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GEOTECHNICAL EVALUATION OF LATERITIC SOILS FOR EMBANKMENT DAM DESIGN

EVALUATION GEOTECHNIQUE DES SOLS LATERITIQUES POUR LA CONCEPTION DE BARRAGES EN TERRE

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SYNOPSIS: Extensive geotechnical investigations were carried out at four alternative dam sites for a water supply project in Burkina Faso, with particular emphasis on the engineering properties of lateritic soils for embankment dam foundation and dam construction materials. The permeability characteristics of the dam foundation and reservoir underground were considered to be a factor of particular importance, considering local conditions such as high evaporation, anticipated shallow and wide open reservoir surface, and short precipitation period.

Based on the results of field and laboratory tests, a dam site was selected in the Nakanbé River to assure drinking water supply for the capital city. In this paper the characteristics of the investigated lateritic soils are discussed along with certain design aspects to be considered in arid climate soils.

1. INTRODUCTION

The study of alternatives for a drinking water supply system for Ouagadougou, capital city of Burkina Faso, performed by Lahmeyer International Consulting Engineers, comprised of extensive geotechnical investigations at four alternative dam sites in the Nakanbé River (previously the White Volta River) and near the village of Loumbila. The first two are river closure dams, whereas the latter are circular off-channel type dams. The four altertive dams require a volume of over 5 million m^3 compacted fill with a total dam crest length of some 20 km.

The climate is characterized by a rainy season with considerable precipitations, followed by a hot dry season without any rainfall. The mean annual rainfall in the project areas amounts to about 700 mm, but the precipitation values show high fluctuations and sequences of dry years are well-known. High evaporation values and rapid run-off lead to intermittent rivers, becoming completely dry during the dry season.

Despite the fact that the relatively impermeable subsoil is unable to accumulate rainwater, the subsoil characteristics, especially permeability of the dam and the reservoir underground are of particular importance for an economic design and the construction of the embankment dams.

Under consideration of these aspects, the geotechnical investigations were particularly aimed at determining:

- variation of subsoil permeability which is to be commonly expected in lateritic soils,
- engineering properties of undisturbed and compacted lateritic soils
- borrow areas for economically exploiting embankment dam materials
- availability of filter and riprap material and concrete aggregates in the proximity of the project sites.

In this paper results of the geotechnical investigations are evaluated and summarized along with dam and foundation design considerations.

2. ENGINEERING PROPERTIES

The four alternative dam sites are mostly covered with lateritic soils and decomposed granite. According to site explorations comprising of some 20 boreholes of 8 - 20 m depth and about 60 test pits of 3 - 5 m depth, the lateritic soil layer is about 10 to 20 m thick. In some boreholes moderately to slightly weathered granite was encountered at depths of 13 - 20 m. The slightly weathered granite was hard with point load strength indices of $I_S(50)$ = 14 MPa and 10.5 MPa for dry and saturated conditions respectively.

The lateritic soils consist of a 1 - 3 m thick upper layer of reddish-brown lateritic gravels, followed by a less pervious layer of lateritic clays and silts, down to moderately to slightly weathered granite stratum. The transition from the coarse-grained to fine-grained layers was evident in the open test pits. However, it was also found that the lateritic gravels are frequently intercalated in the layer of the lateritic clays and silts.

2.1 Index Properties

The lateritic gravels contain about 50 - 70 % gravel, 15 - 25 % sand and 5 - 20 % clay fraction. Sometimes the sand and/or silt fractions were considerably less or completely missing. The investigated lateritic gravels (Figure 1) exhibit a similar grading envelope obtained from other West African laterite gravels, as summarized by Gidigasu (1976). The lateritic clays and silts contain little gravel, but a significant amount of clay fraction.

The lateritic soils have low to high plasticity and plot on both sides of the A-line on the plasticity chart (Figure 2). The lateritic gravels are classified

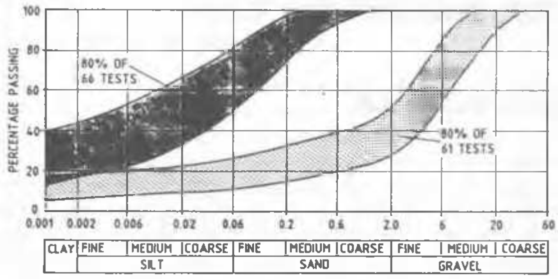

Fig. 1. Grading envelope of the investigated lateritic soils

as GC and GM. The lateritic clays and silts mostly belong to CH, CL and MH soils.

The colloidal activity for the granite derived lateritic soils ranges generally from 0.5 to about 1.0, in comparison with 0.2 - 0.4 for the fine-grained alluvial deposits in the project areas along the Nakanbé River. It confirms colloidal activity characteristics of other West African laterite soils exhibited by Gidigasu (1976).

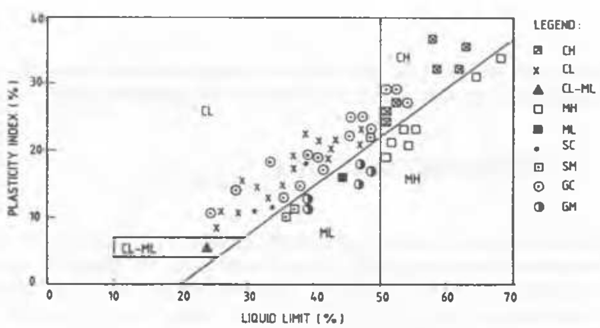

Fig. 2. Plasticity chart

According to the results of the standard penetration tests, the lateritic soils show a high degree of densification. The SPT values were generally significantly higher than 50 - 100. Based on the in-situ density tests from the test pits, the lateritic gravels showed a high natural density of 2.03-2.44 g/cm³, compared to 1.95 - 2.14 g/cm³ for the lateritic clays and silts which could be excavated without difficulty with a medium-heavy backhoe. However, some efforts were needed to excavate test pits by backhoe in the hard concretionary gravels, particularly in cemented cuirasses, which were encountered on the top of gentle hills where vegetation is frequently missing. It was found that the cemented cuirasses were commonly 10 to 20 cm and occasionally up to 50 cm thick.

The lateritic cuirasses and stones dispersed within the project areas are almost dry. Their point load strength indices amount to $I_s(50)$ = 0.85 MPa and 0.65 MPa, respectively. The lateritic stones did not disintegrate after water immersion over a period of 2 - 3 months. Some properties of the lateritic stones and cuirasses are compared with those of the granite in Table 1.

The natural moisture content of the lateritic gravels varied from about 5 % to 13 %, while the lateritic clays and silts had a slightly higher water content of about 9 % to 16 %. In general, the moisture content of the lateritic gravels tended to increase with depth in the investigated test pits (Figure 3).

Table 1. Properties of Lateritic Stone, Cuirasse and Original Granite

	Lateritic Stone	Lateritic Cuirasse	Granite
Natural moisture content	0.7	0.73	0.01
Absorption	5.8	7.0	0.27
Point load strength I_s (50) (MPa) dry	0.65	0.85	10.5
Point load strength I_s (50) (MPa) saturated	0.55	0.45	8.5
Strength loss due to saturation (%)	15	47	19
Density (g/cm³)	2.2-2.3	2.2-2.3	2.65
Rip-rap	good	moderate	very good

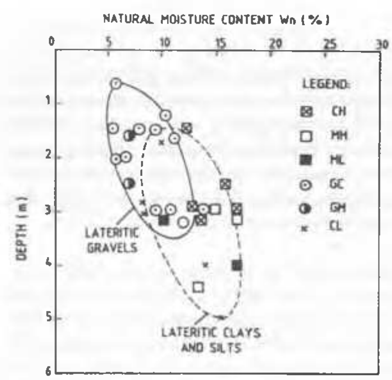

Fig. 3. Variation of natural moisture content with depth

The specific gravities varied over a wide range. The lateritic gravels showed in general higher values than those of the lateritic clays and silts, as summarized in Table 2. It was observed that, in the lateritic gravels, the specific gravity of larger grains greater than 2 mm ranged from 2.81 to 3.11, while that of the smaller grains resulted in lower values of 2.69 to 2.95. This trend corresponds to the results of investigations on other West African lateritic soils performed by Horn and Schweizer (1978). The main reason for the different values of the specific gravity is attributed to the fact that the heavy iron oxide is more frequently concentrated in the gravel fraction.

2.2 Moisture - Density

According to the standard Proctor tests, the optimum moisture content of the lateritic soils lay between about 11 and 22 % (Figure 4), which is approximately 4 % to 7 % higher than the natural moisture contents of

Table 2. Engineering Properties of Lateritic Soils

Soil type	Lateritic gravels	Lateritic clays and silts
Soil classification	GC, GM	CL, CH, MH
Clay content (%)	5 - 20	18 - 45
Liquid limit (%)	25 - 55	25 - 70
Plasticity index (%)	10 - 28	10 - 35
In-situ density (g/cm^3)	2.03 - 2.44	1.95 - 2.14
Specific gravity of larger and smaller grains	2.69 - 3.11	2.61 - 2.88
Natural moisture content w_n (%)	5.1 - 13.3	8.6 - 16.4
Max. dry density γ_d(g/cm^3)	1.68 - 2.09	1.67 - 1.92
Optimum moisture content (%)	10.5 - 20.0	11.0 - 22.0
Field permeability (cm/s)	10^{-4} - 10^{-6}	10^{-5} - 10^{-6}
Laboratory permeab. (cm/s)	10^{-5} - 10^{-7}	10^{-6} - 10^{-8}
Compression index c_c	0.164	0.097
Shear strength in optimum condition	ø' = 32.5° - 38.5° c' = 15 - 30 kPa	ø' = 30° - 34° c' = 20 - 80 kPa
Average shear strength in saturated condition	ø' = 31° c' = 10 kPa	ø' = 25.5° c' = 20 kPa
Dispersivity	non-dispersive	non-dispersive

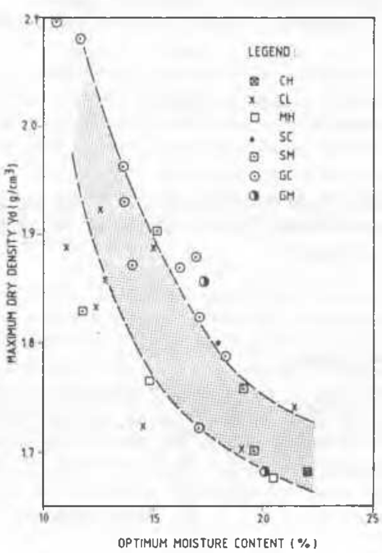

Fig. 4. Relation between maximum dry density and optimum moisture content

the corresponding soils. The lateritic gravels could be compacted well, achieving high maximum dry density values of about 1.7 g/cm^3 to 2.1 g/cm^3 due to their high specific gravity. Mitchell and Sitar (1982) and Townsend (1985) report that a higher maximum dry density of over 2.2 - 2.3 g/cm^3 was obtained elsewhere.

2.3 Permeability

In view of the identified importance of underground tightness, the permeability of the lateritic soils was extensively investigated by carrying out some 70 field tests; over 50 tests in the boreholes using the Lefranc/Maag method and about 20 tests in the test pits. Furthermore, about 20 laboratory tests were performed on compacted samples.

Because of the heterogenity in micro- and macrofabrics of the lateritic soils, the results of the permeability tests were not consistent and the variation was very high. However, in general the undisturbed soils revealed higher permeability when compared with those of compacted soils:

- Lateritic gravels:
  - Field: k = 10^{-4} - 10^{-5} cm/s (sporadically 10^{-6} cm/s)
  - Laboratory: k = 10^{-5} - 10^{-7} cm/s
- Lateritic clays and silts:
  - Field: k = 10^{-5} - 10^{-6} cm/s
  - Laboratory: k = 10^{-7} - 10^{-8} cm/s (occasionally 10^{-6} cm/s)

It should be noted that in some isolated areas the in-situ permeability was found to be as high as 10^{-3} cm/s. Since pronounced cavities were not encountered in the relevant test pits, the high permeability was considered to be most probably associated with termite activities occasionally observed in the project areas.

2.4 Shear Strength

The shear strength characteristics were studied using CU and CD triaxial tests and direct shear tests. Samples were sheared under both optimum moisture and saturated conditions. The samples for the saturated condition were allowed to soak for 24 hours or longer before being consolidated under the specified normal stress. The well compacted lateritic gravels showed a friction angle varying from 32.5° to 38.5° (average 36.5°). When soaked, the shear strength decreased to $ø'_{av}$ = 31°. In case of the lateritic clays and silts the reduction in shear strength due to saturation was more significant, decreasing from 33° to 25.5° (Figure 5). A selection of engineering properties for the lateritic soils is summarized in Table 2.

2.5 Compressibility

The consolidation tests on the lateritic clays and silts produced values of compression index C_c varying between 0.097 and 0.164. These values are generally lower than those determined by the Skempton's formula (1944) for temperate-zone soils.

2.6 Dispersivity

The dispersivity of the lateritic clays and silts and the lateritic sands and gravels was investigated by means of some 10 pinhole tests and SCS-dispersion tests. The investigated lateritic soils were not dispersive.

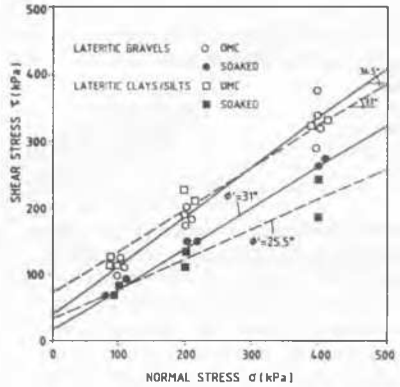

Fig. 5. Drained tests on lateritic soils

3. DESIGN CONSIDERATIONS

The water supply for Ouagadougou has to be based on surface water resources. Despite considerable mean annual precipitation falling mainly from June to October, the rainwater is not able to penetrate into the subsoil to create groundwater reserves. The impermeable subsoil and the lack of significant porous layers in the underground results in a quick run-off to the rivers, which then become almost dry from the beginning of the dry season.

To assure water supply for the rapidly growing city, reservoirs are required to equalize the unsteady flow within the year and to compensate for drought years with less than the average annual run-off.

Unfortunately, the only adequate river, the Nakanbé River, shows no favourable storage conditions. The mostly gentle slopes of the river bed and the river banks allow only a large and shallow reservoir to be stored up by a dam.

To satisfy the water demand of Ouagadougou up to the year 2010, a net reservoir volume of about 150 million m³ would be needed.

The optimum solution for a drinking water reservoir was found to be located at a distance of some 50 km from Ouagadougou on the Nakanbé River in the neighbourhood of the village of Ziga. The reservoir surface would cover an area of about 75 km², with a mean depth of about 2.60 m.

Due to the large open water surface and the existing climatic conditions high losses of evaporation had to be taken into account, based on the available evaporation data (Table 3).

Table 3. Evaporation Data

O	N	D	J	F	M	A	M	J	J	A	S	Mean evaporation per year
185	170	165	180	185	230	230	225	185	160	140	145	2200 mm

The annual evaporation loss is considerable since it amounts to 40% of the inflow. It was therefore worthwhile studying also the possibility of off-channel reservoirs with minor reservoir surface and greater depth.

This alternative solution has to construct an intake at the Nakanbé River, a pumping station and pipelines to the artificial reservoirs to be situated near the village of Loumbila.

The main features of the four alternative dams under investigation are summarized in Tables 4 and 5.

Table 4. River Closure Dams in the Nakanbé River

Alternative	Dam height (m)	Crest length (m)	Net reservoir volume (Mio m³)	Maximum water surface (km²)	Dam volume (Mio m³)	Spillway design flood (m³/s)
Ziga I	15	4900	150	75	0.86	350
Ziga II	14	3500	150	75	0.70	350

Table 5. Off-Channel Reservoirs at Loumbila I and II

Alternative	Dam height (m)	Crest length (m)	Net reservoir volume (Mio m³)	Maximum water surface (km²)	Dam volume (Mio m³)
Loumbila I	17	6500	20.3	3.0	1.1
Loumbila II	18	5660	20.5	2.1	1.9

The selected solution (Ziga II) consists of a 14 m high embankment dam with a crest length of about 3500 m (Figure 6). A typical dam cross section is shown in Figure 7.

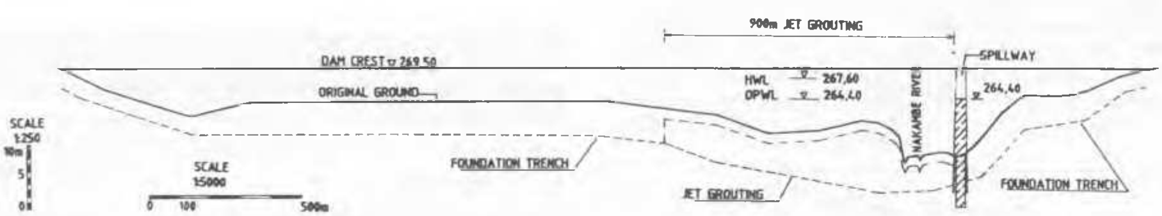

Fig. 6. Longitudinal section of the Ziga dam

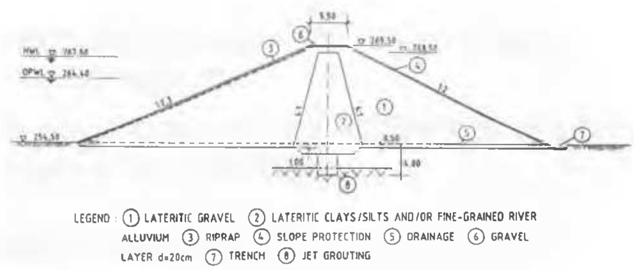

Fig. 7. A typical dam cross-section

The dam design is based on the assumption that the lateritic soils located downstream of the dam shall be exploited for the dam construction. The lateritic soils upstream of the dam should not be excavated to avoid any damage to the natural impervious layer.

The available lateritic gravels are suitable for use as earthfill dam shoulder material. The lateritic gravels having a clay content of about 5 - 20 % can be well compacted, easily achieving a density of 2 g/cm³. In the laboratory compaction tests, a density of up to 2.1 - 2.2 g/cm³ was possible with an optimum moisture content. The well compacted lateritic gravels showed an average shear strength of $\varnothing'_{av} = 31°$ and $c'_{av} = 10$ kPa under saturated conditions. The permeability of $k = 10^{-5} \sim 10^{-6}$ cm/s is considered to be favourable.

Similar to the lateritic gravels, the lateritic clays and silts also compact well to a density of 2 g/cm³. An average shear strength of $\varnothing'_{av} = 25°$ and $c'_{av} = 20$ kPa can be expected under saturated conditions. Because of relatively high clay content of about 20 % - 45 %, the compacted material is rather impervious and can be used as a dam core material. As an alternative, the fine-grained alluvium deposited in the riverbed and in the inundated area along the Nakanbé River is also considered to be suitable for dam core material.

For the riprap and downstream slope protection, the lateritic stones (frequently cobble and occasionally boulder size) and cuirasses dispersed in the project areas will be utilized. Their engineering properties are regarded to be sufficient for this purpose, as presented in Table 1.

During the geotechnical investigations no filter material was found in the vicinity of the four alternative dam sites at an economically exploitable depth. Some natural sand and gravel sources encountered about 30 - 35 km from the village of Loumbila seemed to be limited and not sufficient. Thus a quarry opening and expensive processing was taken into consideration for the dam design. Consequently, a minimum drainage blanket in combination with geotextiles has been arranged in the bottom of the downstream shoulder.

After trench excavation through the upper lateritic gravels, the central dam core will be connected to the lower layer of less pervious lateritic clays and silts. Because of the heterogenity in the underground permeability, due in part to isolated gravel lenses, jet grouting below the dam core will be performed, where necessary, to assure water tightness and stability against piping. In another case, De Mello et al. (1988) reported that grouting of canaliculae in more permeable residual soils of Balbina dam foundation using the tube-a-manchette technique was proved to be the best choice, considering the logistic and climatic peculiarities of the Amazon region.

4. CONCLUSION

A geotechnical evaluation of lateritic soils is presented together with some design aspects to be considered in arid climate soils. Based on the results of field and laboratory tests, the following conclusions can be made:

- The lateritic gravels available in the Ziga and Loumbila areas show satisfactory engineering properties for use as embankment dam material.

- When saturated, the loss in shear strength appeared to be more pronounced in the lateritic clays and silts than in the lateritic gravels. However, the characteristics of the compacted lateritic clays and silts were found to be suitable for a dam core material.

- The in-situ permeability of the lateritic soils was heterogeneous, partly attributed to lateritic gravel lenses as well as occasionally observed termite activities in the dam site. A better water tightness and higher stability against piping can be achieved by varying the core trench levels according to the subsoil conditions in combination with a jet grouting or equivalent method, where required.

- The laterite dam can be suitably adapted to the natural savannah landscape.

REFERENCES

De Mello et al. (1988). Grouting of Canaliculae in residual soils and behaviour of the foundations of Balbina Dam. *Proc. of 2nd Intern. Conf. on Geom. in Tropical Soils*, Singapore, Vol. 1.

Gidigasu, M.D. (1976). *Laterite Soil Engineering*, Elsevier, Amsterdam.

Horn, A. and Schweitzer, F. (1978). Tropische Böden als Baugrund und Baustoff. *Baugrundtagung*, Berlin.

Mitchell, J.K. and Sitar, N. (1982). Engineering properties of tropical residual soils. *ASCE Geot. Eng. Specialty Conf. on Eng. and Const. in Tropical and Residual Soils*, Honolulu, Hawaii.

Skempton, A.W. (1944). Notes on the compressibility of clays. *Q. Journal of Geology Soc.*, London, Vol. C: pp. 119-135.

Townsend, F.C. (1985). Geotechnical characteristics of residual soils. *J. of.Geot. Eng.*, ASCE, Vol. 111, No. GT1.