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The Influence of Stress-path in the Collapse-swelling of Soils at the Laboratory

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SUMMARY The influence of stress-path in the collapse-swelling of soils has been thorougly studied at the laboratory. The final volume change is path dependent in the swelling zone, but not in the collapse zone. Notwithstanding, for most of the wetting processes around foundations or in canals, a final state curve for every final suction value may be used. The equivalent oedometric moduli to be used for the use of elastic methods in these soils have been studied.

NOTATION

E_{oed} = oedometric modulus (MPa)
N = number of points to find the regression
p = external pressure (kPa)
p_m(kPa) = geometric average external pressure corresponding to the interval of E_{oed}
p_s = external soaking pressure (kPa)
S.E. = standard error
ε = strain (%). Negative values correspond to swelling and positive values to settlement

1 INTRODUCTION

So as to serve as a basis for the finite element methods indicated in two companion papers, the influence of stress-path in the collapse-swelling behaviour of partly saturated soils is being thoroughly studied at the laboratory.

Test have been carried out in several types of common oedometers, in constant moisture content oedometers (Justo and Saetersdal, 1981) and in suction-controlled oedometers. Both compacted and undisturbed samples have been tested.

A partly saturated soil may suffer volume changes due to pressure or suction changes. It has been observed that the stress-path has an important influence in the final void ratio reached.

It has also been observed that the type of oedometer has an important influence in volume changes probably owing to friction along the walls. For this reason the conclusions reached may be considered as preliminary.

2 SOILS TESTED

From the soils tested, the following are the most important:

a) Clay of El Arahal (Seville)
Sand 14%, silt 36%, clay 50%
w_L = 55-75 I_p = 30-44 w_s = 20-23
CEC 21,8 meq./100 g
Mineralogical analysis of clay:
kaolinite 14%
illite 34%
montmorillonite 52%
CO_3 Ca 27.8%

b) Clay from Camas (Seville)
Sand 1%
w_L = 59-66 w_P = 18-22 I_P = 39-44

c) Soils from Puente Genil (Córdoba)

3 THE COLLAPSE-SWELLING OF COMPACTED SOILS

Most of the tests refer to the clay of El Arahal. The Atterberg limits were:

w_L = 75 w_P = 31 I_p = 44 w_S = 20

The compaction conditions were:

w_{opt} = 29.5% ρ_{max} = 1.40 $g.cm^{-3}$
w = 23% ρ_{max} = 1.43 $g.cm^{-3}$ I_L = -0.18

The soil was thus compacted at the Proctor maximum density, 3% above the shrinkage limit, 8% below the plastic limit and 6,5% below the optimum moisture content.

3.1 Tests in normal oedometers

Fig. 1 shows the "natural moisture content" curve of loading. This curve may be obtained in two ways:

a) Loading a sample with one day duration increments in a natural moisture content oedometer.

b) Employing immediate load increments in a common oedometer so as to avoid the drying of the sample.

The results obtained in both cases are not very different, but in case b) settlements are larger, specially for large pressures.

The same figure shows the curve obtained soaking the sample under loading. The "soaking under loading" curve obeys to the equation:

$$\varepsilon = -20.40+16.07 \log p -6.37(\log p)^2+1.49 (\log p)^3 \quad (1)$$

"Free swelling" is defined as the swelling of a soil under a small "nominal" pressure that according to the authors may range from 1 to 10 kPa. This definition implies that the value of the nominal pressure is not important as far as it is small. Figure 1 shows that this is untrue. So, the word free swelling alone should never be used, and the nominal pressure should be clearly specified.

When we apply the "swelling pressure-3" to the sample, soaking does not produce any deformation on it. Below the swelling pressure-3, soaking produces swelling, and above collapse. It is obtained by

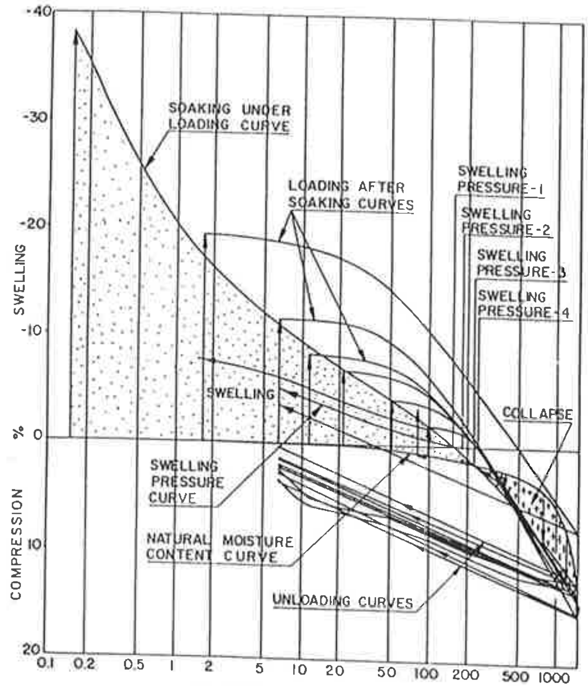

Figure 1 Soaking tests on compacted samples of El Arahal

intersection of the "natural moisture content" and the soaking under loading" curves.

The "swelling pressure-2" is the one obtained in a swelling pressure test, and is slightly smaller than the swelling pressure-3, and similar to "swelling pressure-1", corresponding to the intersection of the "soaking under loading" curve with the null deformation line.

The "loading after soaking" curves stay above the "soaking under loading" curve in the swelling zone (fig. 1). This result, confirmed by several authors (v. Justo and Saetersdal, 1981), contradicts the assertions of Blight (1965) who found a unique loading curve, coinciding with the "soaking under loading" one. This point will be commented when talking about the double oedometer test.

The "swelling pressure-4" corresponds to the crossing of any of the "soaking under loading" curves with the null deformation line, is independent of the soaking pressure when this soaking pressure is somewhere between 5 kPa and a pressure somewhat below the swelling pressure-1, and is similar to swelling pressure-3. When the soaking pressure becomes smaller than 5 kPa, the intersection of the "loading after soaking" corve with the null deformation line (that we do not call any more swelling pressure-4) greatly increases.

The fact that swelling pressure-2 is somewhat smaller than swelling pressure-3 shows that swelling pressure slightly increases with soaking pressure, as in the first case the soaking pressure is the small pressure applied by the piston cap, and in the second case the soaking pressure coincides with the swelling pressure.

We see that not only the final values of pressure and suction are important, but also stress-path, although as far as the swelling pressure is concerned, the differences are not important (v. Brackley, 1975; Chen, 1975).

On the other hand, in the collapse zone stress-path has little influence in the final deformation reached (fig. 1), a result already found by other authors (v. Blight, 1965; Justo and Saetersdal, 1981).

The "soaking under loading" curve is nearly independent upon whether we have employed method a) or b) of loading.

Shrinkage before flooding does not affect greatly the final void ratio reached. Subsequent cycles of shrinkage-swelling have a negligible influence upon strain.

Although some differences have been noticed, from a practical point of view the slope of the different unloading curves in a semilog scale is relatively constant.

Stress-path is also very important when unloading processes are implied. As indicated in figure 1, if the soil is soaked under load and then unloaded, the final expansion is much less than when the soil is unloaded under natural moisture conditions and then soaked (in this case it reaches the "soaking under loading" curve). It is very important to follow the right stress-path in the study of canals in cut on expansive clay.

3.2. Tests in suction-controlled oedometers

In suction-controlled oedometers the sample was first loaded and then suction was brought up to zero step by step (fig. 2). Unfortunately very few tests have been made, but the following preliminary conclusions have been reached:

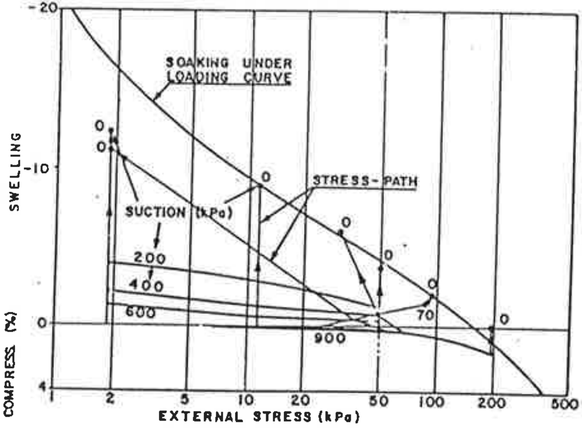

Figure 2 Suction-controlled tests on compacted samples from El Arahal

1. The swelling obtained in this way when suction is brought up to zero, is not very different to the swelling obtained by soaking in normal oedometers. This logical result disagrees with the assertions of Chou and Mou (1973), according to which the swelling by soaking is much larger.

2. The larger part of the volume change occurs in the last small reductions of suction.

When a clay swells around a pier foundation, the pier friction induces stresses in the soil to counteract the tendency to swelling. So, the suction decrease is coupled with an increase in total stress (above the base of the pier) or a decrease in total stress (below the base of the pier). When suction is decreased as the sample is loaded or unloaded, the final swelling reached is little dependent upon stress-path, and depends mainly on the final suction and total stress (fig. 2), reaching finally the "soaking under loading" curve.

4 UNDISTURBED SAMPLES

The following samples have been tested:

Clay from Camas
ρ_d = 1.45-1.68 g.cm^{-3} I_L = 0.08 to 0.26

Clay from El Arahal I_L = -0.11 to 0.25

It is difficult to obtain conclusions from tests carried out on undisturbed samples, owing to lack of homogeneity. On the other hand the liquidity index (I_L) of the undisturbed samples tested was larger than the one of the compacted samples. Notwithstanding, a large range of liquidity indexes has been employed in the undisturbed samples tested, and the following tentative conclusions may be drawn:

1 The difference between the swelling pressures 1 and 2 on one hand, and 3 and 4 on the other hand, is large (fig. 3). Swelling-pressure-3 might be larger than swelling pressure-4 when the liquidity index is high.

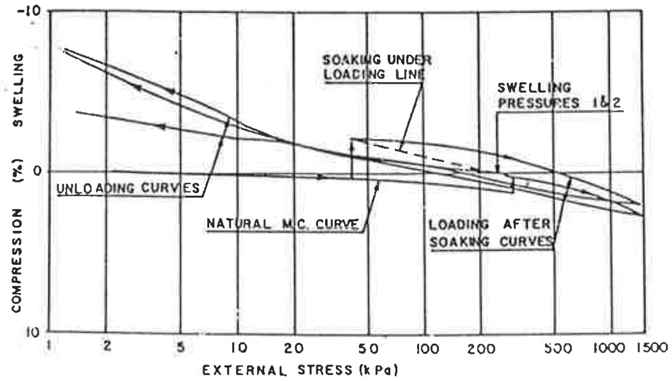

Figure 3 Soaking tests on undisturbed samples of El Arahal(ρ_d = 1.51 g.cm^{-3} I_L = -0.15)

2 With liquidity indexes larger than 0.2 and dry densities not very low, the "natural moisture content" and the "loading after soaking" curves become assymptotic (fig. 4) as assumed in the double oedometer test. Notwithstanding, the expansion under loading is much less than would be deduced from this test (fig. 4). Possibly, in these soils there is no collapse. On the other hand, if the dry density is low (1.38 g.cm^{-3}) the swelling pressure-3 may be very low and collapse for larger pressures may be important.

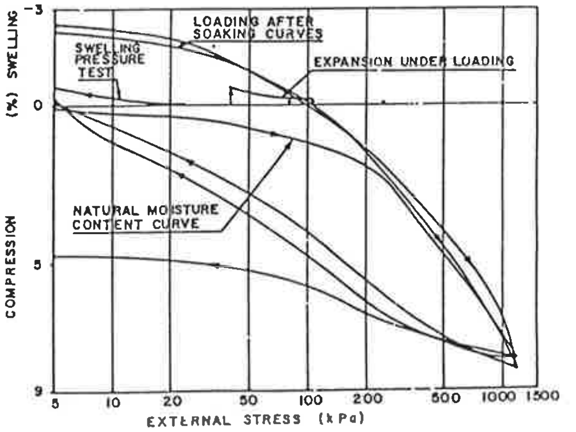

Figure 4 Swelling on undisturbed samples of Camas (I_L = 0.22 - 0.24)

Contradicting what was said about the compacted samples, in undisturbed samples shrinkage before soaking greatly reduces the final void ratio reached.

5 THE DOUBLE OEDOMETER TEST

As stated by Brackley (1975), it is vital to follow at the laboratory the expected stress-path to which the sample will be subjected in the field.

By allowing a sample to swell freely before loading, as indicated in the double oedometer test, one is certainly not following the expected stress-path. Normally one would expect the soil to wet-up after construction is complete, and the laboratory sequence should be similar.

As deduced from figures 1 to 4, swelling under loading is seriously overestimated by the double oedometer test.

In the double oedometer test, the curve corresponding to the soaked sample greatly depends on the small nominal pressure placed upon it (fig. 1). So, the scientific character of the corresponding method of settlements calculation is greatly impaired.

When the initial degree of saturation of the sample is high, the two curves of the double oedometer test become assymptotic (fig. 4). On the other hand, when the sample is dry, the two curves cross a little further of the swelling pressure of the sample(fig.1). For this reason the correction of the test indicated by Jennings et al. (1973) might be correct for very wet clays, but not for dry soils, as already suggested by Jennings (1973).

The double oedometer test overestimates measured in situ heave (Justo and Saetersdal, 1981).

6 THE INFLUENCE OF WALL FRICTION AT THE OEDOMETER

Swelling tests have been carried out in several types of oedometers. In all cases the soaking pressure was the small, nominal pressure, corresponding to the piston cap. In some cases the soil was preloaded under "natural moisture conditions" (table I). Each result is the average of up to four tests. The cells used are indicated in table II.

The soil from Puente Genil is a silty clay with the following characteristics:

Sand 13% w_L = 27 w_p = 18 I_p = 8

w_{opt} = 13.5% ρ_{max} = 1.83 g.cm^{-3}

The soil was compacted at -2% of the optimum moisture content and at the maximum density.

The following conclusions have been reached:

1 Floating ring oedometers may have swellings much larger than fixed ring types (compare a and b types).

2 The low swelling of the 1b type may be explained by the small diameter and some rust on the walls.

3 Wall friction is more important in silty clays than in plastic clays.

4 The influence of preloading under "natural moisture conditions" does not seem important.

Fortunatly for larger soaking pressures the influence of oedometer type is negligible.

7 THE USE OF ELASTIC METHODS IN EXPANSIVE-COLLAPSING SOILS

TABLE I

INFLUENCE OF OEDOMETER TYPE AND STRESS-PATH IN SWELLING UNDER NOMINAL LOAD

Soil from	Oedometer	Soaking pressure (kPa)	Swelling				Comments
			Max. pressure under "natural m. c."				
			1.8 kPa	80 kPa	100 kPa	170 kPa	
Pte Genil	1a	1.8	7.3%				Cell outside the loading frame
	2a	1.5	10.6%				
	3b	1.7	7.4%				
	1b	1.8	2.5%	2.5%		2.8%	Cell inside the loading frame
	2b	1.5	4.4%	4.0%		5.8%	
	3b	1.7	4.4%	6.2%		6.2%	
El Arahal	1a	1.8	20.2%				Cell outside the loading frame
	2a	1.5	25.7%				
	3b	1.7	18.5%				
	4b	1.2	16.6%				
	1b	1.8	12.5%		11.2%		Cell inside the loading frame
	2b	1.5	17.8%				
	3b	1.7	19.1%		17,1%		
	4b	1.2	17.2%				

TABLE II

OEDOMETER CELLS CORRESPONDING TO TABLE I

Oedom.	Type	Ring mat.	Diam. (mm)	Height (mm)
1a	Partly floating ring	Bronze	45	12
1b	Fixed ring			
2a	Partly floating ring	Bronze	70	12
2b	Fixed ring			
3b 4b	Fixed ring	Stainless steel	70 70	25 20

Expansive-collapsing soils are neither elastic nor linear and so stress-path must be continuosly borne in mind.

Notwithstanding, as shown in two companion papers, linear-elastic methods are applicable to expansive soils, as far as we take into account the factors that influence the equivalent elastic parameters.

We shall study below the different branches indicated in figure 1.

Unless otherwise stated the regressions indicated below correspond to different soils from Puente Genil.

7.1. Natural moisture content curve

The oedometric modulus, in the pressure range applied by foundations on expansive soil, may be considered as approximately constant.

In canals on expansive clay in cut, the processes are mainly of unloading and reloading. The oedometric moduli during unloading and reloading nearly coincide.
The regression corresponding to oedometric moduli in processes of unloading and reloading for compacted and indisturbed samples is:

$$\log E_{oed} = 1.11 - 0.0095\, w_L + 0.586 \log p_m \qquad (2)$$

$$S.E. = 0.359 \qquad N = 122$$

The soaking under loading curve supposes a relationship between strain and stress. As we shall see in a companion paper, in elastic methods an "equivalent oedometric modulus" may be used. The following regression has been found for undisturbed soils:

$$\log E_{oed} = -0.19 - 0.0143\, w_L + 0.941 \log p_m \qquad (3)$$

$$S.E. = 0.358 \qquad N = 47$$

And for compacted soils:

$$\log E_{oed} = 3.94 - 3.89 \frac{\rho}{\rho_{max}} - 0.03\, w_L + 0.903 \log p_m \qquad (4)$$

$$S.E. = 0.378 \qquad N = 42$$

Figure 5 represents the regression between E_{oed} and p_m found for the compacted soil of El Arahal (p_m correspond to very different ranges).

In a canal in expansive clay, the upper part of the soil may become submerged after soaking. The regression of the corresponding oedometric modulus, in unloading after soaking, for compacted and undisturbed samples, is:

$$\log E_{oed} = 0.28 - 0.0210\, w_L + 0.985 \log p_m \qquad (5)$$

$$S.E. = 0.300 \qquad N = 32$$

The oedometric modulus in the curves of "loading after soaking" depends mainly upon the stress ratio between every pressure and the soaking pressure(fig6). For El Arahal compacted soil the regression is:

$$\log E_{oed} = 1.45 + 1.60 \log \frac{P}{P_s} + 0.60 \left(\log \frac{P}{P_s}\right)^2 \qquad (6)$$

$$S.E. = 0.073 \qquad N = 16$$

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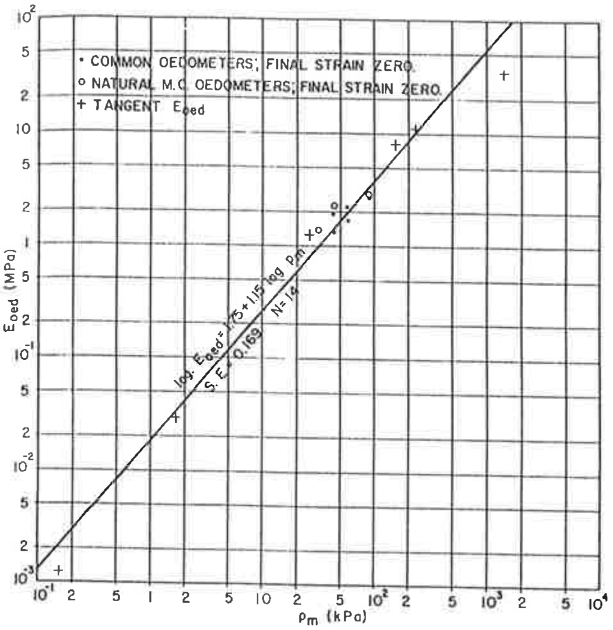

Figure 5 "Equivalent oedometric moduli" corresponding to the "soaking under loading" curve in compacted soil from El Arahal

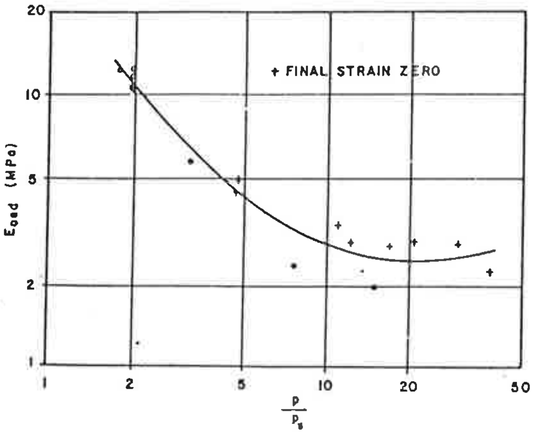

Figure 6 Oedometric modulus of the loading after soaking curves

8 CONCLUSIONS

The final volume change of expansive-collapsing soils, in the expansion zone, does not depend only upon the final values of external pressure and suction, but upon stress-path. On the other hand, in the collapse zone the volume change is little path dependent.

Notwithstanding that, for many of the wetting processes around foundations and in canals on expansive clay, the final state seem to be well represented by the "soaking under loading" curve or the corresponding curves for other values of suction.

The use of the double oedometer test for settlement calculations is not supported by a scientific basis.

The oedometric moduli for the use of elastic methods in expansive-collapsing soils have been studied. Most of them depend, for a given soil, upon the average external pressure.

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