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# Soil Failure in the Luanda Region, Geotechnic Study of These Soils

## Etude géotechnique de la structure instable des sols de la région de Luanda, Angola

by H. N. FERREIRA, Engineer Chief of Laboratory of Engineering of the Public Works of Angola,  
and

C. A.F. DA SILVA, Engineer Chief of Section of Foundations of the Laboratory of Engineering of Public Works of Angola. Laboratório de Engenharia da Direcção de Obras Públicas e Transportes de Angola, Luanda, Angola

### Summary

The authors describe their researches on a soil of marine origin locally known as "muceque". Results of identification tests, grain size analysis, chemical and differential thermal analysis, CBR, compaction, static penetration and load tests on piles and plates, are presented.

They have confirmed that this soil shows a variation of dry density with the moisture content, in the ascending branch of the compaction curve, which is above normal, thereby revealing an excessive sensitivity to water. The relationship between dry density ( $\gamma$ ) and the CBR is normal ( $\gamma = a + b \log \text{CBR}$ ), although there is appreciable dispersion.

Conclusions have been drawn on the following subjects: granulometric fractions and their chemical composition; behaviour of these soils in high-way embankments; bearing capacity of the natural soil with usual moisture content and when saturated.

### 1. Introduction

In the study of foundations it is found that an unstable soil may be capable of bearing a definite load under the normal conditions of moisture content, but that it may undergo rapid settlement of great amplitude when the moisture content is increased.

Such soils must be relatively permeable to allow the conditions of natural moisture to be easily modified (which excludes clays), and must be above the water table, thereby differing from quicksands, in which instability is related to uplift. Sandy soils present a special case, where they are above the water table and have a relatively low dry density; these soils may be found in dry climates and under tropical conditions favourable to desert formation.

Soils of this type have been identified since about 1956 in Southern regions of Africa, Rhodesia and the Union of South Africa. In Angola these soils occupy, amongst others, a vast area near the sea coast between Luanda and Porto Amboim, forming the upper layer of the Luanda platforms, bound by the Bengo and Cuanza rivers and the Quissama plateau. In this area they are red coloured and are locally described as "muceque". Their study has been carried out since 1955.

### 2. Geological origin

In Fig. 1 some typical borehole results are shown, indicating the geological nature of these soils.

Their windblown origin has been recognised in the red sands of Kalahari (7, 8, 9 and 10). Unstable structures have been found also in residual soils of granite, in localities where drainage is easy, as a result of dissolution and removal of soluble salts from rocks (12). It has been assumed that the red quaternary sand known as "muceque" is of marine origin.

### Sommaire

Cette étude portera sur un sol à fort tassement rencontré dans les région de Luanda, et appelé localement « muceque ». On montrera que celui-ci est d'origine marine.

On trouvera dans ce rapport, les résultats des essais suivants: identification, granulométries, analyses chimiques et thermiques différentielles, CBR, compactage, pénétration statique et essais de chargement par pieux et plaques.

Il est vérifié que la densité sèche du sol varie plus rapidement que prévu avec sa teneur en eau de compactage, dans la branche ascendante de la courbe de compactage; ce qui démontre une sensibilité excessive à l'eau.

La relation entre la densité sèche ( $\gamma$ ) et le CBR est normale: ( $\gamma = a + b \log \text{CBR}$ ) mais cependant avec une grande dispersion.

Finalement les conclusions à tirer portent sur les sujets suivants: fractions granulométriques et leur composition chimique; comportement de ces sols comme matériau de remblais routiers; force portante du sol naturel avec une teneur en eau normale, puis immergé.

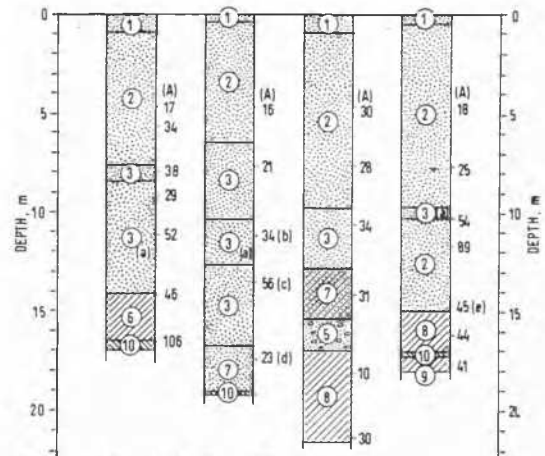


Fig. 1 Geological profiles:

- 1 brown fine sand;
  - 2 red sand (muceque), collapsing soil;
  - 3 light yellow consolidated sand;
  - 4 silty sand;
  - 5 coarse sand with gravel;
  - 6 brown clay;
  - 7 grey clay with ferruginous vein;
  - 8 light grey clay;
  - 9 yellow silty clay;
  - 10 silt clay sandstone.
- (a) With ferruginous vein;  
 (b) For a penetration of 0,10 m;  
 (c) — — — 0,14 m;  
 (d) — — — 0,02 m;  
 (e) — — — 0,18 m.  
 (A) Terzaghi penetration test.

Profils géologiques:

Table I  
Summary of chemical analysis of several samples  
Sommaire des analyses chimiques de quelques échantillons

	Min. per cent	Max. per cent	Average per cent	Average with depth		
				35 cm per cent	70 cm per cent	100 cm per cent
Loss upon ignition	1.19	3.00	2.02	1.67	2.36	1.81
Silica total (Si O <sub>2</sub> )	86.95	93.20	90.54	91.55	90.02	89.98
Insoluble silica	83.30	91.24	86.78	88.36	86.49	85.98
Soluble silica	1.96	5.58	3.76	3.18	3.53	3.96
Sulphuric anhydride (SO <sub>3</sub> )	—	—	—	—	—	—
Alumina (Al <sub>2</sub> O <sub>3</sub> )	4.80	8.36	6.18	5.83	6.43	6.47
Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> )	1.04	2.40	1.60	1.36	1.68	1.77
Lime (CaO)	0.10	0.20	0.16	Traces	0.16	0.16
Magnesia (MgO)	Traces	0.16	0.04	Traces	0.12	Traces
Relation $\frac{\text{SOL. SIL.}}{\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3}$	0.25	0.70	0.49	0.45	0.42	0.51
Relation $\frac{\text{Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3}$	2.21	5.56	4.11	4.31	4.16	3.91

Number of samples : 16

This origin is attributed to them by Soares de Carvalho (4), based on microscopic morphological and fossil arguments. That author, observing grains of 0.3 mm diameter through a binocular magnifying glass, obtained percentages of dull-gloss grains varying between 50 and 92 per cent, with a minimum of 20 per cent in a sample. In agreement with Cailleux (4), with percentages above 20 per cent, a marine origin is probable, and if above 30 per cent the marine origin is practically certain.

Still in agreement with Cailleux, he has defined the indices of dullness of first order ( $1000 \frac{2r}{L}$ ) and of second order

( $1000 \frac{2R}{L}$ ) expressed in millesimals,  $r$  being the smallest radius of curvature of the grain angles,  $R$  the radius of curvature immediately above, and  $L$  the length of the grain. The variation curves of the indices representing length  $L$  obtained for the "muceque" have defined two types, one with maximum diameter of 0.3 mm and the other of 0.5 mm, and with values around 200 millesimals, but always below 300. The wind-carried sands of Angola show higher maxima, corresponding to a length of 0.7 mm.

Soares de Carvalho has also said : "Reinecke (VERRIER, 1953) has found in the sands of Quelo ferruginous concretions which contained marine molluscs".

Thus the marine genesis has been clearly established, demonstrating that there are also unstable sedimentary soils of this origin.

### 3. Type of soil

The mineralogical analysis carried out by Soares de Carvalho (4) shows that the characteristic association is zircon + cyanide. The chemical analysis was made on a soil profile (table I) and shows a relative uniformity along the profiles.

Analyses effected in fractions separated from the material show the characteristic almost exclusively siliceous of the rough fraction and a high percentage of alumina in the fine fraction (tables II and III).

The silica/sexquioxide molecular ratio (table III) is above 1. In agreement with Winterkorn's classification (11, page 22),

Table II  
Chemical analysis of a sample by sizes  
Analyses chimiques  
d'un échantillon par subdivisions granulométriques

Tests	Total sample per cent	Material passing the No. 200 sieve per cent	Material retained on the No. 200 sieve per cent	Material in suspen- sion at total elapsed time of 2 min. per cent
Loss upon ignition	1.45	5.31	0.22	15.85
Silica	93.54	78.24	96.47	48.89
Sulphuric anhydride (SO <sub>3</sub> )	No	No	No	No
Insoluble silica	90.41	71.73	95.07	46.52
Ferric oxide (Fe <sub>2</sub> O <sub>3</sub> )	0.96	2.70	0.56	6.07
Alumina (Al <sub>2</sub> O <sub>3</sub> )	4.71	11.90	3.22	25.93
Lime (CaO)	0.38	0.67	0.17	0.59
Magnesia (MgO)	Traces	0.41	Traces	0.45
Organic matter	0.11	—	—	—

Table III  
Chemical tests  
Essais chimiques

Sample No.	4993		4994
	Total	< 5 μ	< 5 μ
Loss upon ignition	0.9	12.27	13.09
SiO <sub>2</sub> (total)	92.5	48.42	44.07
Fe <sub>2</sub> O <sub>3</sub>	0.9	8.18	9.60
Al <sub>2</sub> O <sub>3</sub>	4.7	26.47	29.25
Ca O	—	0.14	0.18
Mg O	—	0.42	0.47
Molecular relation $\frac{\text{SiO}_2}{\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3}$	16.5	1.40	1.13

**Table IV**  
**Summary of physical tests**  
**Résumé des essais géotechniques**

	<i>Number of tests</i>	<i>Max.</i>	<i>Min.</i>	<i>Average</i>			
$L_L$ (per cent)	44	24	N.P.	N.P.-21 *			
$P_L$ (per cent)	44	16	N.P.	N.-12 *			
$P_I$ (per cent)	44	15	N.P.	N.P.-9 *			
Group Index	44	2	0	0			
Classification	44	A-6	A-2-4	A-2-4 •			
Grain size analysis Material passing (per cent)	Sieve analysis	No. 10	61	100	100		
		No. 40	61	97	52	75	
		No. 200	61	44	14	28	
		Hydrometer analysis	5 $\mu$	57	29	0	12
			2 $\mu$	56	28	0	10
Specific gravity, $g\ cm^{-3}$	9	2.64	2.58	2.60			
Natural density, $g\ cm^{-3}$	48	1.82	1.52	1.64			

\* Some samples were not plastic (N.P.). The number indicates the average value of the "Atterberg Limits" of the sample which have shown plasticity.  
 • The most frequent group.

the soil is not lateritic although it displays a red colour and contains some iron.

It has been defined as the type of soil commonly found in sand dunes (1, page 40).

In the differential thermal analysis of the clayey fraction ( $\leq 2\mu$ ), thermograms were obtained (Fig. 2) which denote

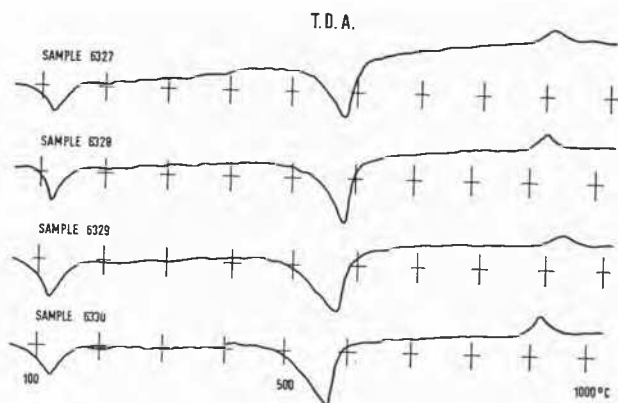


Fig. 2 T.D.A.

the presence of minerals belonging to the caulinite group. No minerals of any other group were detected.

Identification tests according to AASHO standards have led to the results shown in table IV, which gives specific weights and natural dry density. The dry densities "in situ" are very low (Table V) especially when compared to those obtained by compaction tests (Table VI).

Tests were carried out with samples taken from three different depths (0.50, 1.00, 1.50 m) in 10 boreholes distributed within a 15 km radius. The results of these compaction tests are shown in Table VII.

Comparing these values with the compaction curves given by the Road Research Laboratory (16, pp. 158) or with those indicated by the Highway Research Board (6, pp. 42), we find that, on the ascending branch of the compaction curve, the dry density increases with moisture content more rapidly than in the tests carried out by the authors. It is therefore a soil which has a natural low dry density, and which is also more sensitive to water than normal soils, a fact which contributes to its instability.

**Table V**  
**Natural density**  
**Densité naturelle**

	<i>Values</i>	<i>Frequency distribution</i>
Natural density, $g\ cm^{-3}$	1.50-1.53	1
	1.54-1.57	3
	1.58-1.61	10
	1.62-1.65	10
	1.66-1.69	24
	1.70-1.73	4
	1.74-1.77	2
	1.78-1.81	5
	1.82-1.85	1
		60

**Table VI**  
**Compaction and CBR**  
**Compactage et CBR**

	<i>Number of tests</i>	<i>Max.</i>	<i>Min.</i>	<i>Aver.</i>	
Standard Proctor	$\gamma_d, g\ cm^{-3}$ W (per cent)	68	2.10	1.84	1.98
			10.0	7.0	8.9
Modified A.A.S.H.O.	$\gamma_d, g\ cm^{-3}$ W (per cent)	49	2.17	1.95	2.04
			7.9	6.3	7.3
CBR (per cent) ( $\gamma = 0.95$ standard proctor density)	39	13.0	3.4	7.0	
CBR (per cent) ( $\gamma =$ Natural density)	without soaking	40	14.5	0.7	3.5
		with soaking	40	9.8	0.5
CBR in situ (per cent)	39	11.0	1.0	3.5	

The CBR values obtained in the laboratory test, as well as those obtained with samples after soaking according to the conditions of a laboratory test, are adjusted to the same

Table VII  
Compaction tests  
Essais de compactages

Moisture content <i>W</i> (per cent)	Standard proctor $\gamma_d$ g cm <sup>-3</sup>	Modified A.A.S.H.O. $\gamma_d$ , g cm <sup>-3</sup>
0	1.70	1.80
4.5		1.92
5.5		1.90
6.5		1.96
7.5	1.89	1.97
8.5	1.89	1.98
9.5	1.92	1.97
10.5	1.89	1.91
11.5	1.84	1.88
12.5	1.85	1.85
13.5	1.79	

zone on the curve (Fig. 3); all the values observed are contained between the straight lines :

$$\gamma = 1.75 + 0.240 \log \text{CBR}$$

$$\gamma = 1.55 + 0.293 \log \text{CBR}$$

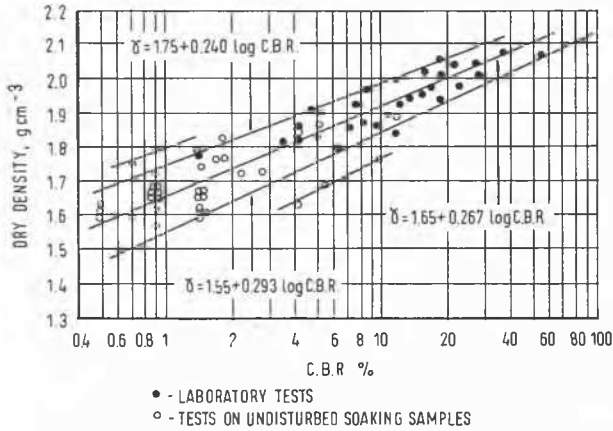


Fig. 3 Dry density. CBR curves.  
Densité sèche. CBR.

The most frequent values are near the last one.

These straight lines are agreed on the point (CBR = 5.600;  $\gamma = G_s$ ) which is a characteristic common to the soils of Angola, and which the authors assume to be common to all soils.

The field CBR tests with previous local soaking of 2 hours lead to CBR values such as : (CBR *in situ*/laboratory CBR) = 1.8 to 2.1, which is another general characteristic of soils found in Angola.

#### 4. Foundations for Buildings

4.1. Cone penetration tests—The geological soundings undertaken by the authors supplemented by penetration tests show that the layer of red sands within the zone of Luanda city has a depth varying from 5 to 10 metres. The appearance of the underlying stratum, formed by more compact yellow sands, is shown in the diagram of the penetration tests by a sharp increase of resistance at the point (Fig. 4).

The fundamental properties of these soils obtained from the static penetration test (table VIII and Fig. 4) are as follows :

(a) slight variation of resistance at the point with increased depth ;

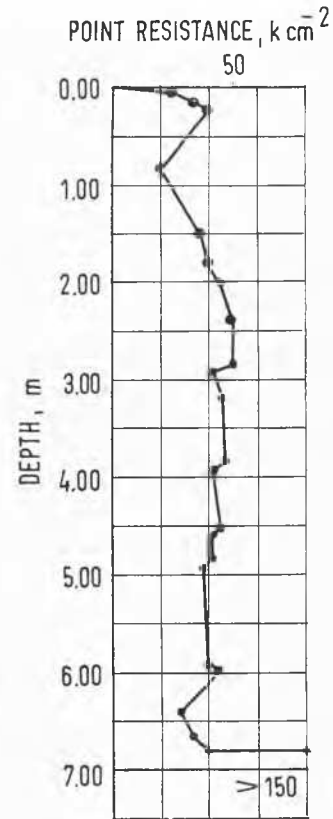


Fig. 4 Typical penetration resistance.  
Résistance à la pénétration.

Table VIII  
Cone penetration tests  
Essais de pénétration au cône

(A) Resistance at the point frequency distribution						
Depths m	10-20	20-30	30-40	40-50	50-60	60-70
1-2	2	4	4	4	2	1
2-3	—	6	—	5	4	2
3-4	—	5	4	3	5	—
4-5	—	3	5	2	6	1

(B) Summary of tests						
Depths m	Resistance at the point kg/cm <sup>2</sup>			Allowable bearing capacity $q = R_p/37$ (13)		
	Min.	Max.	Average	Min.	Max.	Average
1-2	15	65	37	0.4	1.8	1.0
2-3	23	65	41	0.6	1.8	1.1
3-4	22	53	39	0.6	1.4	1.1
4-5	27	85	45	—	—	—

(C) Depth <i>D</i> at which $R_p$ increased suddenly						
Depth	4-5	5-6	6-7	7-8	8-9	9-10
Number of tests	1	1	7	6	1	1
Average $R_p$ kg cm <sup>-2</sup>	160	170	152	179	140	170

(b) low value of this resistance; an average value of 40 kg per sq. cm can be assumed for any depth.

4.2. *Load tests on plates*—Having carried out load tests on saturated ground, lower load bearing values were obtained than those derived from tests on ground with its natural moisture content.

In Fig. 5 are shown the load settlement curves for ground under the following conditions :

- (a) with its natural moisture content in dry weather;
- (b) saturated;
- (c) in the condition (a) up to a load of 1 kg per sq. cm and saturated for the higher loads.

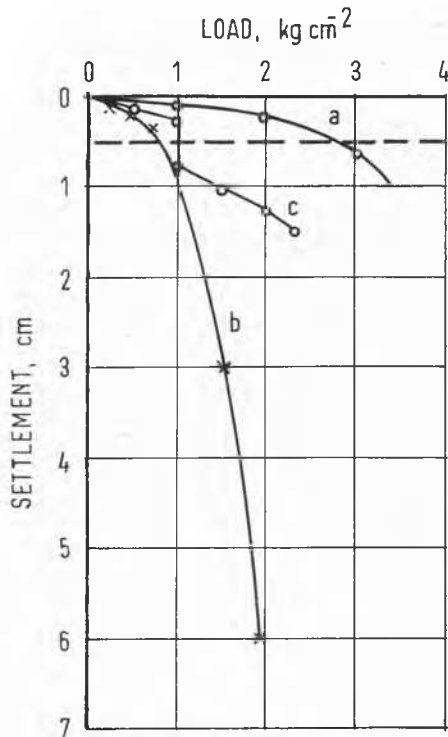


Fig. 5 Load tests.  
Essais de chargement.

The loads, for 0.5 cm settlement, are respectively 2.8 kg per sq. cm and 0.9 kg per sq. cm in curves (a) and (b). Their ratio is approximately 3 : 1.

4.3. *Tests with piles*—The influence of saturated soil is clearly evident in tests on piles.

The piles were made of cast-in-place concrete, some 6 m long and others 8 m long. Their minimum diameter was 0.42 m and their estimated bearing capacity was 55 tons. The tests carried out on them with ground having its natural moisture content in dry weather gave load/settlement curves of the type shown in Fig. 6 where one of the curves is depicted.

In the test carried out on an 8 m pile, after raising the test load to 140 tons (with a settlement of 5 mm), water was allowed to flow from a tap to the ground around the head of the pile. The settlement attained after 48 hours was 12 cm (Fig. 6).

## 5. Erosion

The erosive action of rain on these soils is remarkable. In the natural formations, this revealed by the gullies which abound in the upper part of Luanda and its progressive action gives rise to special urban problems. (14).

During the heavy rains of March 1955, within a period of three days a recession of approximately 60 m occurred in one

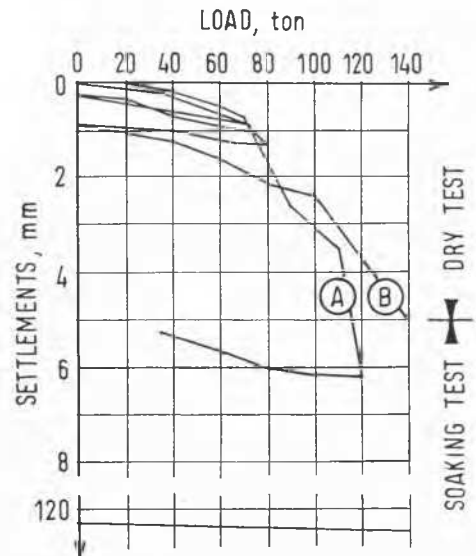


Fig. 6 Load settlements curves for individual piles.  
Courbes chargement. Pénétration pour pieu isolé.

gully. The erosion stopped at the level of the underlying stratum (5).

In the case of roads where paving was limited to a mere coating of asphaltic rock over compacted soil, water infiltration has caused spectacular erosion in which gullies exceeding 4 metres in depth have been formed.

Erosion of slopes still remains a fundamental problem of highway construction in such soils.

## 6. Conclusions

From the results of their tests the authors have found that "muqueque" is a soil formed by two completely different fractions : one is coarse and siliceous, the other is fine and contains compounds of iron and aluminium. The first fraction is found stabilised to some extent by the bonds resulting from these metallic compounds, which have been largely dehydrated. The instability of the soil thus originates from the breakdown of these bonds by the action of water, thereby proving that this soil is particularly sensitive to this action.

Where they concern the foundations of buildings, load tests show the need for reducing loads on the foundation soil, in order to avoid heavy settlements which may result from an occasional increase of moisture content.

The sensitivity of bearing capacity to the saturation of soil, is translated in the tests carried out, into reductions in the admissible load of 3 and 2 kg per sq. cm, to 1 and 0.6 kg per sq. cm respectively. Considering the permeability of these sands, the latter values are those that should be used. On the other hand, the foundations should be taken below the level of drains and sewers as settlement has already resulted from erosion of soil close to fractures in the sewage system.

In piles foundations it is necessary, to drive the toes of the piles down to the underlying stratum, the resistance of which is much higher. A comparison of the results of load and penetration tests shows that the estimated permissible loads on these soils can be calculated precisely.

For highway and airport construction, "muqueque" deserves special study where problems of compaction and erosion are concerned. Attention is therefore drawn to the following recommendations : recompaction of cuttings down to a depth to be determined by the CBR of the natural ground ; covering of slopes and berms ; careful control of compaction ; judicious choice of the CBR value after obtaining reliable local information about the control of compaction obtainable on the construction site.