

Evaluation of the Collapsibility of Soils in the Semiarid Region of Pernambuco, Brazil

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Abstract: Some unsaturated soils may undergo volumetric changes when submitted to an increase in its water content or are inundated under applied loads. This behavior is related to the volumetric instability when the water content is changed. Natural collapsible soils in Brazil are generally found in alluvial, colluvial and residual soils. There are known occurrences of natural collapsible soils in many states of Brasil. In the last two decades, many public projects have been developed in areas where the occurrence of collapsible soils has been associated to geotechnical problems. The present paper devoted to study the collapsible soils in the state of Pernambuco which has been associated with large engineering projects such as housing and irrigation canals. The geotechnical investigation program included test with a field apparatus, called Expanso-collapsometer, which allows the measurement of the field settlements of a small 0.10 m of diameter plate inserted at any depth inside an auger boring hole. Reconnaissance borings with SPT (standard penetration test), investigation pits with undisturbed block sampling and disturbed samples for laboratory tests were also made in order to assess the type and characteristics of the soil. Field tests used the Expanso-collapsometer to measure the settlement of the soil in selected depths under controlled flooding. Laboratory work included double and standard oedometer tests with a controlled rate of water inflow of 1.0 mL/s. It was found that the volume change of the soils when flooded depends on their natural stress state (vertical stress, suction head and structure of soil).

Key words: Collapsible soils, field tests, laboratory tests.

1. Introduction

In nature, there are structurally unstable soils, unsaturated, in which there are sudden changes in the stress-deformation behavior when the degree of saturation increases. These changes occur either under the in situ overburden stress (self weight), or under increased vertical loading due to engineering constructions done before the degree of saturation increase. They are called collapsible. The collapsible soils can still be considered as: “truly collapsible soils” when not support its own weight, when saturated and collapsed, and “conditionally collapsible soil” when these soils are able to support a certain levels of stress upon saturation [1].

Some conditioning factors are required for the collapse to occur. Some researchers [2-4] identified four conditions: a high enough total stress so that the structure is metastable, an open, partially unstable, unsaturated soil fabric, cementing agent to stabilize the structure when dry or a strong enough clay binder and the addition of water to the soil which reduces the soil suction and, thus, produces the collapse.

The identification of collapsible soils and prediction of collapse are important in preventing damage to structures and foundations. Ferreira [5] classified the research methods of collapsible soils in direct and indirect methods. Indirect methods utilize simple relationships among several physical parameters of soils, such as moisture content, voids ration, dry density, Atterberg limits and clay content, which have been proposed in the literature as indicators of the soil

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collapse potential [6-10]. Rafie et al. [11] made applications of these criteria for central desert Semnan soil, Iran.

These are only qualitative and limited, not taking into account the influence or state of stress acting on the soil mass or the intergranular cemented soils, even slightly cemented. Direct methods are based on the extent of collapse potential and collapse prediction of deformations using field and laboratory tests and consider the stresses acting by measuring vertical deformations at natural moisture content and saturation [6, 12-17].

Collapsible soils may manifest in residual, colluvial, alluvial, aeolian, soporific and compacted soils. These soils are found in many parts of the world, United States of America, Brazil, Argentina, Uruguai, Spain, Australia, Kuwait, Egypt, Iran, South Africa and China, particularly in arid and semi-arid regions [2, 18]. The majority of naturally occurring collapsing soils are wind-deposited sand and/or silts [1, 5, 11, 19, 20]. Alluvial soils are laid down by water in a saturated state. They become hard and less compressible with relatively low density as they dry. The structure is usually open and porous, and soil grains are bonded together by cementing agents during the deposition. Residual soils have suffered a pedogenic process which results in a macro-voided structurally unsaturated soil [13, 14].

In Brazil, they occur in several states: Amazonas, Bahia, Ceará, Goiás, Mato Grosso, Minas Gerais, Pernambuco, Piauí, Rio Grande do Sul, São Paulo, Tocantins and the Federal District. This paper presents characteristics of volume change due to inundation of collapsible soils of the States of Pernambuco, in northeastern Brazil, in cities of Petrolina, Petrolândia and Salgueiro. These soils are enough evolved containing with a predominant clay mineral kaolinite [5]. The soils from these three sites are chosen because they are involved in irrigation projects and in large housing construction.

In Petrolina, there are fluvial deposits with

predominance of sandy soils (dystrophic quartz sands) with a slightly undulating to planar relief. The climate is hot, with a mean temperature above 18 °C, and the rainy season in the summer. The mean annual precipitation lies between 250 mm and 500 mm with peaks of 800 mm.

In Petrolândia, there is an alluvial surficial soil from the Tacaratu Formation, which is characterized by a medium to coarse sandstone, occasionally conglomeratic. The relief is planar, the climate is hot and semi-arid. The mean annual temperature is above 18 °C, and the maximum and minimum rainfall is 930 mm/y and 80 mm/y, respectively, with a mean of 437 mm/y.

In Salgueiro, there are fluvial deposits with predominance of sandy soils (dystrophic quartz sands). The climate is tropical semi-arid and its average annual temperature is 25 °C. Rainfall in the city ranges from 450-600 mm/y, the wettest months from December to March, with scarce and poorly distributed rains, xerophytic scrub vegetation and temporary rivers.

2. Geotechnical Investigation Program

The investigation program developed in order to analyze the behavior of collapsible soils has two phases: field and laboratory work.

The field investigations consisted of geotechnical characterization of the subsoil, extraction of representative soil samples and undisturbed block samples, and evaluated the volumetric changes in situ due to inundation at different depths with the Expanso-collapsometer. The laboratory tests consisted of grain size analysis and the evaluation of the influence of the stress state on the collapse behavior due to inundation, by means of single and double oedometer tests.

In the single oedometer tests, the applied vertical stresses were increased with the ratio $\Delta\sigma/\sigma = 1$, with an initial stress of 10 kPa up to 1,280 kPa. The duration of each stage was such that the deformation

between two consecutive time intervals ($\Delta t/t = 1$) were less than 5% of the total deformation up to the previous recorded time. The vertical deformations due to inundation were measured at 0, 0.10, 0.25, 0.50, 1, 2, 4, 8, 15, 30, 60, 120, 480 and 1,440 min.

Some tests of the Petrolina soils adopted a specific methodology which was employed in order to compare the field results of Expanso-colapsometer with laboratory results of single oedometer tests.

In double oedometer tests, a specimen was loaded at the natural water content while the other was previously inundated under a vertical stress of 1.35 kPa with an inundation rate of 1.0 mL/s. In other aspects, the procedure was similar to that of single oedometer tests. The vertical stresses were the same as those used in the single specimen tests. The unloading stresses were 640, 160, 40 and 10 kPa. Each stage (loading and unloading) was maintained during 24 h.

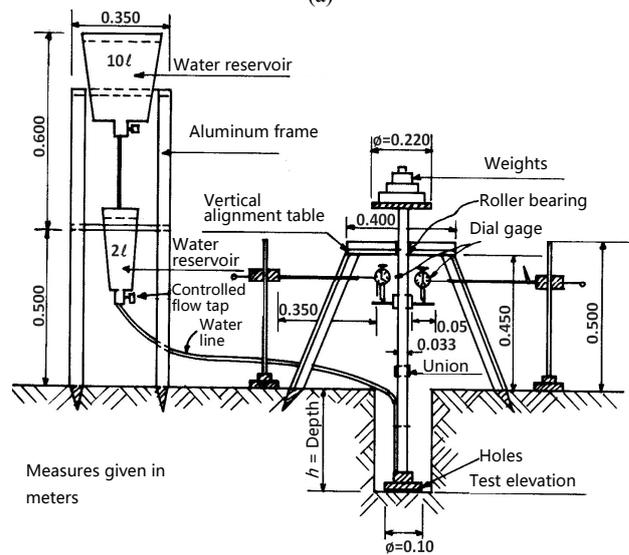
In the field, the Expanso-colapsometer was used, shown in Fig. 1. Some authors [16, 21-24] describe its principles in details. It is a simple equipment that permits the measurement of vertical movements of unsaturated soils. It permits to follow in the field the same stages of single and double oedometer laboratory tests, preserving the natural water content and structure of the soil. The curve of stress applied at the plate against vertical deformation is obtained at the desired depths. Inundation can be applied with control of the discharge rate. This equipment identifies potentially collapsible or expansive soils. The equipment is composed of two parts. The first simulates a plate load test (plate diameter of 100 mm) and the second is the controlled inundation kit. These tests were done at the three locations. In Petrolândia, tests were made at a depth of 0.5 m and the loading stages followed the ratio $\Delta q/q = 1$. The vertical stresses at which inundation was allowed were 10, 20, 40, 80 and 160 kPa. The duration of each stage was established such that the difference in vertical movements between two consecutive readings was less than 5% of the previous movement, with time

intervals $\Delta t/t = 1$. The soil was inundated with a discharge rate of 1.0 mL/s.

In Petrolina, the tests were performed at different locations, depths and inundation at different vertical stresses: 50, 130, 140 and 180 kPa, with inundation rates between 0.8 mL/s and 1.0 mL/s. In Salgueiro, the tests were performed at different locations and depths and inundation at different vertical stresses: 50 kPa and 100 kPa, with inundation rates at 1.0 mL/s. After the tests, the water content of the soil under the



(a)



(b)

Fig. 1 Expanso-colapsometer—equipment for in-situ measurement of volume change with time under controlled water flow: (a) Expanso-colapsometer—first version [21, 22]; (b) Expanso-colapsometer—current version [24].

plate was performed each 0.10 m under the plate depth until the water content was the same of the original soil. This permitted the evaluation of the wetting bulb at all sites.

3. Results and Discussion

3.1 Geotechnical Soil Profiles

The soil profile at Petrolina consists of two layers before the impenetrable layer from SPT (standard penetration test) borings was reached (Fig. 2a). The first layer consists of clayey sandy silt, loose to medium dense, yellow brownish in color, with a thickness of 3.5 m. The second is silty fine sand, with gravel, mica, very dense, grayish yellow, with a thickness of 0.15 m. The impenetrable layer to standard penetration resistance (N_{SPT}) is a schist of equigranular texture, moderately weathered with a slight dip and small quartz veins. The phreatic level was found at a depth of 2.9 m.

In Petrolândia, two SPT soundings were performed. The first was without water circulation, with the soil in its natural water content. The second was in a previously inundated soil. In both cases, the soil is about the same, fine sand with little medium sand, yellow, medium to very dense (Fig. 2b). At a depth of 5.5 m, there is a highly resistant layer (45 blows/0.1 m). No water level was found up to 5.6 m when the boring was interrupted (impenetrable to the SPT sampler). N_{SPT} values ranged from 10-56 at a depth of 5.3 m, the number of blows increases almost linearly with depth. These high values are due to the high suction of the soil that had a natural water content varying from 1.6%-3.3%. The second boring, with pre-wetted soil, showed N_{SPT} values ranging from 7 blows/0.30 m at 0.35 m to 19 blows/0.30 m at 5.3 m, a reduction of 30% at shallow depths to 70% at the end of the collapsible layer, showing that the reduction in suction is the governing factor in the standard penetration test results. This sounding was continued up to 9.4 m, as shown in the Fig. 2.

The soil profile at Salgueiro up to 3.0 m deep,

obtained of the auger boring, is a silty sand and it is non-plastic in majority (Fig. 2c). The groundwater level was not found until the depth of investigation.

Fig. 3 shows the activity and plasticity chart of these soils. The points are located slightly above Line A and the liquidity limits lie between 15% and 65%. The soil from Petrolândia is non-plastic. The majority of the soils from three sites are classified as SP (poorly graded sand) and SM (silty sand).

3.2 Oedometer Tests

The variation of collapse and expansion potentials with the vertical stress obtained from double oedometer tests (Eq. (1)) is shown in Fig. 4. The collapse potential

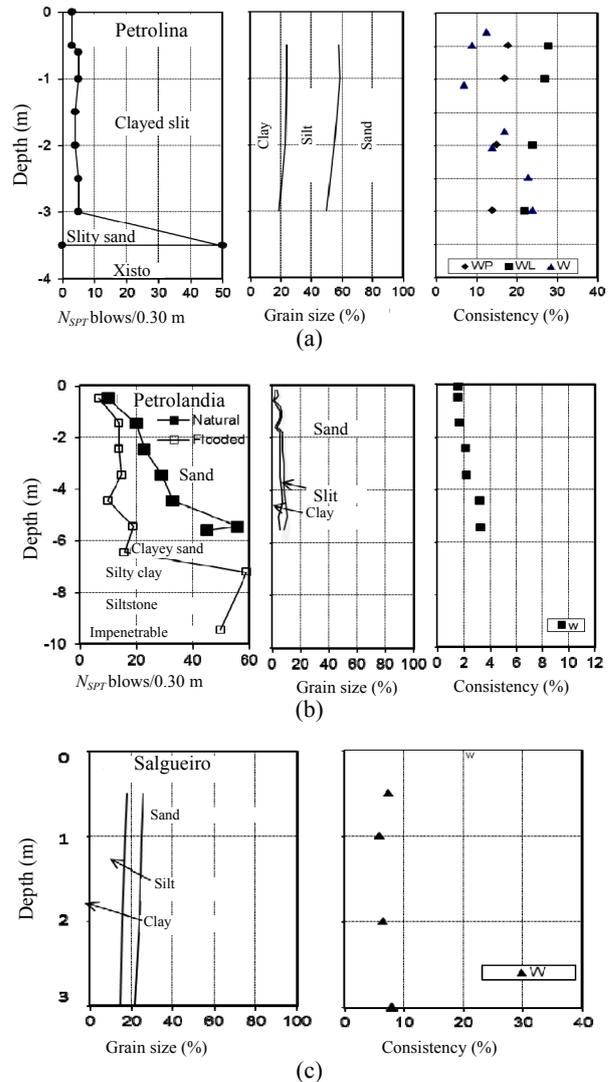


Fig. 2 Typical soil profiles at the three sites.

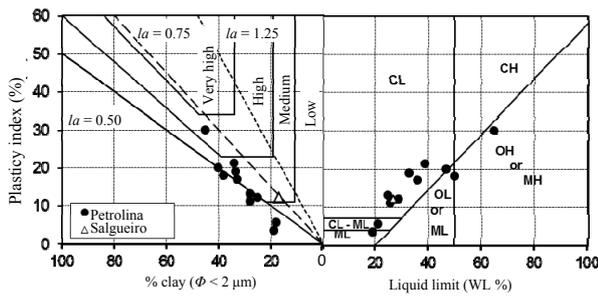


Fig. 3 Plasticity and activity charts [25] of the soils.

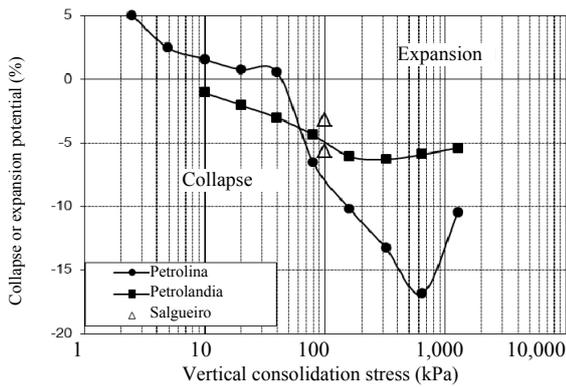


Fig. 4 Collapse/expansion potential as a function of vertical consolidation tests—double oedometer tests.

of the Petrolândia soil increases with vertical stress, reaching a maximum at 320 kPa. The same behavior was observed with the Petrolina soil, which showed maximum collapse under a stress of 640 kPa. This is a typical behavior of collapsible soils [5, 25-27]. In Petrolina, a small expansion was measured for vertical stress smaller than 40 kPa, indicating the presence of expansive minerals. The activity clay [28] varies from the mean to normal activity (Fig. 3).

$$CP \text{ or } SP (\%) = (\Delta H/H_i) \times 100 \quad (1)$$

where, *CP* is collapse potential, *SP* is swelling potential, ΔH is the variation of the specimen thickness due to saturation and H_i is the initial thickness.

Based on parameters extracted from the oedometer test and considering the basic engineering judgment

concerning soil collapsibility, some data have been summarized in Table 1. Criterion offers various different judgment for soil collapsibility. The soils of the three sites are collapse intensity by Abelev [6]. Medium and high collapsibility judgment by Lin and Wang [29] and trouble judgment by Jennings and Knight [13]. The soils of Petrolina and Salgueiro are conditional collapsible soils and Petrolândia is conditional collapsible soils and truly collapsible soils by judgment (Fig. 5) [1].

A comparison of the collapse potential obtained from single and double oedometer tests is presented in Fig. 6. The values of collapse potential determined through single oedometer tests are greater than those obtained in double oedometer tests (Eq. (2)). The wetting path followed in these tests (loading— inundation or inundation—loading) has an influence on the values of the collapse potentials. Similar results were found by Ferreira [5] and Benvenuto [30].

$$CP_{DO} = 1.04 CP_{SO} + 1.08|r| = 0.949 \quad (2)$$

where,

CP_{DO}—collapse potential, double oedometer test;

CP_{SO}—collapse potential, single oedometer test;

|*r*|—correlation coefficient.

3.3 Comparison between Field and Laboratory Values

Typical curves of variation of collapse (%) due to wetting with the logarithm of time (min) and the variation of the volumetric strain variation with the applied vertical stress obtained from single oedometer tests and with the Expanso-collapsometer are shown in Fig. 7.

In the laboratory, the time necessary for 98% of the total deformation due to collapse after inundation varies from 1 min to 30 min. The values of collapse

Table 1 Collapsibility coefficient and collapse intensity results regarding to defined criteria.

Proposed criterion	Petrolina	Petrolândia	Salgueiro
[1]	5.9% > 2 collapse intensity	14.1% > 2 collapse intensity	5.8% > 2 collapse intensity
[29]	4.8% medium collapsibility	9.2% high collapsibility	4.6% medium collapsibility
[13]	Trouble	Trouble	Trouble

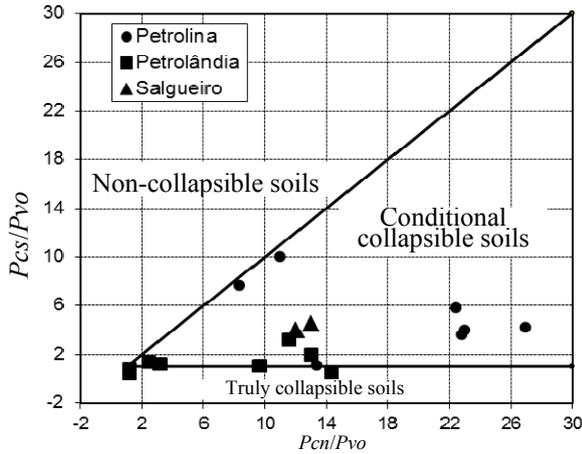


Fig. 5 Judgment of Ref. [1] (P_{cs} —collapse stress for saturated soil, P_{cn} —collapse stress for soil at natural moisture content, P_{vo} —vertical stress due to overburden stress).

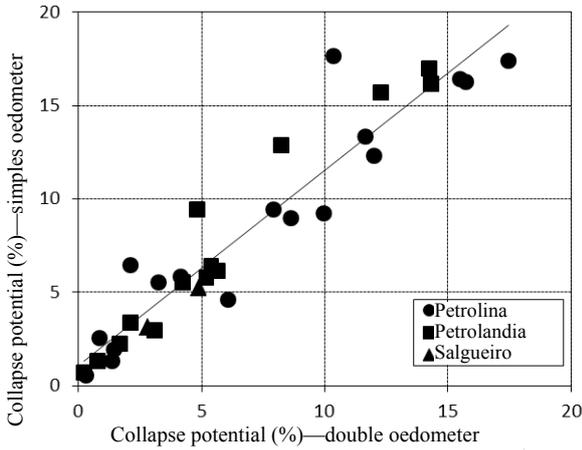


Fig. 6 Correlation of collapse potential in single and double oedometer tests.

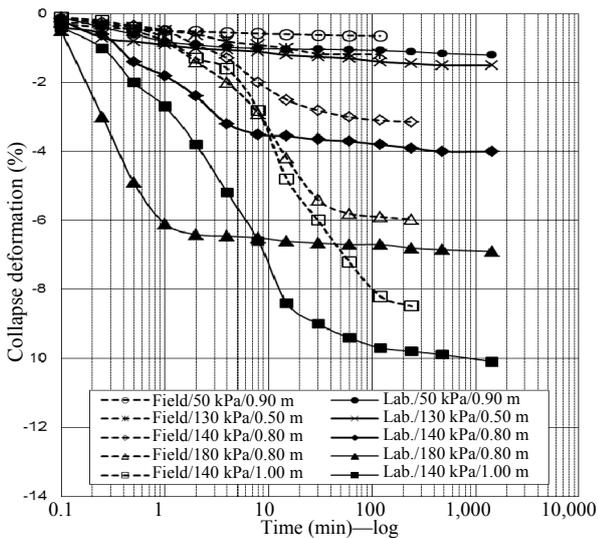


Fig. 7 Collapse vs. log time—Petrolina soil.

potential with time determined in the field are smaller than those of the laboratory tests from ranging 20% to 40%. The difference can be attributed to the smaller percolation path in the laboratory specimen, about 2 cm in thickness, thus, reaching the final water content in less time, as the curves of the Fig. 6 show. This behaviour had been verified before [5].

Furthermore, it was found that the collapse potential measured in the field is smaller than those measured in the laboratory (Fig. 8). The relationship between these two values is approximately linear (Eq. (3)). A similar value 0.85 was also found in another study in a collapseable soil of Petrolândia [5].

$$CP_{field} = 0.84 CP_{lab} \quad (3)$$

Such a fact is associated to the following factors: non uniformity of the vertical stress under the plate in

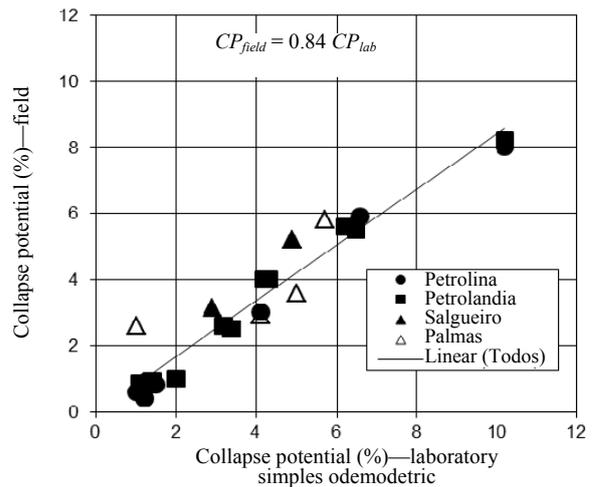


Fig. 8 Relationship between collapse potential obtained in field and laboratory tests.

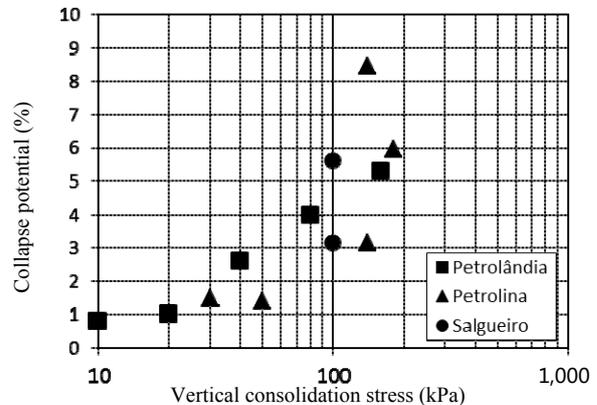


Fig. 9 Collapse potential values obtained in field tests.

the field, which diminishes with depth but it is natural, and the non-uniformity of water content, which also decreases with depth. This behavior was similar to that found in collapsible soil of Petrolândia and Palmas [16, 22, 24].

The results of field collapse potential against vertical stress for the three sites are shown in Fig. 9. The values of the collapse potential grow with the addition of stress flooding. The lowest values of the collapse potential were found in soils of Petrolina in relation to those obtained in soils of Petrolândia and Salgueiro.

4. Conclusions

The volumetric strain of the studied is about 15% smaller in the field as compared to laboratory tests.

The collapse potentials measured in the field are, for all locations, smaller than those measured in the laboratory. The relationship between these two values is approximately linear, $CP_{\text{field}} = 0.84 CP_{\text{lab}}$.

The Expanso-collapsometer performed satisfactory, its main advantage being that it is not necessary to carve undisturbed blocks in a very unstable and dry soils, besides maintaining the original state of stress in the field practically unchanged.

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