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COLLAPSE POTENTIAL OF SOILS AND SOIL-WATER CHEMISTRY

SUSCEPTIBILITE A LA RUPTURE BRUSQUE ET INTERACTION CHIMIQUE ENTRE LE SOL ET L'EAU
ПРОСАДОЧНЫЕ СВОЙСТВА ГРУНТОВ В ЗАВИСИМОСТИ ОТ ХИМИЧЕСКОГО СОСТАВА ВОДЫ

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SYNOPSIS: A new criteria to predict collapse potential of soils is presented, based on double oedometer tests. The concept of "collapse pressure" and the Coefficient of Collapsibility C_c , are established. Truly and conditionally collapsible soils are defined. Results of oedometer tests of Argentine soils saturated with various types of liquids disclose variable collapse behavior, depending on whether saturation is caused by drinking water, sewage, or acidic water. Analysis of soil-liquid chemical interaction suggest that collapse of soil tested is due to dispersion of the intergranular clay cementing fraction.

SOMMAIRE: On presente ici un nouveau critere pour predire la susceptibilite a la rupture brusque des sols fonde sur des essais oedometriques doubles. On determine la notion de "pression de rupture brusque" et le coefficient de rupture brusque C_c . Il est aussi donne la definition des sols vraiment susceptibles de rupture brusque ou conditionnellement susceptibles de rupture brusque. Des resultats des essais oedometriques faits avec des sols argentins, satures avec des differents sortes de liquides, signalent un comportement variable a la rupture brusque selon qu'ils soient satures avec de l'eau potable, avec des liquides des cloaques, ou de l'eau acide. L'interpretation de l'action chimique entre le sol et l'eau indique que la rupture brusque des sols essayes est due a la dispersion de la fraction argile qui constitue le ciment intergranulaire.

INTRODUCTION

Some macroporous soils, located above the ground water table and normally non-saturated are able to withstand loads with minor deformations as long as the degree of saturation remains low. If these soils become saturated a sudden and large reduction of volume takes place, due to the collapse of the intergranular structure. Sometimes this phenomena occurs even with no increase of the loads acting on the soil mass.

Several criteria have been established by various researchers to predict whether a soil is susceptible to collapse upon saturation. A fairly complete and comprehensive resume of the criteria developed up to 1969 was submitted by Sultan⁷ (1) to the Specialty Session on Loess and Other Collapsible Soils, at the

(1) Numbers refer to the Reference List at the end of this paper.

VII ICSMFE, Mexico. Most of these criteria are based on rather simple relationships among several physical parameters of soils, such as voids ratio, moisture content, Atterberg limits, and density. These are only qualitative and limited, not taking into account the influence of the state of stress acting on the soil mass, or the intergranular cementation. Thus, it happens that for some cemented soils, even slightly cemented, these criteria may indicate danger of collapse, which never takes place when the soil is actually saturated and loaded. Denisov⁷, and Jennings and Knight³, used double oedometer tests to determine the magnitude of settlement due to collapse, by measuring vertical deformations at natural moisture content and saturation.

For collapsible soils, the magnitude of settlement which takes place upon collapse is generally of such magnitude that almost no structure can tolerate it. Therefore it is

more important to determine whether collapse will occur, rather than how much settlement will take place. In addition, when analyzing the susceptibility of a soil mass upon saturation, it is necessary to consider the stresses acting on the soil due to external forces, the body stresses, and the stress level which the soil can support without excessive deformation, for several degrees of saturation.

The new criteria presented herein to determine the susceptibility to collapse meets the requirements stated above. It is based on double oedometer tests, from which a pair of logarithm of pressure vs. strain (or voids ratio) curves are obtained, one at natural moisture content, other under saturated conditions. (Figure N^o 1). A "Coefficient of Collapsibility" is computed on the basis of results of these tests.

For these tests various specimens are trimmed from the same undisturbed sample. One is tested at natural moisture content, with non-absorbent disks above and below, and the others are saturated and subjected to conventional consolidation tests, with porous disks above and below the specimen.

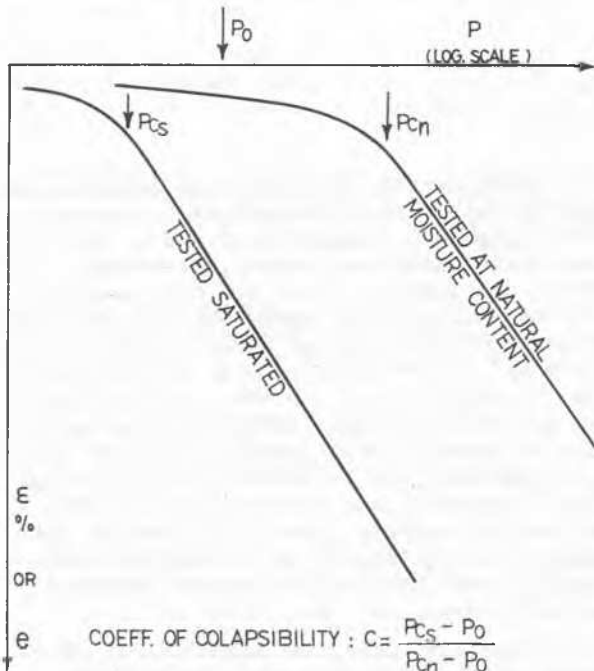


FIGURE 1

TRULY COLLAPSIBLE AND CONDITIONALLY COLLAPSIBLE SOILS

In several ways the collapse phenomena is the opposite to the classical consolidation process. Water is absorbed by the soil and the moisture content at the end of the collapse is higher than before the process started; the shear strength of the soil is considerably reduced; the volume reduction due to collapse takes place in a rather short period of time upon saturation. However, the test curves obtained from oedometer tests for both processes are fairly similar (Fig. 1). There is a limiting value for pressures, beyond which deformations increase considerably. This particular pressure value, however, cannot be considered to be a pre-consolidation pressure, because it varies with the degree of saturation and with the type of liquid saturating the soil, as it is shown in the second part of this paper. Furthermore, in this case the better ability of the soil to support loads at stress levels below this limiting value is not due to past stress history, but to the strength of the intergranular cementation of the soil. It is proposed herein that the term "collapse pressure" be used to define this limiting pressure when analyzing collapsible soils.

The following pressure parameters will be used to determine degrees of susceptibility to collapse:

P_0 : Vertical pressure due to overburden stress

P_{cn} : Collapse pressure for soil at natural moisture content.

P_{cs} : Collapse pressure for saturated soil

P : Total vertical pressure acting on the soil at a given level.

P_{cn} and P_{cs} are determined from oedometer tests. For collapsible soils, $P_{cn} > P_{cs}$. In general, for any kind of soil in natural state $P_{cn} \geq P_0$. For collapsible soils, however, oedometer test results indicate that in many cases $P_{cs} < P_0$. When this occurs, the soil will not support its own weight upon saturation, and large settlements will take place even if no external forces are acting.

By comparing the values of P_0 , P_{cn} , P_{cs} and P for a given soil and state of stress, it is possible to predict the soil behavior upon saturation, to determine whether there is danger of collapse, and at what stress level such collapse will take place.

1) When $P_{cs} < P_0$: The soil will not support its own weight when saturated. Soils with these characteristics are defined as "Truly

Collapsible Soils".

2) When $P_{cs} > P_0$: These soils will be able to support a certain level of stress upon saturation. The possibility of collapse depends on whether P is larger or smaller than P_{cs} . Soils with these characteristics are defined as "Conditionally Collapsible Soils". When $P < P_{cs}$, no collapse will take place when the soil becomes saturated. The maximum stress increment above P_0 which the soil can support is $P_{cs} - P_0$. If $P_{cs} < P < P_{cn}$, collapse will occur when the soil becomes saturated after loading. If $P > P_{cn}$, collapse will happen even at non-saturated conditions.

COEFFICIENT OF COLLAPSIBILITY

The above concepts could be better defined by the following relationship:

$$\text{Coefficient of Collapsibility } C = \frac{P_{cs} - P_0}{P_{cn} - P_0}$$

When $C < 0$, the soil is truly collapsible. Large settlements will take place upon saturation even if no external loads are acting.

When $0 < C < 1$, the soil is conditionally collapsible. Whether collapse will occur will depend on the value of P in relationship to P_{cs} and P_{cn} .

When $C = 1$ the soil behavior will be the same for any degree of saturation. Very few soils will behave like this. C is usually smaller than 1 for most soils, including non-collapsible ones.

When $C = -\infty$, $P_{cn} = P_0$. This is the case of non-cemented, normally consolidated soils.

VARIATION OF SUSCEPTIBILITY TO COLLAPSE OF SOILS WITH CHEMICAL CHARACTERISTICS OF SATURATING LIQUIDS

Analysis of actual cases of collapse in soils predominant in the Córdoba region of Argentina (Reginatto⁵), indicate that such phenomena is strongly dependent on the characteristics of the liquid saturating the soil. Thus it is frequently noted that damage to buildings is generally more severe for cases of ruptured sewage pipes, than for cases of saturation with plain water, for instance.

A research program to investigate the susceptibility of soils to saturation with various liquids was developed at the Soil Mechanics Laboratory of the National University of Córdoba. Basically it consisted of performing a series of oedometer tests on specimens trimmed from undisturbed samples, at natural

moisture contents, and saturated with three different types of liquids which could normally be expected to seep into the soil mass under various circumstances. Susceptibility to collapse for the different soils tested under these conditions was determined with the Coefficient of Collapsibility C , defined in the first part of this paper. The chemical interaction between saturating liquids and soils was also analyzed by means of chemical tests, to determine amount of soluble cations, pH, cation exchange capacity, sodium absorption ratio, percentage of interchangeable Na, and other characteristics for soils and liquids.

Soil Characteristics

The soils tested are macroporous, from loessic deposits which are common in the Córdoba area. Figure 2 shows the Atterberg limit values for representative samples.

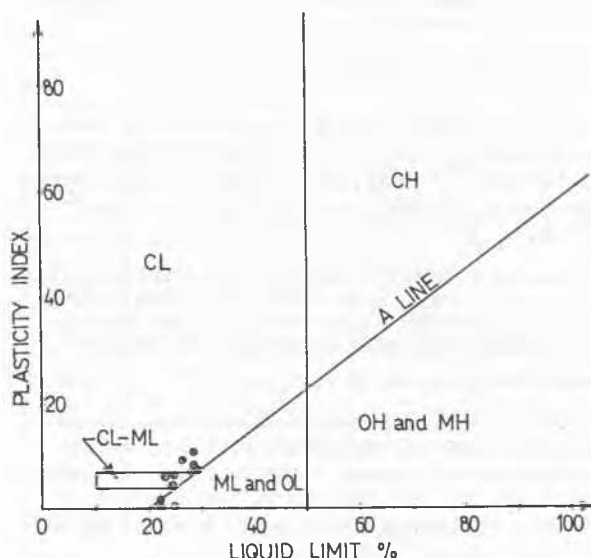


FIGURE 2

The material could be described as buff to brown clayey SILT to SILT & CLAY, and contains a small amount of calcareous concretions. It classifies as ML and CL in the Unified Classification System. Mineralogical X-ray tests indicate that the clay minerals are predominantly illite, with small proportions of montmorillonite and kaolin. Soil pH values are on the alkaline side, ranging from 7,5 to 8,5. Table 1 shows chemical characteristics

It is difficult to differentiate the material from different levels and places on the basis of routine identification tests. Yet the behavior upon saturation is quite different

TABLE 1

SAMPLE N°	DEPTH m	SOLUBLE CATIONS me/liter						EXCHANGE CATIONS me/liter						SAR	
		Ca	Mg	Na	K	Σ	Na%	Ca	Mg	Na	K	Σ	T		Na%
A-1	1.0-1.2	2.3	3.1	16.0	2.2	23.6	67.7	8.4	4.5	3.0	2.7	18.6	18.5	16.1	9.7
A-2	2.0-2.2	2.4	3.4	20.8	1.1	27.7	75.1	5.7	1.9	4.0	1.8	13.4	13.5	29.6	12.3
B-1	0.7-1.0	3.6	2.4	0.8	0.1	6.9	11.6	11.6	3.2	1.3	1.8	17.9	18.0	7.3	0.5
B-2	1.3-1.7	14.0	2.8	1.2	0.2	18.2	6.6	11.9	4.1	2.0	2.2	20.2	20.0	9.9	0.4
B-3	2.0-2.4	10.0	6.0	26.0	0.2	42.2	61.6	8.7	3.8	3.8	1.8	18.1	17.9	21.0	9.2
B-4	3.0-3.4	3.0	2.3	52.8	1.4	59.5	88.7	7.6	3.3	6.0	1.5	19.4	19.4	31.0	32.5
B-6	4.7-5.0	3.1	2.9	104.0	0.5	110.5	94.1	3.6	3.3	10.0	1.9	20.8	20.6	48.0	60.0
B-7	5.7-6.0	8.0	6.8	50.8	0.2	65.8	77.2	3.8	4.1	9.6	1.6	19.1	17.6	50.5	18.7
B-8	6.7-7.0	5.6	1.6	44.0	0.1	51.3	85.9	5.8	5.3	11.7	2.0	24.8	22.2	47.0	23.1
B-9	7.7-8.0	6.0	2.0	70.4	0.1	78.5	89.6	4.1	3.3	15.3	1.8	24.5	21.2	62.2	35.2
70/132	12.0-12.2	2.4	0.8	0.8	0.5	4.5	17.7	19.5	3.9	1.2	1.0	25.6	25.1	4.7	0.6

depending upon the nature of the liquid, location and depth of the sample, etc. Normally these soils are not saturated in natural state. Common values for natural moisture contents range between 10 and 15%. Saturation values are 30 to 35%.

Liquid Characteristics

The liquids used in the tests were:

1) Plain drinking water from the city water supply system, with a pH value varying from 6.5 to 6.8. It could seep into the soil from pipe leaks, garden irrigation, and other causes.

2) Domestic sewage (septic tank effluent), which could seep into the soil from broken pipes, or through seepage pits from household sewage disposal systems. pH values ranged from 8.5 to 9.0.

3) Acidic water with pH values from 5.5 to 5.6, obtained by leaching distilled water through topsoil mixed with decayed vegetable matter (peat). It simulated percolation of rain water through the upper topsoil layer into the deeper soil mass.

Table 2 presents results of chemical tests on these liquids.

TABLE 2

	Drinking water	Domestic Sewage	Acidic water
pH	6.5-6.8	8.5-9.0	5.5-5.6
Na me/l	0.5	2.2	0.5
K "	0.08	0.7	0.7
Ca "	1.9	2.1	0.5
Mg "	3.1	2.6	0.4
Total cat.	5.58	7.6	2.1
SAR	0.3	1.4	0.8

me/l: milliequivalents / liter.

SAR: Sodium absorption ratio.

OEDOMETER TEST RESULTS

Figures 3 through 5 show typical results of the oedometer tests. The letters identifying each curve indicate test conditions as follows

- A: Test at natural moisture content.
- B: Saturated with drinking water
- C: Saturated with domestic sewage
- D: Saturated with acidic water.

Some of the curves show either a vertical drop or a rise at the beginning of the test. This is due to sudden collapse or slight

expansion upon saturation, respectively.

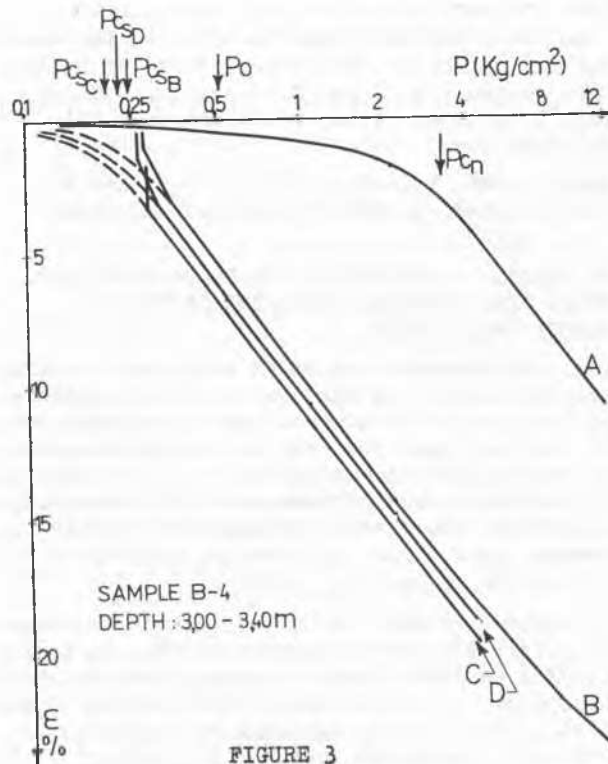


FIGURE 3

Figure 3 shows behavior of a soil which is truly collapsible regardless of the type of saturating liquid.

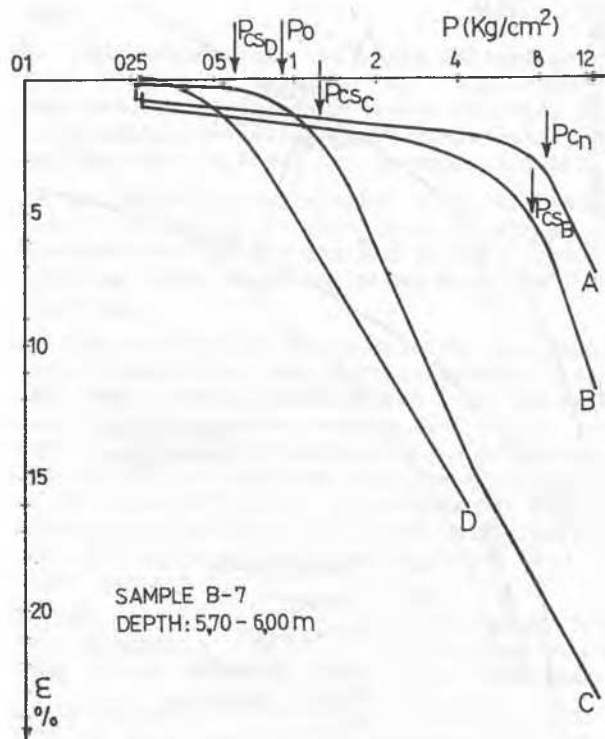
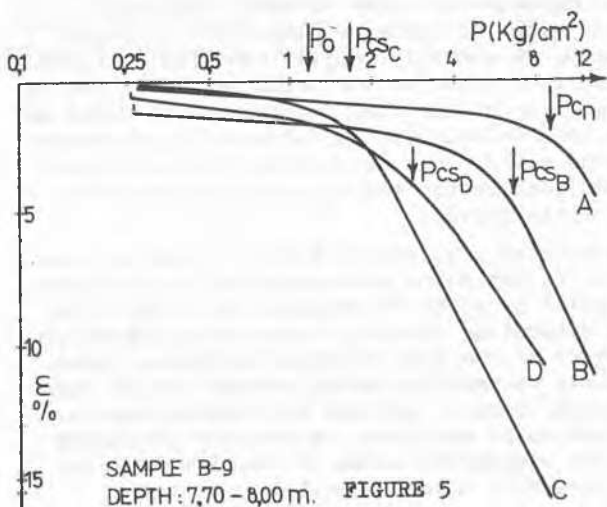


FIGURE 4

Figure 4 shows a slightly cemented soil which is capable of supporting a fairly large pressure (7.6 Kg/cm²) when saturated with drinking water, but it is conditionally collapsible if saturated with sewage, and truly collapsible with acidic water.



The soil in Figure 5 presents some cementation and can withstand fairly large pressures when saturated with drinking water (6.7 Kg/cm²), or acidic water (2.9 Kg/cm²), but it is conditionally collapsible if saturated with sewage.

Table 3 presents the values of the Coefficient of Collapsibility C obtained for the three saturating liquids and different soil samples. It is noted that dry density is not a governing factor for collapse. In fact, some of the most stable soils have the lowest densities.

TABLE 3

SAMPLE N°	DRY DENS. g/cm ³	VALUES OF COEFF. OF COLLAP. C		
		Drinking water	Sewage	Acidic water
A-1	1.28	C > 0 Condit. Collaps.		
A-2	1.33	C > 0 Condit. Collaps.	C = -0.015 Truly Collaps.	
B-1	1.28	C = +0.018 Condit. Collaps.	C = +0.487 Condit. Collaps.	
B-2	1.28	C = +0.024 Condit. Collaps.	C = -0.01 Truly Collaps.	
B-3	1.29	C = +0.024 Condit. Collaps.	C = -0.026 Truly Collaps.	C = -0.016 Truly Collaps.
B-4	1.28	C = -0.094 Truly Collaps.	C = -0.01 Truly Collaps.	C = -0.104 Truly Collaps.
B-6	1.28	C = +0.071 Condit. Collaps.	C = -0.17 Truly Collaps.	
B-7	1.24	C = +0.87 Stable	C = +0.045 Condit. Collaps.	C = -0.04 Truly Collaps.
B-8	1.28	C = -0.024 Truly Collaps.	C = -1.12 Truly Collaps.	
B-9	1.38	C = +0.69 Stable	C = +0.063 Condit. Collaps.	C = +0.21 Stable
70/132	1.20	C >>> 0 Stable	C >>> 0 Stable	

CHEMICAL INTERACTION BETWEEN SOILS AND SATURATING LIQUIDS

Various researchers (Aitchison and Wood¹, Kassiff and Henking⁴, Sherard⁶) have demonstrated that piping erosion phenomena observed in earth dam embankments is caused by dispersion or deflocculation of the clay fraction upon saturation. The dispersion of the clay is governed by a number of properties of the clay, including the Sodium Adsorption Ratio (SAR), exchangeable sodium percentage (ESP), pH, soil type, and the content of dissolved salts in the water. Ingles and Aitchison² have generalized this to natural soil deposits and embankments.

An analysis of the chemical interaction between collapsing soils and saturating liquids strongly suggests that, for the soils tested, the collapse is due to dispersion of the clay fraction which provides the interparticle bonding cement. Ingles and Aitchison² have related graphically the total concentration of cations of liquids with the ESP of soils, setting up the limits for flocculated stable, potential deflocculation, and deflocculated stable states, for illite and montmorillonite clay soils. Such a plot is shown on Figure 6.

One interesting fact to be pointed out is the variation noted in the pH of the acidic water after saturating the soil. Oedometer tests were performed in fixed ring consolidometers, saturated from bottom to top. After the acidic water seeped through the soil, the water collected at the top of the sample had changed to pH values of about 8, while no appreciable change took place for either drinking water or sewage. This fact has not been yet fully investigated. Additional research is being carried to determine how liquids are chemically modified by soils, and the effect of such changes in collapse.

Some of the points plotted on Figure 6 do not correspond exactly to the limits set by Ingles and Aitchison²; a few points representing collapsible soils fall outside the limiting curves into the stable areas. The two points at the lower right for acidic water may not belong there, since the chemical characteristics of the liquid was changed by the soil, and therefore it may be more correct if the points be displaced in accordance with the modified chemical composition of the liquid, probably upwards.

On Figure 6 the values corresponding to the soil and liquid combinations tested have been plotted, indicating whether the behavior of the soil was truly or conditionally collapsible, or stable.

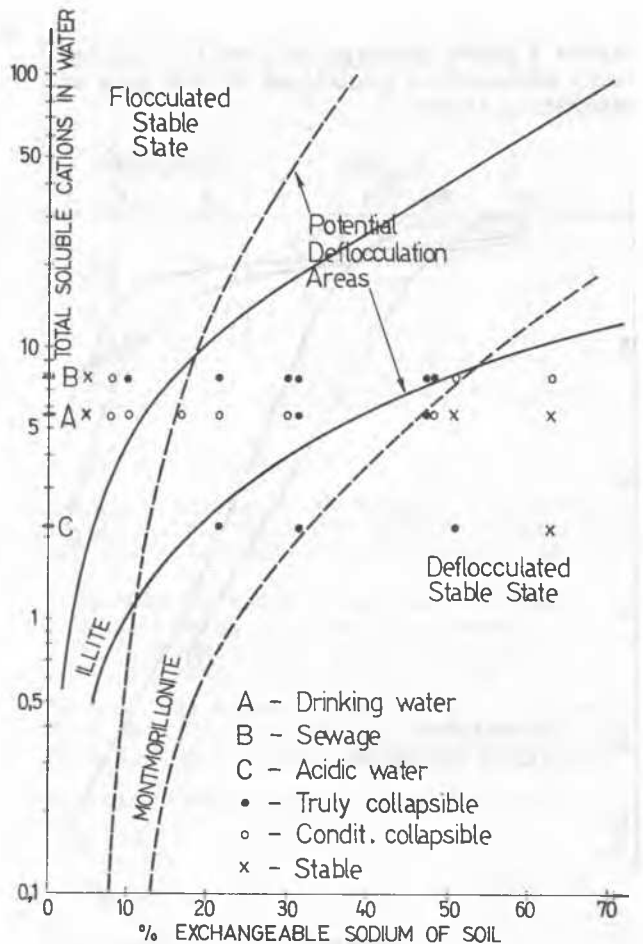


FIGURE 6

There are enough correlations of points representing truly and conditionally collapsible soils with the areas of potential deflocculation, to strongly suggest that the collapse which took place in the soils tested is due to dispersion of the clay fraction which makes up the bond between the particles of these macroporous soils. Thus sensitivity to dispersion or deflocculation would govern collapse for the soils tested.

The authors are confident that it may be possible to determine susceptibility to collapse of soils by means of chemical tests on soils and saturating liquids, which are quicker and cheaper to run than multiple oedometer tests. Further research is being carried out on this subject. Results and new conclusions are expected to be available in time for inclusion in the Discussion Volume of the Proceedings of this VIII International Conference.

CONCLUSIONS

1- Determination of soil collapsing potential by means of the Coefficient of Collapsibility C , furnishes a quantitative way to predict the expected behavior of soils upon saturation.

2- Truly collapsible soils are defined as those which when saturated will not support the stresses produced by the overburden, P_0 . Large volume reductions take place upon saturation even without any external loading.

3- Conditionally collapsible soils are those able to support a certain level of stress upon saturation. The maximum stress increment above P_0 which these soils can stand is $P_{cs} - P_0$.

4- Oedometer tests at natural moisture content and at saturation with various types of liquids which could normally seep into the soil mass (drinking water, sewage, and acidic water) disclose variable collapse behavior. Some soils are truly collapsible regardless of the type of liquid, but others may be stable when saturated with drinking water, and show various degrees of collapse for other liquids.

5- Dry density is not a governing factor for the collapse of the soils tested. Some of the most stable soils have the lowest densities.

6- An analysis of the chemical interaction between soils and liquids suggests that the collapse of the soils tested may be due to dispersion or deflocculation of the clay fraction which constitutes the cementing bond between the mineral particles of the soil. Thus sensitivity to dispersion would govern collapse for the soils tested.

7- The determination of the sensitivity to collapse of soils by means of chemical tests of soil and saturating liquids, which are simpler and quicker to run than multiple oedometer tests, is a promissory possibility.

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