Collapsible clayey soils in the north-eastern region of Venezuela

José I. Amundaray, Alvaro Boiero
Amundaray Ingeniería Geotécnica, C.A., Caracas, Venezuela
Escuela de Ingeniería Civil – Universidad Católica Andrés Bello, Caracas, Venezuela.-

2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
In Venezuela, collapsible soils are encountered mainly in the West of the country, especially in the south plains of the states of Anzoátegui and Monagas, and in the south region of the Orinoco River, from the city of Ciudad Bolívar to city of Puerto Ordaz. These soils typically require special treatments to avoid the use of expensive foundation systems. Recently, extensive deposits of collapsible soils have been found in the industrial area called Jose, where even though intense industrial construction activity has been developed, the existence of collapsible soils was not known. In this work, the characteristics of collapsible soils from this region are described, as well as the methods recommended for field exploration, in situ, and laboratory testing. Useful correlations are proposed for the identification and treatment of these soils. The main objectives of this article are to make the geotechnical community aware of the presence and potential risks of collapsible soils in this region, as well as to provide tools for their recognition and treatment.

RESUMEN
En Venezuela, los suelos colapsables se encuentran principalmente en el oeste del país, especialmente en las llanuras del sur de los estados Anzoátegui y Monagas, y además en la región al sur del río Orinoco, desde Ciudad Bolívar hasta Puerto Ordaz. Estos suelos por lo general requieren tratamientos especiales para evitar el uso de sistemas de fundación costosos. Recientemente, extensos depósitos de suelos colapsables han sido encontrados en la zona industrial de José, donde a pesar de una intensa actividad de construcción industrial, la existencia de suelos colapsables no se conocía. Este trabajo describe las características de los suelos colapsables de esta región, así como los métodos recomendados para su exploración en campo, y los ensayos de campo y de laboratorio. Además, se proponen correlaciones útiles para la identificación y el tratamiento de estos suelos. Los principales objetivos de éste artículo son el hacer la comunidad geotécnica consciente de la presencia y riesgos potenciales de los suelos colapsables en esta región, y el proporcionar herramientas para su reconocimiento y su tratamiento.

1 INTRODUCTION

In Venezuela, collapsible soils are encountered mainly in the West of the country. In the last decades, this type of soil has been identified and studied in diverse sites where important industrial plants have been constructed, especially in the south planes of the states of Anzoátegui and Monagas, and at the south regions of the Orinoco River, from the city of Ciudad Bolívar to the city of Puerto Ordaz. These soils typically require the use of soil improvement techniques or the use of expensive foundations to ensure the good behavior of the structures to be supported on them (Amundaray & Lupini, 1986). Recently, extensive deposits of collapsible soils have been found in the area called Jose, where even though an intense industrial construction activity has been developed in the last years, it was not known for having collapsible soils. In the past, hard soils with swelling potential and big pockets of liquefiable soils have been identified in the developments executed in the North area of Jose; which is near the sea and shows a flat morphology.

The deposits of collapsible soils found recently are located at the south where the morphology is formed by low slope hills. The collapsible soils of Jose are likely of alluvial origin, made up of earth flows generated by the typical intense rains of this region.

When earth flows are developed, their saturation levels are high and their corresponding void ratios are high. After they reach a static condition, these soils dry off quickly by evaporation. Then, the generated capillary tension draws smaller particles of clay, silt, and probably disolved salts towards the points of contacts among sand particles, forming bridges of cementation that keeps an stable structure while the partial saturation is maintained, Figure 1. These deposits are erratic with variable thicknesses depending on the topography (Coduto, 1994).

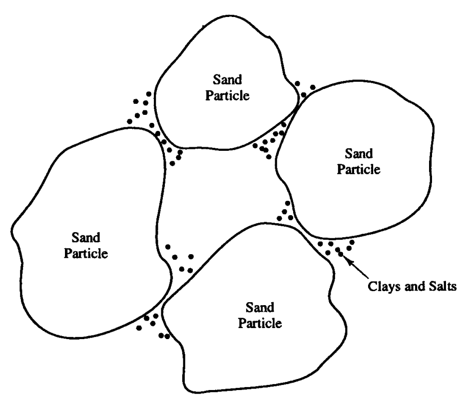

Figure 1. When deposits of highly saturated earth flows dry off by evaporation, clay particles and salts move towards the points of contact among sand particles (from Coduto, 1994)

The identification and characterization of collapsible soils in the area of Jose becomes a new requirement for future industrial developments in the zone. Therefore, there is a need for making the industrial and geotechnical communities aware of the potential risks that these soils represent, as well as for developing practical tools for their recognition, study, and treatment.

2 IDENTIFICATION OF COLLAPSIBLE SOILS

Collapsible soils are characterized by low density, high void ratio, and partial saturation . They show light cementation and suffer drastic volume reductions under full saturation, without requiring any change in external pressures. These soils are usually found in shallow deposits quite homogeneous in their composition but with variable thickness. In the Jose area, such deposits have been found with thicknesses up to 6 m.

2.1 Standard Penetration Test

The penetration resistance values (SPT) of these soils are generally lower than 10. However, it is necessary to take some precautions when performing the SPT such as avoiding the use of water injection and the use of driven casing to prevent the collapse of the soil prior to the execution of the SPT. Usually, the hole walls are stable for collapsible soils and the use of casing is unnecessary. The effect of early collapse during the execution of the SPT is shown in Figure 2, where SPT penetration resistance values from dry test are compared with others where water was used for perforation.

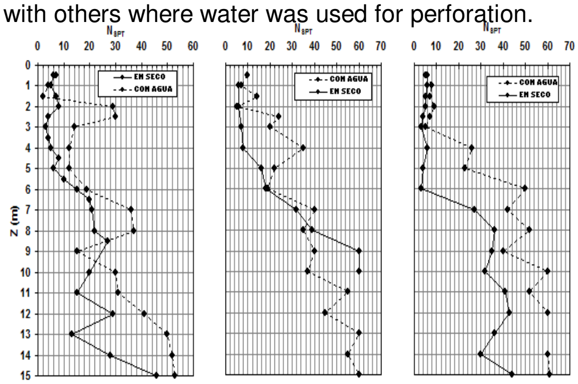

Figure 2. Comparison of values of SPT values measured in dry conditions and using water injection.

The use of water and a driven casing induces a significant and random increment in soil density, giving the impression that the soil has a higher penetration resistance than its actual value (Geohidra, 1997; Geohidra, 1998).

2.2 Test pits exploration

Visual identification of collapsible soils in test pits is of crucial importance. In test pits excavated in collapsible soils in the area of Jose, it was observed that walls are stable.During the excavation, the soil broke down in big and fragile blocks, as shown in Figure 3. These blocks are light easy to disaggregate with bare hands.

Figure 3. Excavation in collapsible soils showing vertical walls and big lumps of soil.

Along the walls of the test pits, typical cavities and voids are frequently observed, they act as natural pipes for percolating rain water, producing piping and increasing the fragility of these soils. Many cavities are also associated with the activity of insects and other animals. Typical cavities found in tests pits are shown in Figure 4.

Figure 4. Natural cavity in collapsible soils found during an excavation.

3 UNDISTURBED SAMPLING

Undisturbed sampling of collapsible soils in the area of Jose can be done easily due to the cementing agents and high fine content of these soils. It can be done with Shelby tubes or manually in the test pits. Shelby tubes of 5,40 cm and 7,50 cm diameter have been used successfully to retrieve undisturbed samples, as well as carved cubic samples, and 4 and 6 inch diameter ring samples. However, retrieving undisturbed samples in other regions could be more difficult if the soils are more sandy or have less cementation. Retrieving of undisturbed collapsible soil sample with ring sampler is shown in Figure 5.

Figure 5. Undisturbed samples with ring.

4 COLLAPSIBLE SOILS CLASSIFICATION

The soil classification tests performed on undisturbed samples, that were used for collapse tests, showed unexpected results since the visual classification of such soils in the field always indicated fine clayey silty sands (SM-SC). However, the vast majority of the laboratory classification indicated low plasticity clays (CL) or sandy silty clays (CL-ML), as shown in Figure 6.

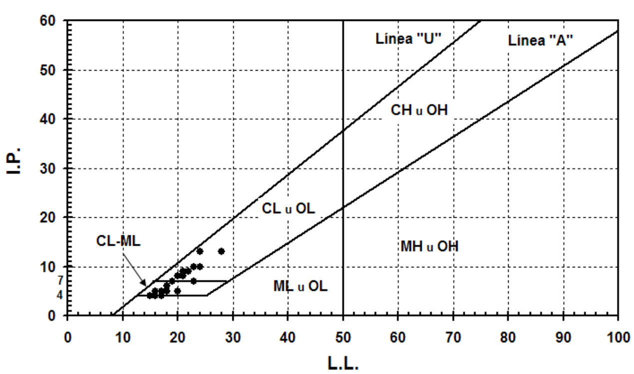

Figure 6. Classification of collapsible soils using the Casagrande's plasticity card

These soils, in their natural moisture content (w = 5,4 ± 1,6 %) present a very fragile consistency and a sandy texture, but once saturated they shift into the typical plastic and soft consistency of clayey soils. For the case of collapsible soils found in Jose, the application of the Unified Soils Classification System (U.S.C.S.) can generate confusion, because the fragile behavior of these soils does not correspond with the traditional definition of clays.

The average grain size distribution curve for 10 samples that were used to perform collapse tests is shown in Figure 7. The envelope of all the measurements is well defined. If the limint between clay and silt is considered as 2µ as per the M.I.T criteria, then 24% is clay, 33% is silt, 37% is fine sand, and 6% is medium to coarse sand.

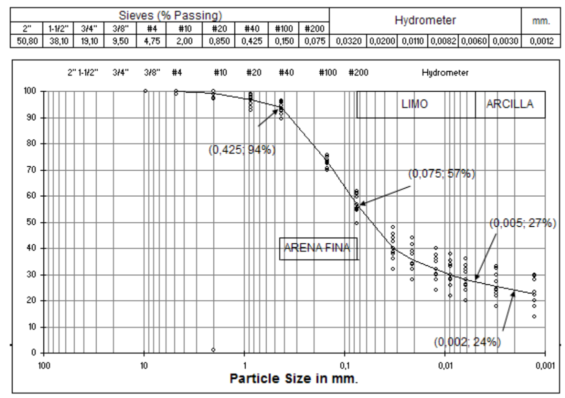

Figure 7. Granulometric curve of average trend of studied collapsible soils

The classification tests are very useful for identifying collapsible soils in this area because they are very homogeneous.Hence, the plots shown in Figures 6 and 7 can be used as guidelines when the presence of these soils is suspected. However, these plots are representative of the Jose area, and particular plots should be developed for different places.

5 MICROSCOPE OBSERVATIONS

Scanning electron microscope (SEM) pictures taken on representative samples of Jose collapsible soils showed that the sand particles have semi-rounded shape, and are surrounded by smaller clusters of fines, as shown in Figure 8. This semi-rounded shape of sand grains is consistent with the hypothesis of an alluvial origin. Furthermore, the fines clusters surrounding the sand particles, might explain the granular behavior of these soils at their low moisture natural condition.

The undisturbed soil structure is shown in Figure 9, where voids of relatively big size can be observed. Some of those voids seem to be associated with the activity of micro-plants. The structure of the same soil once collapse has happened is shown in Figure 10, where a denser particle arrangement and the reduction of the voids is observed.

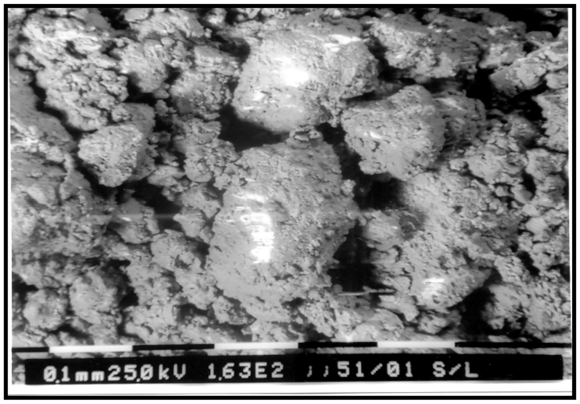

Figure 8. Micrograph obtained in the electronic microscope of sweep of one you show of collapsible soils of Jose.

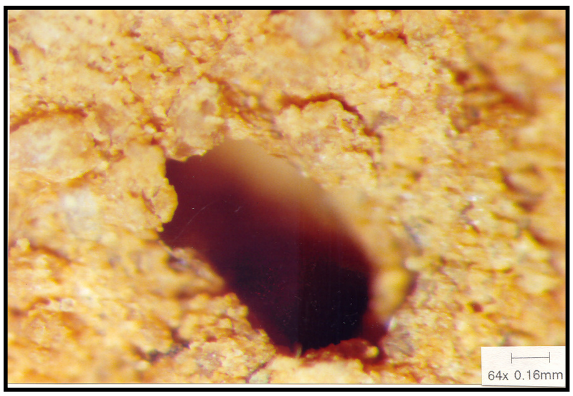

Figure 9. Micrograph showing the structure of collapsible soils of Jose.

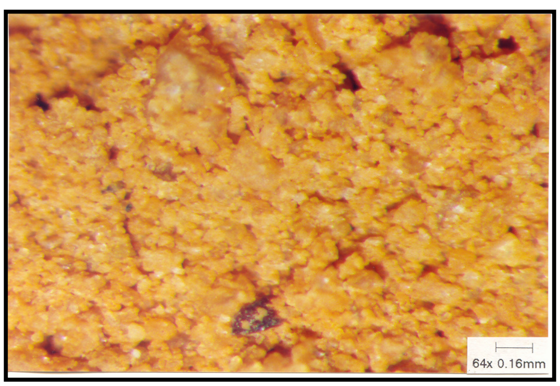

Figure 10. Structure of the soil after collapsed.

6 COLLAPSE TEST

The collapse test was implemented and successfully used to determine the collapse potential of soils from eastern Venezuela in geotechnical studies for industrial plants in the cities of Ciudad Bolívar and Puerto Ordaz (Geohidra, 1986), following the procedure suggested by Jennings and Knight (1975). Later, the American Society for Testing Materials (ASTM), published the standard D-5333 in 1992, under the name *"Standard Testing Method for Measuring the Collapse Potential of Soils"* (ASTM, 2000). The standard method is indeed very similar to that proposed by Jennings and Knight (1975), achieving a precise and clear selection of terms and definitions.

In the ASTM standard D-5333, the *"collapse"* is defined as *"a vertical descent of a confined soil after saturation, under the application of an applied constant vertical stress"*. The standard also specifies that *"a collapsible soil can withstand the application of relatively high vertical stresses with small deformations at a low moisture content, but this same soil will suffer settlement (that could be high) with no additional stress increment when an increment in moisture content occurs. The application of high vertical stresses is not necessary for the collapse to ocurr"*.

The objective of the collapse test is to determine the *Collapse Index (Ie)*, which represents the percentage of the relative collapse magnitude under a stress of 2 kg/cm^2 and calculated according to the expression:

$$Ie = (\Delta h/ho) \times 100 \quad [1]$$

Where Δh = change in sample height after saturation; *ho* = original sample height.

The test consists in placing a soil sample at its natural moisture content in an oedometer cell. then, a pre-established vertical stress is applied and the saturation process is started to induce the sample collapse. With the measured *Ie* value, the probable settlement magnitude can be estimated for a layer of collapsible soil with a thickness H when it is subjected to 100% saturation.

Based on the findings of Jennings and Knight (1975) on the severity of the problems caused to structures by soils with different collapse potentials, the ASTM standard D-5333 proposes the following classification:

Table 1. Collapse Index classification

Degree of collapse	Collapse Index
None	0.0
Light	0.1 – 2.0
Moderate	2.1 – 6.0
Moderately severe	6.1 – 10.0
Severe	> 10.0

Soils with *Moderate* degree of collapse can suffer deformations in excess of 2% when saturated, which can generate undesirable deformations to the structures. For this reason, any soil with a collapse index higher than 2 should be improved to guaranty the stability of a proposed foundation..

The results of 33 collapse tests performed on soils from the Jose area are summarized in in Figure 11 (Group Delta, 2001; Ingeniería Geotécnica Prego 2001, 2002, 2003). This figure shows a linear correlation between the *collapse index* and the *dry density (kN/m³)* of the soil in its undisturbed conditions. The coefficient of determination is R^2 = 0,85.

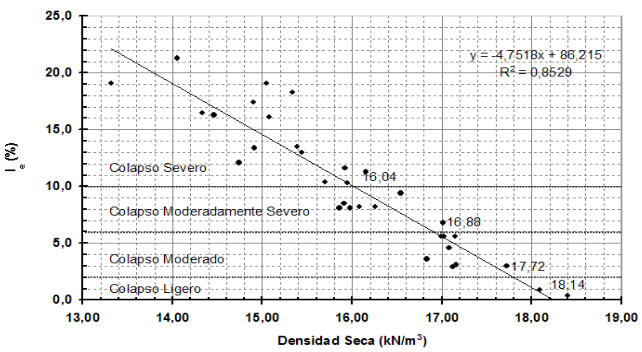

Figure 11. Linear correlation between the *collapse index* and the *dry density (kN/m³)* of collapsible soils from the Jose area. Based on these results, *dry density* ranges can be defined for the different *collapse indices*, as shown in Table 2:

Table 2. Suggested limits for *dry densities* for soils from the Jose area.

Degree of collapse	Collapse Index	Dry density[1]
None	0.0	> 18,14
Light	0.1 – 2.0	17,72 – 18,14
Moderate	2.1 – 6.0	16,88 – 17,72
Moderately severe	6.1 – 10.0	16,04 – 16,88
Severe	> 10.0	< 16,04

[1]dry density in kN/m³

When the presence of collapsible soils is suspected in the Jose area, the in situ *dry density* measurements can be used to estimate the collapsible index from Figure 11. In addition, the soil classification and its grain size distribution can be compared with the trends presented in Figures 6 and 7..

7 LOAD TESTS

In situ load tests have been performed in collapsible soils to validate laboratory results. Figure 12 shows the results of field load tests following the ASTM standard D-1194, which requires the saturation of the area after applying a vertical stress of 2 kg/cm².

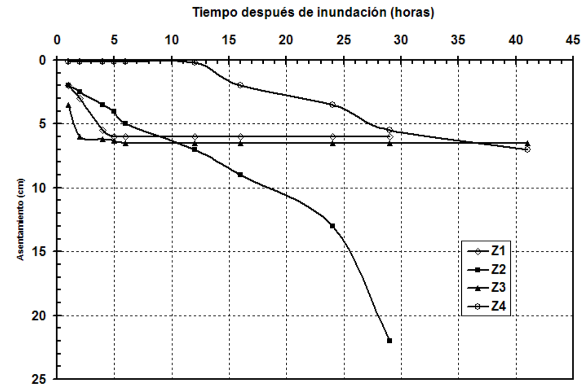

Figure 12. Load test results in collapsible soils of Jose

It can be seen that the magnitude of the recorded collapses varies between 6 cm and 22 cm. These results not only confirm the collapse values obtained in laboratory tests, but also validate the applicability of such tests to reproduce the occurrence of in situ collapse. It is important to highlight, that given the high permeability of these soils (10 a 20 ft/day), water can penetrate fast and quite deeply and produce the settlement of a foundation in a period of 24 hours (Group Delta, 2001).

8 COLLAPSE EVENTS

8.1 Collapse in trench due the rain water

The heavy rains on July the 22nd and the 23rd, 2001, provoked the opening of two sumps on the bottom of a trench opened for the piping of power lines, telephone and fiber optics cables. The size of the sumps was approximately 0,60 X 0,60 m and 1,5 X 1,0 m and it was reported that a large amount of water was flowing into the subsoil through both of those holes. Tension cracks of approximately 15 X 12 m with elliptical shape appeared around the trench. These cracks affected the structures of surrounding buildings and a compressor adjacent to the trench. The phenomenon can be observed in Figures 13 and 14.

The possible cause of the phenomenon is presumed to be the collapsible nature of the soils, composed by fine silty sands and sandy silts, whose structure might be prone to collapse in the presence of water. This soil was isolated from rainwater by a layer of compacted soil, but once the trench was excavated the subjacent collapsible soil was exposed. This fact, together with the occurrence of heavy rains that kept the trench flooded for more than 12 hours was enough to generate the collapse without the application of any external loads.

Figure 13. In-situ measurement of the induced settlement in collapsible soils of area of Jose.

Figure 14. Crack and settlement in the area of collapse of the soils after intense rains.

8.2 Drainage channel collapse

Drainage channels on collapsible soils are prone to generate collapse problems due to water seepage. In Figure 15, the occurrence of a 5 cm settlement due to collapse after a rain can be observed. It is presumed that the water infiltrated through the construction joint saturating the subjacent collapsible soil.

8.3 Settlement around a catch basin

The opening of cavities and natural piping is commonly observed where rainwater tends to pond (see Figure 16). Such cavities can increase in size and number due to the effect of successive rains, provoking larger collapses with time.

8.4 Settlement of soil due to a water truck

In a cut area where collapsible soil outcrops were found, the traffic of water trucks caused settlements of approximately 10 cm after raining (see Figure 17). In the same place, under dry conditions, no settlement was observed.

Figure 15. Settlement of 5 cm induced by the collapse of the underlying soil

Figure 16. Settlement of an area close to a water structure with an opening cavity.

Figure 17. Evidence left by the step of a truck whale on area in court of collapsible material after rain

9 CONCLUSIONS

Recently, large deposits of collapsible soils up to 6 m thick have been found in the Jose area. These deposits are located in what is called south Jose, where the topography is formed by low hills and it is presumed its alluvial origin.

Classification plots for collapsible soils shown in Figures 6 and 7, can be used as a guide for comparison when the presence of collapsible soils is suspected.

There is a linear correlation(R^2 = 0,85) between the *collapse index* and the soil *dry density* (kN/m^3) in undisturbed state, for a statistical sample of 33 collapse tests.

In cases where the presence of collapsible soils is suspected, a measurement of in situ *dry density* can be compared with the plot shown in Figure 11 in order to establish the severity degree of its collapse potential.

The results of in situ load plate tests confirmed that the magnitudes of collapse obtained in laboratory tests, and validate the applicability of laboratory tests to reproduce the occurrence of collapse in the field.

The identification and characterization of collapsible soils in the Jose area is a new compulsory requirement for future industrial developments. Therefore, it is necessary to warn the industrial and geotechnical communities about the potential risks that these soils represent.

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