Collapsible sand and its treatment by compaction

Un sable collapsible et son traitement par compactage

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SYNOPSIS: The growing development of civil engineering works on collapsible soil areas has claimed for better knowledge of geotechnical behaviour of foundation soils upon wetting, with or without additional loadings, in order to provide the proper safety conditions for the establishment of facilities and specific structures. This paper presents and analyses the collapse upon wetting of a fine aeolian sandy soil and its treatment by compaction, for a particular area of 10,000 ha in northeastern Brazil, which is the object of an extensive irrigation program. In addition, other important engineering properties such as shear strength and permeability are also commented upon.

1 INTRODUCTION

The establishment of irrigation programs requires the implantation of some facilities and specific structures as excavated and embankment canals, ponds, earth dikes, bridges and culverts. All civil works are to be done along the irrigation canal alignments over the project area. Although the canals are currently designed with a thin concrete liner, it is recognized that water will be continuously seeping through the porous soil mass (USBR 1963). This leakage causes a wetting front that moves downward till either the phreatic surface or an impervious stratum is contacted, thus leading to the rising of a local ground water level (McWorther and Nelson 1979). The seeping water, reaching sensitive to wetting foundation layers, can cause deformations when the general equilibrium conditions of the mass attain a critical state, thus leading to the appearance of cracks on the liner, or in the canal walls, or even the complete failure of structures (Bally 1965). In order to avoid any damage, both canal watertighting provided by an impervious liner or foundation soil treatment prior to construction are recommended procedures. The soil improvement is the general solution adopted for major irrigation projects on collapsible areas. In the present case, where soils underneath great extents of canals have to be treated, vibratory roller compaction and over-excavation with recompaction were the selected pretreatment techniques which were investigated at the design stage. Those soil improvement procedures present relative low costs, operational simplicity and may properly comply with the design requirements for the depth of foundation to be treated.

2 COLLAPSIBLE SOIL IDENTIFICATION

During the soil investigation phase for design, deep exploratory holes were drilled, and SPT and permeability tests were performed in the bore holes. Some 2,50m deep test pits were dug, making possible soil samplings and measurements of densities and moisture contents. The obtained samples were first submitted to laboratory tests for soil classification purpose.

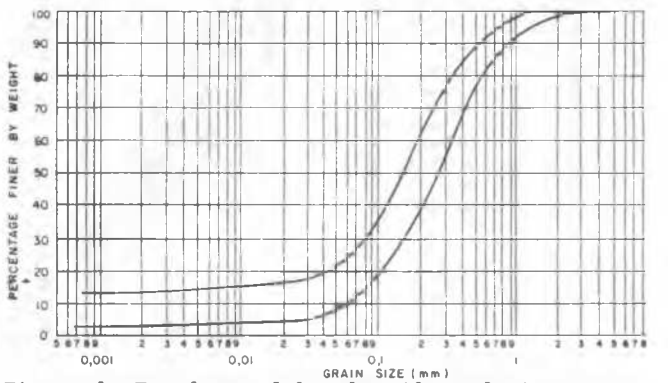

Figure 1. Envelope of local soil gradation curves

The existence of a collapsible structure in local soils was suspected because of the grain size characteristics of the material and its loose and dry natural conditions, as resulted from performed tests. The upper 3 meters of the aeolian deposit consist of a fine to coarse sand, uniformily graded, with 10 % to 30 % of non plastic fines (SM) or with fines of low plasticity (SM-SC) acting as the cementing agent. Figure 1 presents the limits of gradation curves from 60 grain size analyses achieved on foundation soils. Table 1 shows the range of soil index property values measured in 7 block samples taken from test pits.

Table 1. Index property ranges of local soils.

Density of solids kg/m³	Void ratio	Water content %	Unit weight* of solids kN/m³
2630-2680	0.61-0.74	0.8-3.0	15.8-16.5

* Average NP values: $\gamma_{s_{max}}$=20.0 kN/m³; W_{opt}=8.0 %

The final confirmation of soil susceptibility to collapse upon wetting was obtained by running a double consolidation test on a selected undisturbed sample. The specimen was flooded at the loading stage of 50 kPa, and it was measured a

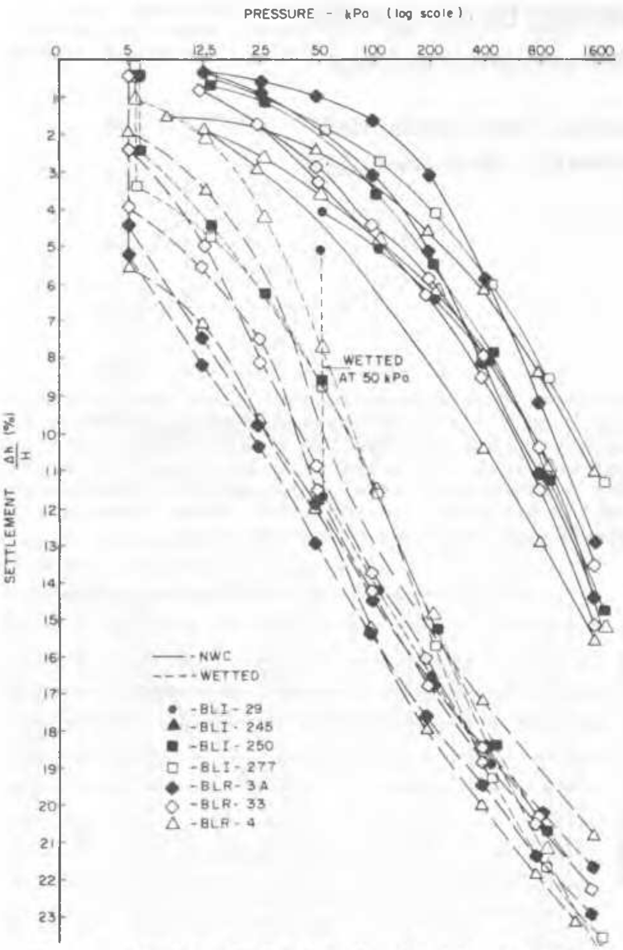

Figure 2. Double oedometer tests for natural ground condition.

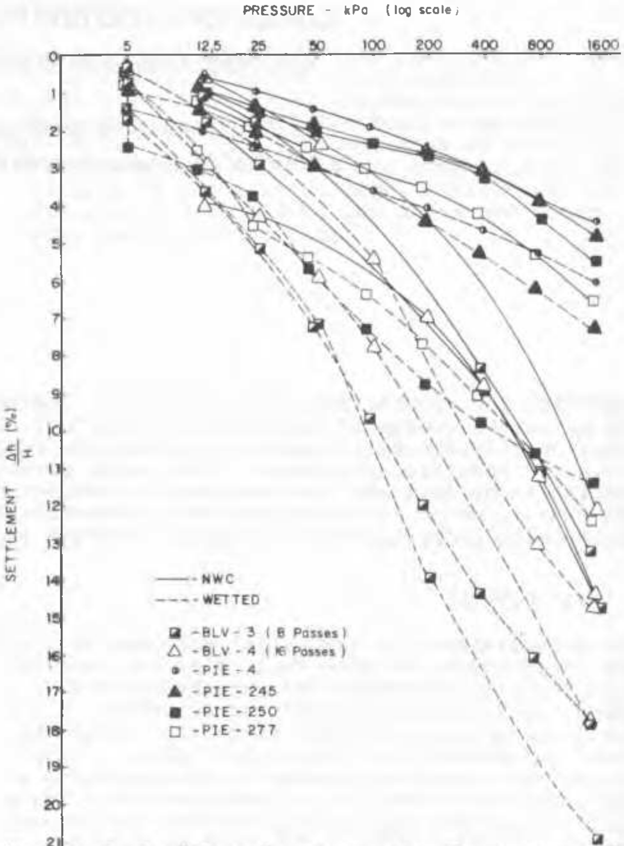

Figure 3. Double oedometer tests for compacted condition.

collapse of 7 %, considered troublesome in the available scale of problem severity(Clemence & Finbarr 1981). The currently called "double oedometer test"(Jennings & Knight 1957) consists of running concurrently two consolidation tests on samples of the same soil, one conducted at natural water content(NWC), and the other conducted as a conventional consolidation test, with water in the confining dam around the sample. The collapse is then determined by the superposition of the consolidation curves from both tests, assuming that no collapse may occur under equilibrium conditions with the overburden pressure in the field. However, it was pointed out later(Reginatto 1970) that some soils may be "truly collapsible", not supporting their own weight upon wetting. To make possible the evaluation of soil susceptibility to collapse upon wetting under its own weight, instead of running conventional oedometer tests on previously saturated samples, it was adopted a somewhat modified technique consisting of a first loading stage of 5 kPa for adjustments, followed by wetting and measurement of corresponding collapse. Test results are presented on stress x strain curves with log-scale for pressures, similar to the conventional consolidation curves(figures 2 and 3), and also on stress x collapse curves(figure 4), where collapse is considered as the unit additional vertical strain experienced by soil upon wetting. Collapse investigations on low stress levels are in accordance with the design stress range not exceeding 250 kPa. Three different soil conditions were studied: undisturbed samples representing natural ground condition (BLI, BLR), remoulded and laboratory compacted soil samples(PIE), and undisturbed samples taken from pits dug in test sections after compaction with respectively 8 and 16 passes of a heavy vibratory roller Dynapac CA-25D(BLV).

3 COLLAPSE EVALUATION

Double oedometer tests performed on samples at natural ground condition are represented in figure 2 by strain normalized consolidation curves. The test results show the natural soil high compressibility and its significant sensibility to collapse upon wetting, even under very low pressures. The tested soil may be classified as "truly collapsible" according to Reginatto's criterion; the superposition of NWC (Natural water content) and wetted curve at overburden pressure is not realistic. Performed tests for the natural ground condition presented a collapse peak behaviour in relation to the applied loadings, thus with a decreasing collapse for greater stress values(as can be well observed in figure 4). Uncommonly, none of the NWC consolidation curves intercepted the corresponding curves for the wetted condition within the ordinary stress ranges of consolidation tests. As it can be seen in figure 2, the wetting process introduced a quite significant remoulding effect, indicating the failure of the original soil structure. The test previously conducted at natural water content with wetting at the loading stage of 50 kPa is also presented in figure 2, and the test result is in perfect accordance with soil behaviour and collapse magnitudes.

Double oedometer tests carried out for both compacted (improved) conditions are represented in figure 3, just beside figure 2, in order to compare the soil stress x strain behaviour after compaction with the prior to construction condition. It is believed that roller vibrations caused effects as deep as 2,50 meters in the subsoil;even though collapse was not fully eliminated,the soil sensibility to wetting was quite reduced,mainly for lower stress levels. The consolidation curves for the remoulded and laboratory compacted samples show greater effects of the soil treatment process in relation to the collapse reduction, since soil compressibility was minimized and wetting effect almost disappeared.

The collapse dependency on applied pressure is shown in figure 4 for all investigated conditions. The peak values ranging from 10 % to 13 % for natural soil condition were reduced to 2 % to 7 % after soil treatment by compaction, the collapse reduction for the vibratory compaction condition falling within the range for the laboratory compacted condition. For pressure values greater than 200 kPa,the laboratory compacted sample results show constant deformations. For the vibratory roller compacted samples, the collapse peak values were displaced to higher stress levels; in addition, it can be noted a decreasing deformation rate for lower stress levels. It is interesting to notice that the major collapse reduction corresponded to the greater vibration energy applied to the soil by the compaction equipment(16 passes).

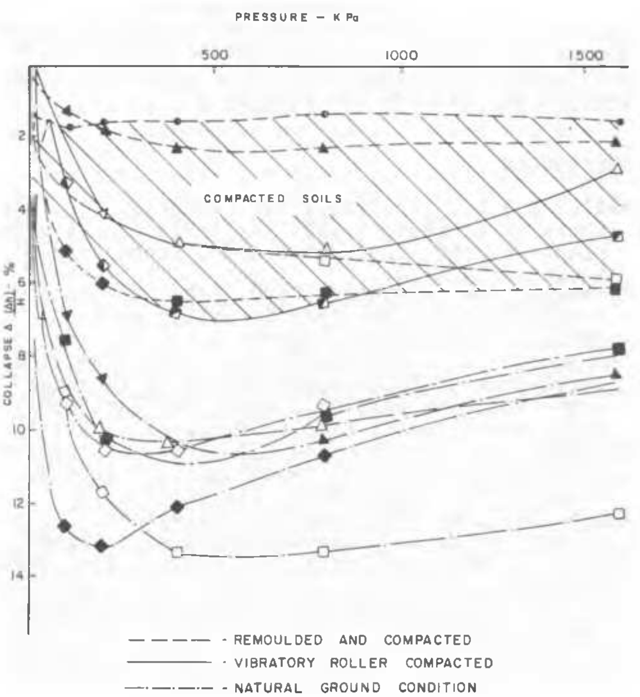

Figure 4. Collapse ranges for both natural ground and compacted conditions.

4 SHEAR STRENGTH AND PERMEABILITY

For the determination of soil shear strength and analyses of its stress x strain behaviour, several consolidated drained triaxial compression tests (CD) were performed, both for undisturbed block samples and remoulded and compacted samples. The specimens were saturated in the triaxial cells by backpressure, at confining pressures of 50 kPa, 100 kPa and 200 kPa. In addition, some direct shear tests(DS) were carried out, on natural water content(NWC) and wetted conditions, in order to investigate the wetting influence on both soil stress x strain behaviour and shear strength parameters ; the tests were performed with normal stresses of 25 kPa, 50 kPa and 100 kPa, for natural ground condition(BLR) and in situ vibratory compaction condition(BLV). Table 2 summarizes all test results, the shear strength parameters being peak values, except BLV-4 at NMC condition. The corresponding stress x strain curves are represented in figures 5 and 6.

Table 2. Shear strength and permeability results.

Samples	Test routine	c' kPa	Ø' º	k m/s
BLI-29				2.4×10^{-6}
BLI-245				2.1×10^{-6}
BLI-250	CD	0	31	6.9×10^{-6}
BLI-277	CD	0	30	2.6×10^{-6}
BLR-3A	DS,wetted	0	34	9.1×10^{-5}
BLR-3B	DS,wetted	0	33	2.1×10^{-5}
BLR-4	DS,wetted	4	32	2.9×10^{-5}
	DS,NWC	24	32	
PIE-29				1.4×10^{-7}
PIE-245	CD	20	34	5.1×10^{-7}
PIE-250	CD	40	33	2.4×10^{-6}
PIE-277	CD	15	31	1.6×10^{-7}
BLV-3	DS,wetted	3	31	8.0×10^{-6}
BLV-4	DS,wetted	3	33	6.0×10^{-5}
	DS,NWC	25	32	

For natural ground condition, almost all performed tests indicated a liner non-cohesive shear strength envelope, with average parameters of c'= 0 and Ø'= 31º for triaxial tests and Ø= 33º for direct shear tests; failure itself was reached at nearly 20 % strain, and did not follow a definite shear plane; the NWC direct shear tests showed an apparent cohesion of 24 kPa that was lost upon wetting, but the angle of internal friction did not change; this additional shear strength is undoubtly associated with the original soil structure cementation, and to the peak resistance observed in stress x strain curves obtained in the NWC test. Vibratory roller's compaction did not increase soil shear strength, although it had introduced a slight cohesion; the corresponding stress x strain curves presented a peak failure behaviour that could be associated to a densification effect; in this case the NWC direct shear test showed highly curved shear strength envelope, but residual shear strength parameters were exactly the same as the peak values for natural ground condition(c'=25 kPa and Ø'=32º). Remoulded and laboratory compacted samples showed a significant shear strength improvement; densification introduced a peak failure behaviour on stress x strain curves, and a greater structural stiffness.

As it may be seen in table 2, the permeabilities

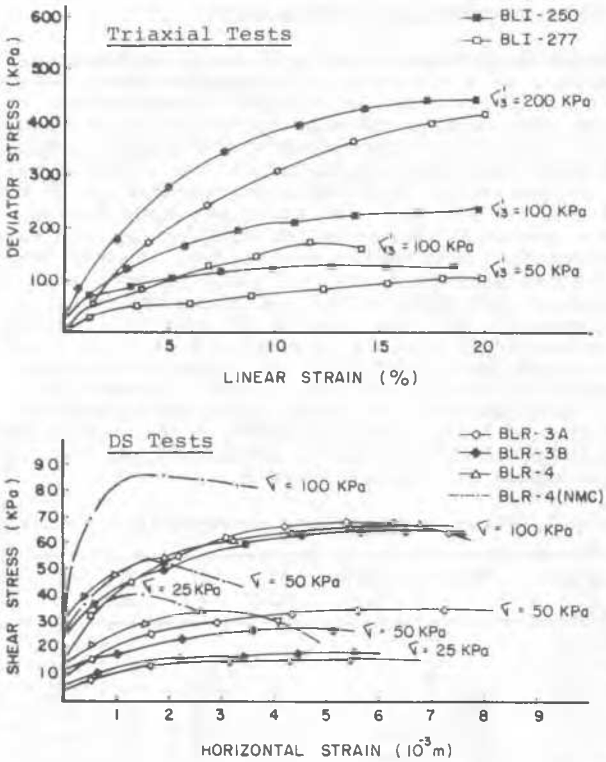

Figure 5. Stress x strain curves for natural ground condition.

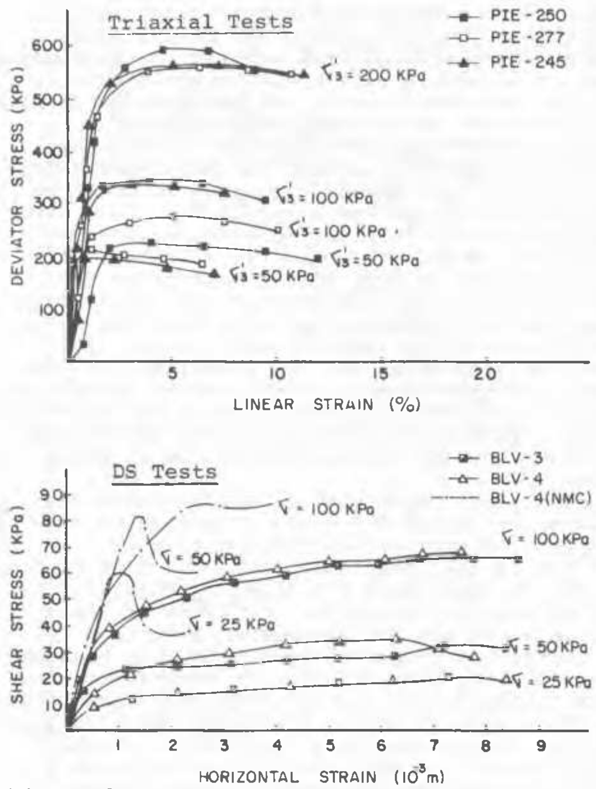

Figure 6. Stress x strain curves for improved soil condition.

were lowered for the laboratory compacted condition, while the effects of the roller vibrations did not cause changes on the permeability.

5 CONCLUSIONS

Two current procedures for sandy soil treatment prior to construction were investigated: in situ vibratory roller compaction and soil recompaction.

Consolidation tests showed the collapse dependency on the stress magnitudes: for natural ground condition the collapse grows in a constant rate up to the peak value of 13 % at 200 kPa, meaning lower risks for light structures or facilities; however, for major structures such as bridges, the stresses on foundation soils approach a critical value and deep foundations are usually adopted. The soil treatment by compaction showed to be a suitable technique for most of the civil engineering works to be carried out along the canal alignments, because the soil deformations on wetting were greatly reduced; the earth filled canal sections can be constructed with compacted material proceeding from the adjacent excavations, and vibratory roller compaction appears to be the more simple and economical solution for foundation treatment prior to construction of small canals or shallow light structures. Combinations of the two soil treatment methods can also be used.

Tested soils may carry a significant cohesion at natural condition, that is lost upon wetting, eventhough the angle of internal friction remained unchanged. Failure occured at very high strain levels, near 20 %, thus, for the stability analises, the shear strength criteria have to be elected strictly according to the expected deformations; for the recompacted soils this condition is not imperative.

The reductions on the coefficients of permeability for the recompacted soils generate a less pervious condition that must be considered in the design, but when the watertighting is required, only proper soil substitution or synthetic liner coating are recommended solutions.

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