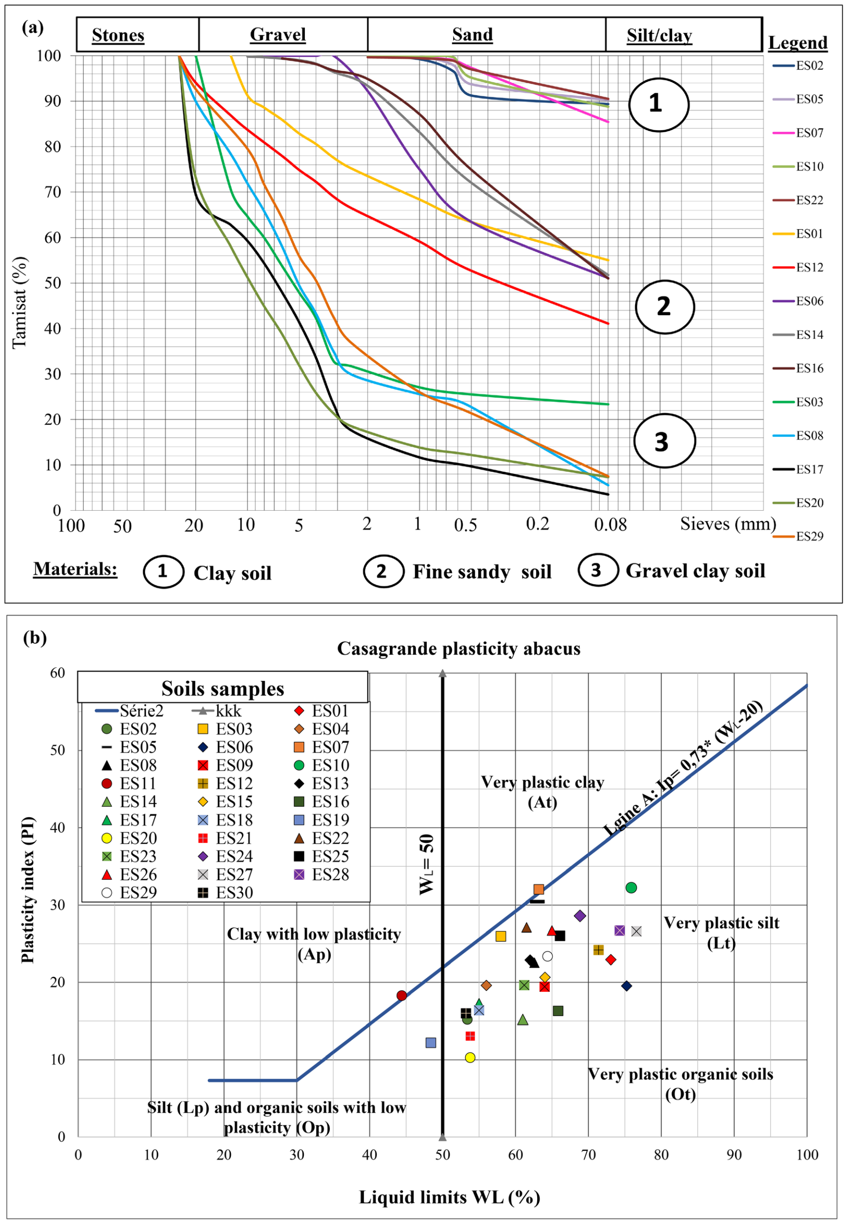

Figure 2. Graphical representation of data: (a) Particle size distribution curves; (b) Casagrande plasticity chart (1948).

4.1.2. Mechanical Properties of Soils: Allowable Stress

A total of ninety (90) dynamic penetrometer test points were carried out at varying depths, reaching up to 6.40 meters. The resulting penetrometer logs (Figure 3) show the relatively contrasting mechanical behavior of the subsurface layers. Analysis of the penetrograms indicates that in fine soils, dynamic resistance values fluctuate between 0.2 and 1.5 MPa (Figures 3(a)-(c)); in fine sandy soils, they range from 0.2 to over 3 MPa (Figures 3(d)-(f)); and in lateritic gravelly soils, values are higher, ranging from 1 MPa to more than 11 MPa (Figure 3(g) and Figure 3(h)), and even higher in ferricrete horizons, where refusal was observed (Figure 3(i)).

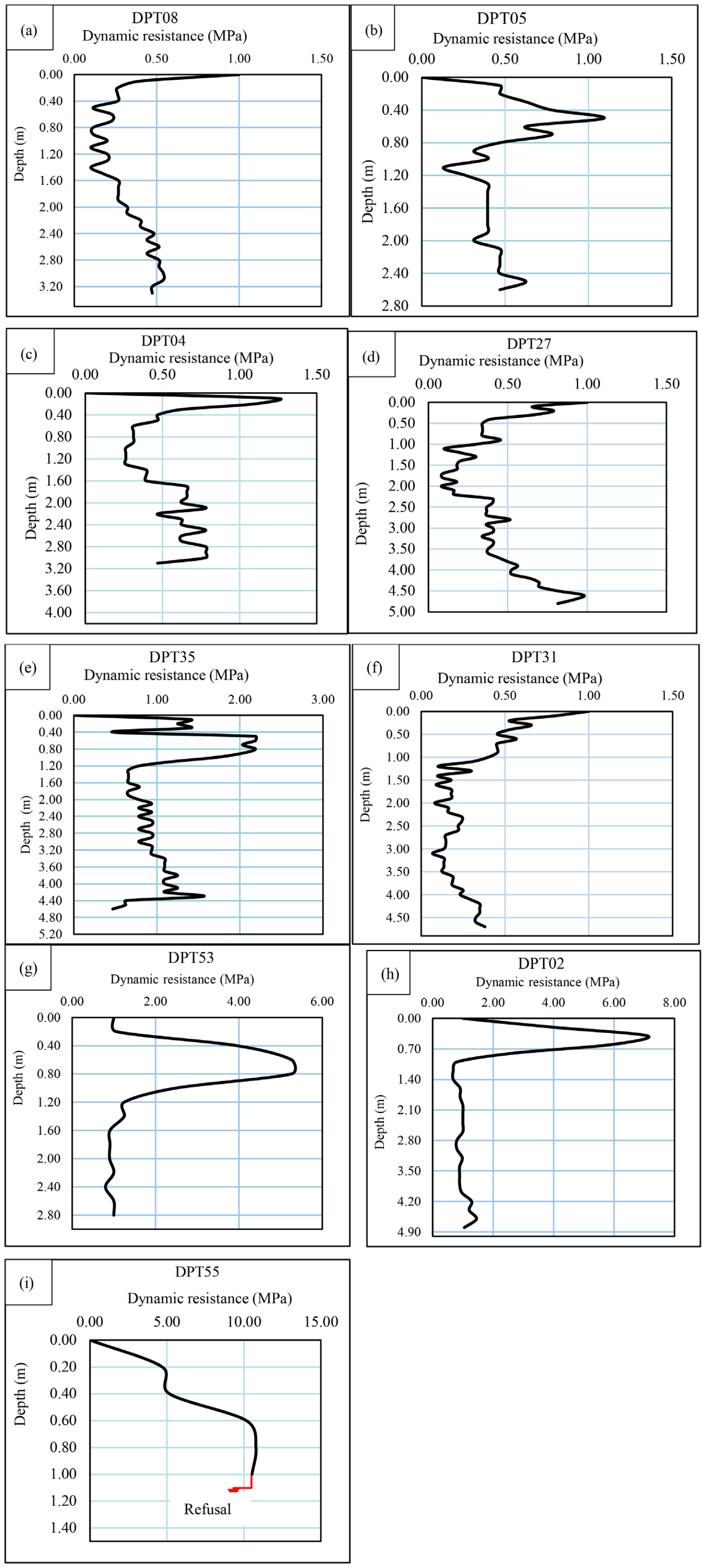

Figure 3. Sample penetrograms: (a)-(c) Clayey soils; (d)-(f) Silty-sandy fine soils; (g)-(i) Lateritic gravelly soils.

The lithological profile (Table 2), reveals a sequence of 3 to 5 distinct layers with various thinknesses. Overall, the allowable bearing pressures (σ_{all}) across the different soil layers range from 0.12 bar to more than 5.84 bars, depending on depth. In clayey soils, allowable pressures vary between 0.12 and 1.07 bars. These values increase to between 0.77 and 2.3 bars in silty-sandy fine soils, and from 2.5 to 5.2 bars in lateritic gravelly soils, exceeding 5.84 bars in cuirass horizons. This increase in allowable bearing pressure may be attributed to several factors, including grain size distribution, soil compaction, and porosity (Dysli & Bobelli, 2001; Martin, 2008). These findings on resistance differences based on granulometry are consistent with those reported by Demanou Messe et al. (2022) for similar lateritic soil types.

Table 2. Lithological profile from selected penetrometer test points.

DPT	Layers	Depth (m)	Qd (MPa)	σall (bar)	Nature
		Clays soil			
DPT04	1	0 - 0.5	0.78	0.39	Top soil
	2	0.5 - 1.7	0.37	0.18	Silty clay
	3	1.7 - 3.10	0.33	0.17	Silty clay
DPT05	1	0 - 0.4	0.52	0.26	Top soil
	2	0.4 - 1.1	0.64	0.32	Silty clay
	3	1.1 - 2	0.35	0.18	Clay
	4	2 - 2.6	0.47	0.24	Silty clay
DPT08	1	0 - 0.4	0.35	0.18	Top soil
	2	0.4 - 1.6	0.22	0.11	Silty clay
	3	1.6 - 2.5	0.68	0.34	Clay
	4	2.5 - 3.3	1.11	0.56	Weathered rock
		Fines sand soil			
DPT27	1	0 - 0.3	0.83	0.42	Top soil
	2	0.3 - 1	0.48	0.24	Silty sand
	3	1 - 2.4	0.28	0.14	Sandy clay
	4	2.4 - 3.7	0.89	0.45	Silty sand
	5	3.7 - 4.8	1.92	0.96	Silty sand
DPT32	1	0 - 0.4	1.41	0.71	Top soil
	2	0.4 - 2	0.53	0.27	Sandy clay
	3	2 - 2.9	0.86	0.43	Silty sand
	4	2.9 - 4.3	1.24	0.62	Silty sand
	5	4.3 - 4.8	0.6	0.3	Silty sand
DPT31	1	0 - 0.3	0.78	0.39	Top soil
	2	0.3 - 1	0.63	0.32	Silty sand
	3	1 - 2.1	0.32	0.18	Sandy clay
	4	2.1 - 3.5	0.24	0.12	Sandy clay
		3.5 - 4.8	0.77	0.38	Silty sand

Continued

			Lateritic gravel soil		
	1	0 - 0.35	2.97	1.48	Top soil
DPT02	2	0.35 - 1.1	5.13	2.57	Silty gravel
	3	1.1 - 2.8	1.15	0.57	Silty sand
	1	0 - 0.3	4.69	2.34	Top soil
DPT03	2	0.3 - 0.8	6.2	3.1	Silty gravel
	3	0.8 - 4.8	1.08	0.58	Silty sand
	1	0 - 0.4	4.92	2.46	Top soil
DPT55	2	0.4 - 0.8	10.49	5.24	Silty gravel
	3	> 0.8	>10.49	>5.24	Lateritic crusts

4.2. Principal Component Analysis (PCA) between Geophysical and Physico-Mechanical Parameters

The eigenvalue table for the extracted factors reveals two dominant factors among the nine identified. The factors selected must together account for at least 75% of the total variance. Factor 1 (F1) accounts for 57.87% and Factor 2 (F2) contributes 18.97% (**Table 3**), which justifies the retention of these two principal axes for analysis, as they represent more than half of the total explained variance. The remaining seven factors are considered residual.

The contribution of the variables to each factor helps identify which parameters characterize each component. It is observed that water content (ω), fine fraction (%fines), porosity (n), and void ratio (e) contribute positively and predominantly to Factor 1 (**Table 4**). On the other hand, allowable stress (σall) and specific gravity (ρ_s) contribute most significantly—but inversely—to Factor 1. This indicates that Factor 1 is characterized by parameters related to the soil's hydric state. The liquid limit (ωL), plastic limit (ωP), and plasticity index (IP) are weakly correlated with Factor 1, but contribute predominantly to Factor 2—with more than 80% influence—compared to other parameters (which are under 30%).

Table 3. Eigenvalues of the extracted factors.

	F1	F2	F3	F4	F5	F6	F7	F8	F9
Eigenvalue	**5.208**	**1.707**	0.891	0.654	0.327	0.196	0.013	0.004	0.001
Variability (%)	**57.867**	**18.967**	9.898	7.261	3.630	2.174	0.148	0.046	0.007
% cumulative	57.867	76.834	86.733	93.994	97.624	99.798	99.947	99.993	100.000

Table 4. Variable contributions to each principal component.

	F1	F2	F3	F4	F5	F6	F7	F8	F9
ω (%)	**0.926**	−0.271	0.169	0.149	0.099	−0.059	−0.066	0.001	−0.015
ρs	**−0.784**	−0.060	0.290	0.421	−0.246	0.243	−0.015	0.003	−0.002
% fines	**0.877**	0.025	−0.156	−0.217	0.163	0.362	0.001	0.000	0.000

Continued

ωL	0.547	**0.819**	−0.036	0.159	−0.021	−0.023	−0.004	0.046	0.001
ωP	0.127	**0.811**	0.553	−0.139	0.032	−0.001	−0.003	−0.031	−0.001
IP	0.654	0.350	−0.539	0.379	−0.116	−0.016	0.004	−0.032	0.000
e	**0.885**	−0.308	0.264	0.221	0.039	−0.028	−0.026	−0.002	0.020
n	**0.893**	−0.270	0.294	0.184	−0.011	−0.018	0.089	0.003	−0.006
σ_{all} (bar)	**−0.800**	0.105	−0.018	0.368	0.461	0.011	0.011	−0.002	0.000

The combined analysis of physical parameters and allowable stress (**Table 5**) shows strong correlations (R > 0.6) between σ_{all} and variables such as water content (r = −0.67), specific gravity (r = 0.66), porosity (r = −0.68), fine fraction percentage (r = −0.70), and void ratio e (r = −0.65). These results are consistent with the findings of Zagalo et al. (2022). However, weak correlations (R < 0.4) are found with Atterberg limits (ωL, ωP) and IP with r equal −0.30, −0.06 and −0.39 respectively, suggesting that plasticity has minimal and negative influence on the mechanical behavior of these soils. These observations on the weak influence of Atterberg parameters on dynamic strength are similar to those made by Zagalo et al. (2022) on Mouraye soils (ωL= 0.08, ωP = 0.13 and IP = 0.03). However, a material with a high Ip may be subject to significant volumetric variations linked to its clayey nature (Nadir, 2024). Consistency parameters are therefore essentially linked to the mineralogical composition, granularity, clay content, humidity and cohesion of the material. The materials studied are essentially plastic silty according to Casagrande's (1948) abacus, which could explain the weak relationship observed between clay-related consistency and dynamic strength. The variable correlation circle (**Figure 4(a)**) highlights their significance: Group 1 (σ_{all} and ρs) lies opposite Group 2 (water content, fine fraction, and porosity). The relationships between these parameters and Factors F1 and F2 indicate that F1 likely represents the "material nature" of the soils, while F2 reflects "consistency".

Table 5. Correlation matrix of measured variables.

Variables	ω (%)	ρs	% fines	ωL	ωP	IP	e	n	σall (bar)
ω (%)	1.00								
ρs	**−0.64**	1.00							
% fines	**0.74**	**−0.78**	1.00						
ωL	0.30	−0.42	0.46	1.00					
ωP	−0.03	−0.05	0.08	**0.69**	1.00				
IP	0.47	−0.51	0.56	**0.73**	0.01	1.00			
e	**0.99**	−0.52	**0.68**	0.26	−0.02	0.41	1.00		
n	**0.97**	−0.52	**0.68**	0.29	0.03	0.40	**0.99**	1.00	
σ_{all} (bar)	**−0.67**	**0.66**	**−0.70**	−0.30	−0.06	−0.39	**−0.65**	**−0.68**	1.00

Once the factors are identified, their meaning is clarified by projecting the variables and individual samples onto the factorial axes and analyzing their distribution (**Figure 4(b)**). The sample projection reveals three distinct groups. Lot 1 mainly consists of gravelly soils, particularly highly plastic silty gravels (ES3, ES8, ES11, ES17, ES18, ES19, ES20, ES21, ES23, ES29); Lot 2 includes silty fine sands (ES01, ES04, ES06, ES09, ES12, ES13, ES14, ES15, ES16, ES30); and Lot 3 consists of highly plastic silty clays (ES02, ES05, ES07, ES10, ES22, ES24, ES25, ES26, ES27, ES28).

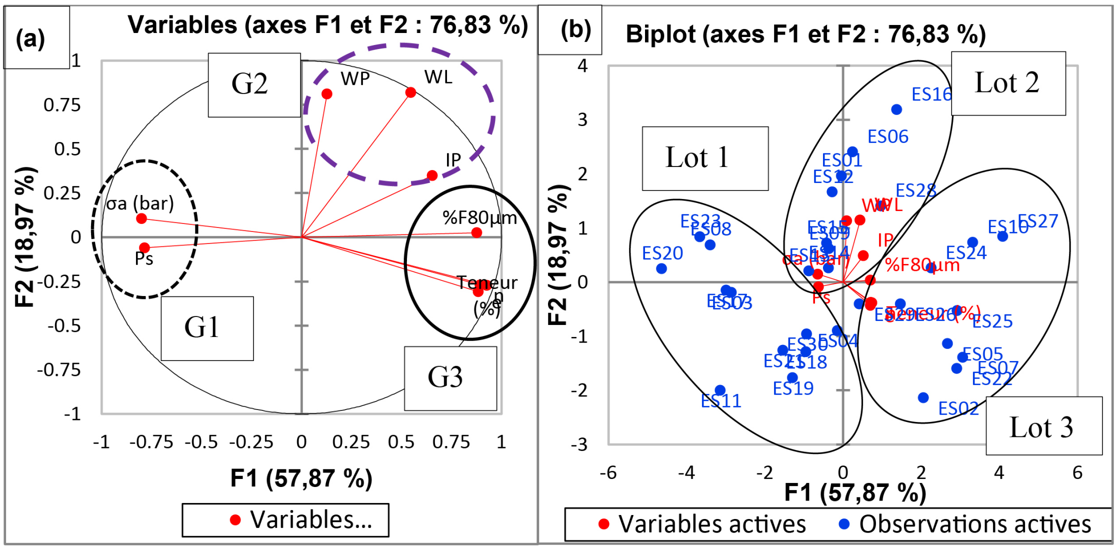

Figure 4. Principal component analysis: (a) Variable correlation circle; (b) Graphical representation of soil samples and studied parameters.

The mechanical behavior of the soils appears particularly sensitive to variations in physical properties, especially water content and fine particle percentage. A classification of the soils based on strength is established using the Robertson (1990) soil classification chart, which is based on cone tip resistance (kg/cm^2) as a function of sleeve friction (Jacquard & Boutet, 2016).

The modification of this chart into a diagram plotting dynamic resistance against fine fraction percentage (**Figure 5**), which influences rod penetration, reveals a distribution of sample points. The diagram produces a soil classification based on these parameters (dynamic resistance Qd – %Fines/Qd ratio). A decreasing trend in dynamic resistance illustrates the transition of materials from sands and gravelly clays to silts and clay-rich soils. This confirms the influence of physical parameters such as fine particle content on the dynamic resistance of soils. An increase in fine content—particularly clays with high water absorption capacity—leads to a decrease in the material's dynamic resistance. This observation is in line with that made by Jurado Sastre et al. (2018) on the considerable influence of the proportion of fine fraction on dynamic resistance. Indeed, the high dynamic resistances observed progressively decrease from lateritic gravels to clays.

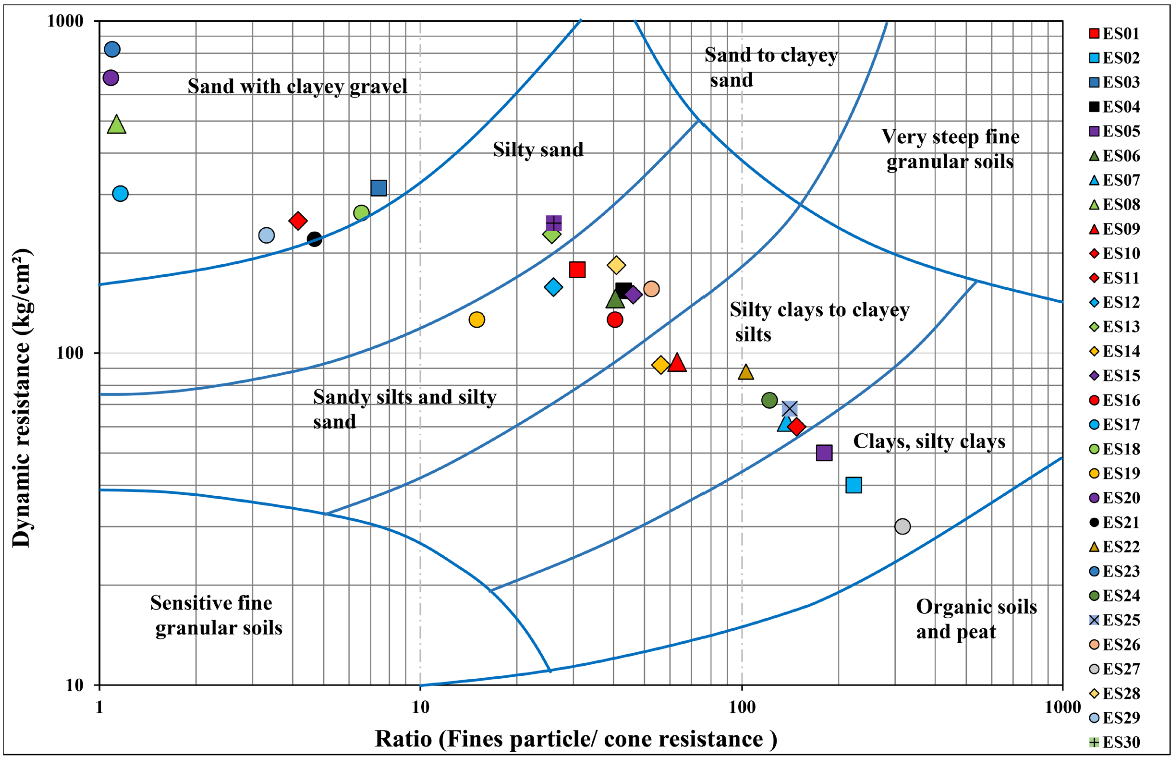

Figure 5. Modified soil classification diagram based on Robertson (1990).

4.3. Implications of Physical Property Influence in Engineering Design

Neglecting the physical properties of soils in engineering design can lead to numerous consequences. Parameters such as water content, particle size distribution, and porosity may be key factors in the degradation of structures, as reported by Jusoh & Osman (2017). Settlement and landslides are examples of structural pathologies directly linked to soil characteristics and their physical properties. In addition, a reduction in the water content of a material considerably improves its mechanical properties, such as dynamic strength and dry density (Dysli & Bombeli, 2001). The mechanical strength of a material depends essentially on its solid matrix, which is a function of its granularity. From these analyses, it emerges that soils with a high-water content, a considerable proportion of particles, high porosity and high plasticity have poor mechanical strength and could be prone to excessive settlement.

Furthermore, a lack of understanding of subsurface property variability can result in short- and medium-term additional costs during project implementation. These may arise due to unforeseen hazards or structural damage stemming from inadequate adaptation of engineering designs to subsurface constraints (Guerrero, 2014; Sivelle, 2016).

5. Conclusion

The choice of foundation type for structures is determined by the soil's ability to bear the load imposed on it. Therefore, it is crucial to understand the mechanical behavior of the soil, which is an essential aspect for the design of foundations, more or less linked to surrounding physical conditions. The objective of this study was to characterize the dependence of the soil's physical properties on its mechanical behavior for the soils of Fokoué. The physico-mechanical tests highlighted the heterogeneity and complexity of the soil through the significant variations observed in the collected data.

Principal component analysis (PCA) and descriptive statistical analysis were performed between the various physical parameters determined in the laboratory and the *in situ* mechanical data. The analysis shows a strong influence of the physical properties on the mechanical behavior, with this influence described as a direct correlation for all the soil classes considered in this study. Water content, specific weight, granularity, and porosity are the parameters that most significantly affect the behavior, in contrast to consistency parameters, which have less of an impact on mechanical behavior. A more in-depth study of these consistency parameters could provide a better understanding of their impact on the foundation-bearing soils.

Declaration of Interest Statement

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