Indian Geotechnical Journal, 25 (4), 1995

Anisotropy in Swelling Characteristics of Clays

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Introduction

It has been generally recognized that the mechanical behaviour of most natural clay deposits is anisotropic to some degree. For a macroscopically homogeneous clay, anisotropy may exist in the preferred particle orientation, or in groups of particles forming direction oriented units. In addition to the effect of fabric on the macroscopic behaviour, other environmental factors such as weathering, frost action, and leaching may affect the phenomenological behaviour such as strength, compressibility, and permeability (Jacobson, 1955; Saada, 1973; Lo et al., 1977; Clough and Hansen, 1981; Mitachi and Fujiwara, 1987; Chen, 1988).

Soils which undergo volume change upon wetting and drying are termed expansive soils. These soils are found in many parts of the world and contain large amounts of clay minerals. In particular, swelling clay exist in abundance in arid and semi- arid regions because the low rainfall has not enabled the montmorillonite clay minerals to weather to less active clay types nor has it allowed sufficient leaching to carry the clay particles far enough into the lower horizons tc reduce its effect. Generally speaking, heave of expansive soils is difficult to predict since the amount of such heave depends on the clay mineralogy, particle orientation, confining pressure, and the instant in situ water content at the reference time (Bowles, 1988; Chen, 1988). Generally speaking, the expansion properties of clays are assessed experimentally by conducting swell tests on samples extracted vertically. The properties so obtained are usually employed to estimate vertical heave. In case of retaining structure, the push against the wall due to clay expansion is lateral. Such a lateral swell may not necessarily be the

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same as the vertical swell. When the property of a soil specimen extracted vertically is different from the lateral one, the soil is termed "anisotropic". The general purpose of this study is to investigate the effects of anisotropy on the swell characteristics of clays.

Sample Extraction

In this study the anisotropy of swell characteristics is investigated through a series of experimental tests on several undisturbed samples extracted from different locations in Northern Jordan. Basically three sampling directions were considered: vertically, horizontally, and inclined at 45 degrees. A total of eleven sites were selected. The whole sampling process took place in August, 1991. After each sampling area was excavated to the desired depth, samples from vertical and horizontal directions were obtained by penetrating a tube which has a vertical edge. The tube used was 40 cm. long and 7.6 cm. in diameter. For samples of inclined direction another tube which has an inclined edge of 45 degrees at one end was used. The ratio of the volume of the soil displaced by the sampler to the total volume of the sample extracted (area ratio) was 0.08. After removing the soil specimen from the sampler using a jack it was immediately folded by aluminium foil and tightly placed in a sealed plastic bag. Figure 1 shows typical scanning electron microgscopic images of Soil B for the three selected dimensions.

Laboratory Study

To conduct the experimental work, samples from each site were initially subjected to standard laboratory tests to obtain specific gravity of solids, natural water content, dry unit weight, consistency limits, particle size distribution, overconsolidation ratio and undrained shear strength properties. All tests were conducted in accordance with ASTM specification (ASTM, 1990). Table 1 lists the general properties of the test soils utilized. The swelling characteristics, namely swell percent and swell pressure, were determined in the laboratory by using the standard one dimensional oedometer apparatus. A brief description of these tests follows.

Swelling Potential Tests

Swelling tests were performed on undisturbed samples for different orientations and for each soil using the one dimensional oedometer apparatus. Test specimens were initially trimmed by a sharp knife to fit exactly the consolidation ring (20 mm in height and 76 mm in diameter). The test specimen was then placed in the consolidation frame and an initial seating load equivalent to the at rest condition was applied. For vertical samples the seating load was equal to the overburden pressure. For horizontal samples, on the other hand, the seating load was equal to the overburden pressure

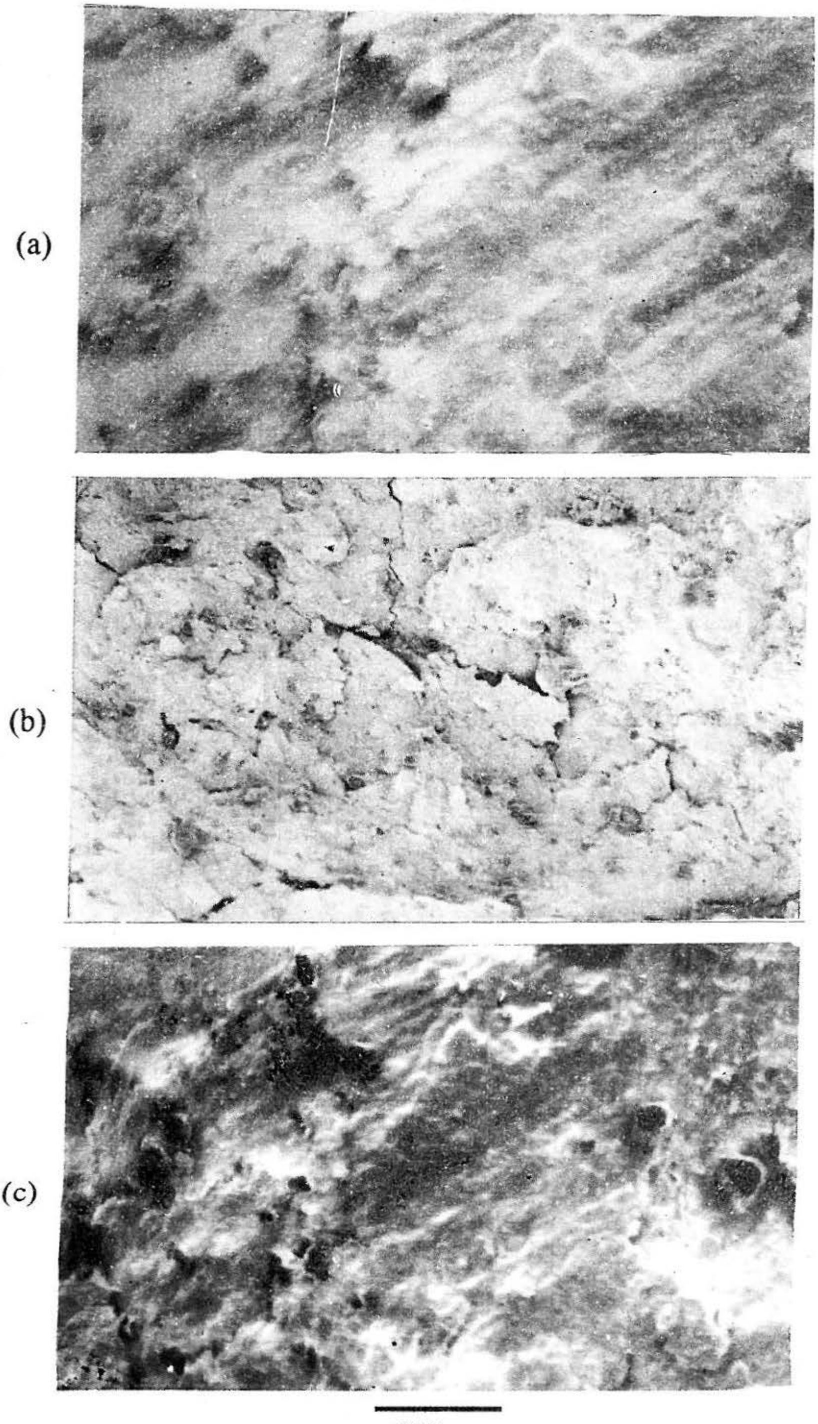

FIGURE 1 : Scanning Electron Micrographs for Soil B
a) Verticle b) 45° Inclined c) Horizontal sample

TABLE 1 : Properties of Selected Soils

Property*		Soil										
		A	B	C	D	E	F	G	H	I	J	K
Depth, m		3.0	1.5	4.0	2.0	1.7	2.5	1.5	5.0	2.5	6.0	6.0
W_n, %		25.7	22.4	26.2	23.7	22.5	24.6	18.2	20.3	23.4	21.6	24.6
γ_d, kN/m^3		18.6	13.4	15.3	14.2	13.6	14.4	14.5	13.3	14.	15.4	13.9
Particle Size	Sand, %	6.0	14.0	7.0	11.0	18.0	3.0	39.0	17.0	21.0	28.0	20.0
	Silt, %	29.0	34.0	32.0	35.0	37.0	22.0	30.0	41.0	31.0	34.0	29.0
	Clay, %	65.0	52.0	61.0	54.0	45.0	75.0	31.0	42.0	48.0	38.0	51.0
Consistancy Limits	LL, %	82.2	76.1	78.4	76.4	74.5	80.3	58.6	68.3	5.6	70.4	73.6
	PI, %	41.3	36.4	38.2	36.1	35.2	39.4	17.3	25.4	22.3	30.2	32.4
Clay Activity		0.64	0.70	0.63	0.67	0.78	0.53	0.56	0.60	0.46	0.79	0.64
OCR		4.2	9.5	3.1	7.3	8.4	5.6	4.	2.6	6.4	2.1	1.7
Shear Strength	ϕ_u, degs.	12.0	15.0	17.0	18.0	13.0	21.0	22.0	16.0	23.0	20.0	21.0
	c_u, kPa	135.0	125.0	110.0	90.0	200.0	150.0	160.0	140.0	80.0	140.0	220.0
Pressure Coefficient at rest K_o**		1.08	1.49	0.95	1.34	1.42	1.21	1.08	0.87	1.25	0.80	0.74

* w_n = natural water content, γ_d = dry unit weight, Sand = 2000-75 μm, Clay < 2 μm, LL = liquid limit, PI = plasticity index, OCR = overconsolidation ratio, ϕ_u = undrained angle of internal friction, c_u = undrained cohesion.

** K_o was determined by Fig. 2.

TABLE 2 : Swell Potential of Selected Soils as Classified by Various Researchers

Method by	Swell Potential										
	A	B	C	D	E	F	G	H	I	J	K
Seed et al. (1965)	High	High	High	High	High	Very High	Medium	Medium	Medium	High	High
Van der Merwe (1975)	High	High	High	High	High	Medium	Medium	High	Medium	High	High
ASTM D4829 (1990)	Very High	High	Very High	High	High	Very High	Medium	High	Medium	High	High
Basma (1993)	Very High	High	Very High	High	High	Very High	Medium	High	High	High	High

TABLE 3 : Quantitative Clay Mineralogy, Percent of Total Clay Minerals

Clay Mineral	Swell Potential										
	A	B	C	D	E	F	G	H	I	J	K
Kaolinite	15.9	21.3	12.8	8.8	10.3	12.9	3.8	29.4	44.1	47.1	2.6
Illite	46.2	42.1	55.7	37.9	38.9	49.8	52.1	53.8	10.2	19.7	27.8
Smectite	37.9	26.6	31.5	21.7	17.7	31.1	8.0	16.8	37.7	22.	26.8
Montmorillonite	–	–	–	18.9	21.3	6.2	–	–	–	10.3	11.7
Mixed Layer	–	10.3	–	12.7	11.8	–	–	–	8.0	–	4.1

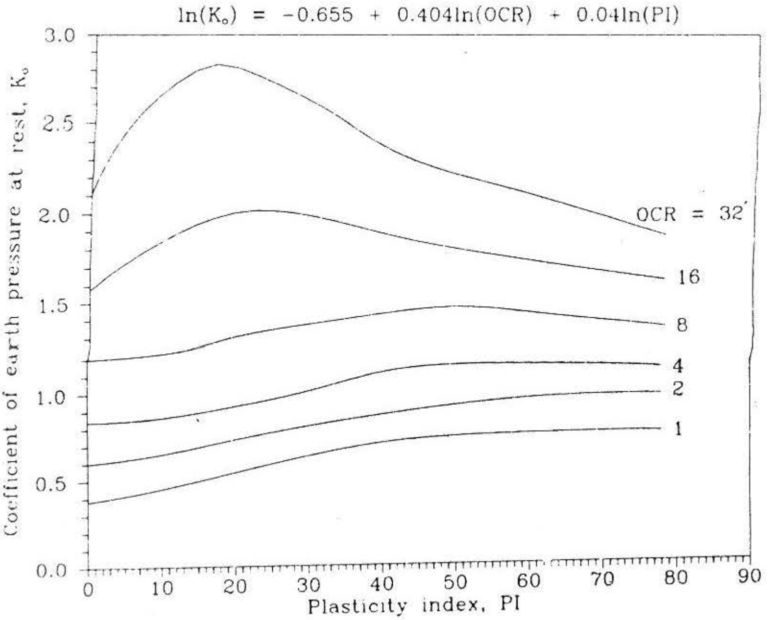

FIGURE 2 : K_o Related to OCR and PI

times the coefficient of lateral earth pressure at rest. By running a series of oedometer tests in which both the vertical and horizontal stresses were measured, Brooker and Ireland (1965) related K_o to overconsolidation ratio OCR and plasticity index PI. Their results are shown in Fig. 2. A non-linear multiple regression analysis of the data in this figure yielded

$$\ln K_o = -0.655 + 0.404\ln(OCR) + 0.041\ln(PI)$$
$$r^2 = 0.952, \qquad SEE = 0.133 \tag{1}$$

This equation was used to assess K_o – values for the test soils and are listed in Table 1. For 45 degrees inclined samples the seating load used was equal to the average of the vertical and horizontal samples. The samples were then submerged in water and allowed to swell with deformation readings recorded at 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 1440 minutes. If appreciable deformation may still be observed, readings were continued to 48 and 72 hours. In most cases, however, it was noted that samples reached full swell after 24 hours. Figure 3 illustrates typical swell versus time curves for soils B and H and for the three orientations. The swelling potential is thus defined as the ratio of the maximum change in sample height upon wetting to the sample's initial height (20 mm). It is important to point out that a standard consolidation test was performed on all swollen samples to

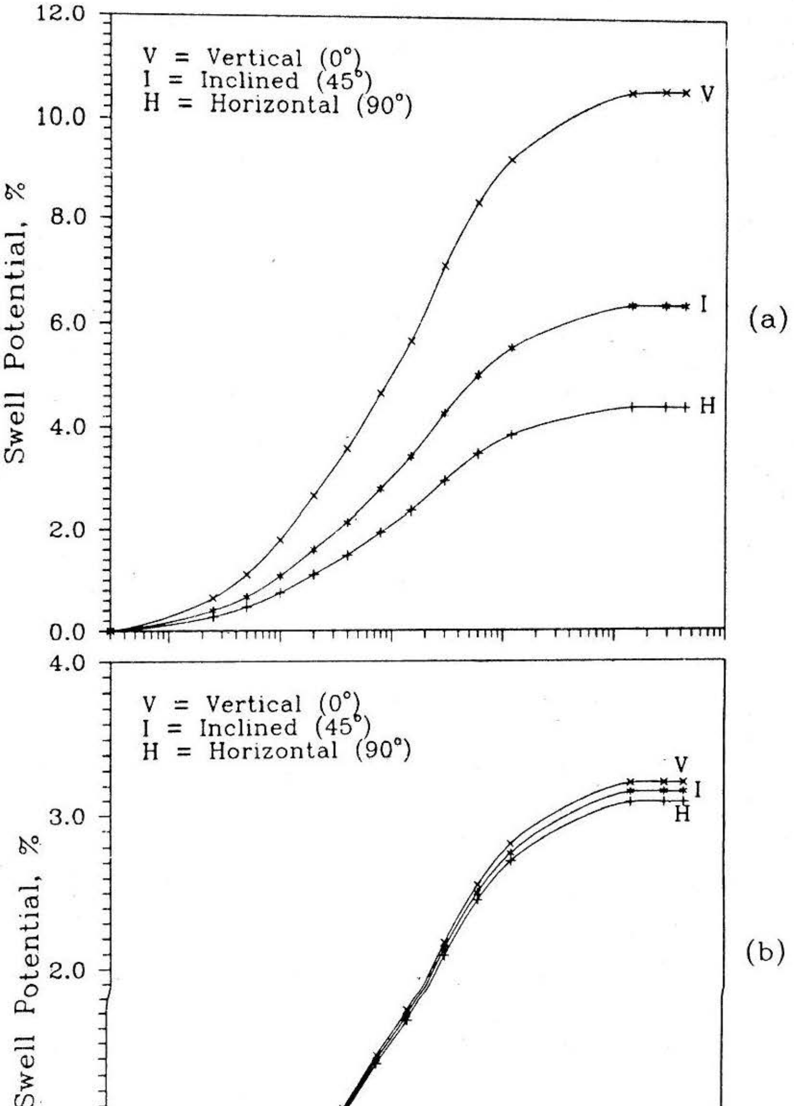

FIGURE 3 : Swell versus Time for a) Soil B b) Soil H

prepare e – log p curve (not shown here). This was carried out by applying incremental loads of 25, 50, 100, 200, 400, 800 and 1600 kPa. For each load increment the sample was allowed to completely consolidate for at least 24 hours before applying the following load. The e – log p curves were used to estimate the pre-consolidation pressure P_c by Casagrande's method. With these values, OCR was evaluated and used in Eqn. (1).

Swell Pressure Tests

In addition to swell potential tests, the constant volume swell tests were performed on the three orientations for each soil to determine the swelling pressure. This test was conducted by continuously adding loads on a saturated specimen at every vertical expansion to prevent swell. The loads were applied by using sand added to a plastic bag hanging off the loading arm. The final load required to fully swelling per unit area of the specimen was used to define the swell pressure p_s.

Anisotropy in Swelling Characteristics

Figure 4(a) depicts the maximum swell percent versus sampling angle for the tested soils. Additionally, Figure 4(b) presents the relationship between the sampling angle with vertical and the swelling pressure. Suffice it to point out that the greatest swell potential or swelling pressure values occurred at sampling inclination angle i = 0, i.e. vertical samples. Furthermore, for soils J and K, observe that the slopes of the lines is zero indicating no difference between the swell at i = 0, i = 45 and i = 90.

Anisotropy Swelling Index

In order to assess the effect of anisotropy on the swelling properties of clays, four indices defining the degree of anisotropy are introduced. Mathematically they are defined as follows

$$I_{s_i} = \frac{SP_i}{SP_v} \tag{2}$$

$$I_{s_h} = \frac{SP_h}{SP_v} \tag{3}$$

$$I_{p_i} = \frac{P_{s_i}}{P_{s_v}} \tag{4}$$

$$I_{p_h} = \frac{P_{s_h}}{I_{s_v}} \tag{5}$$

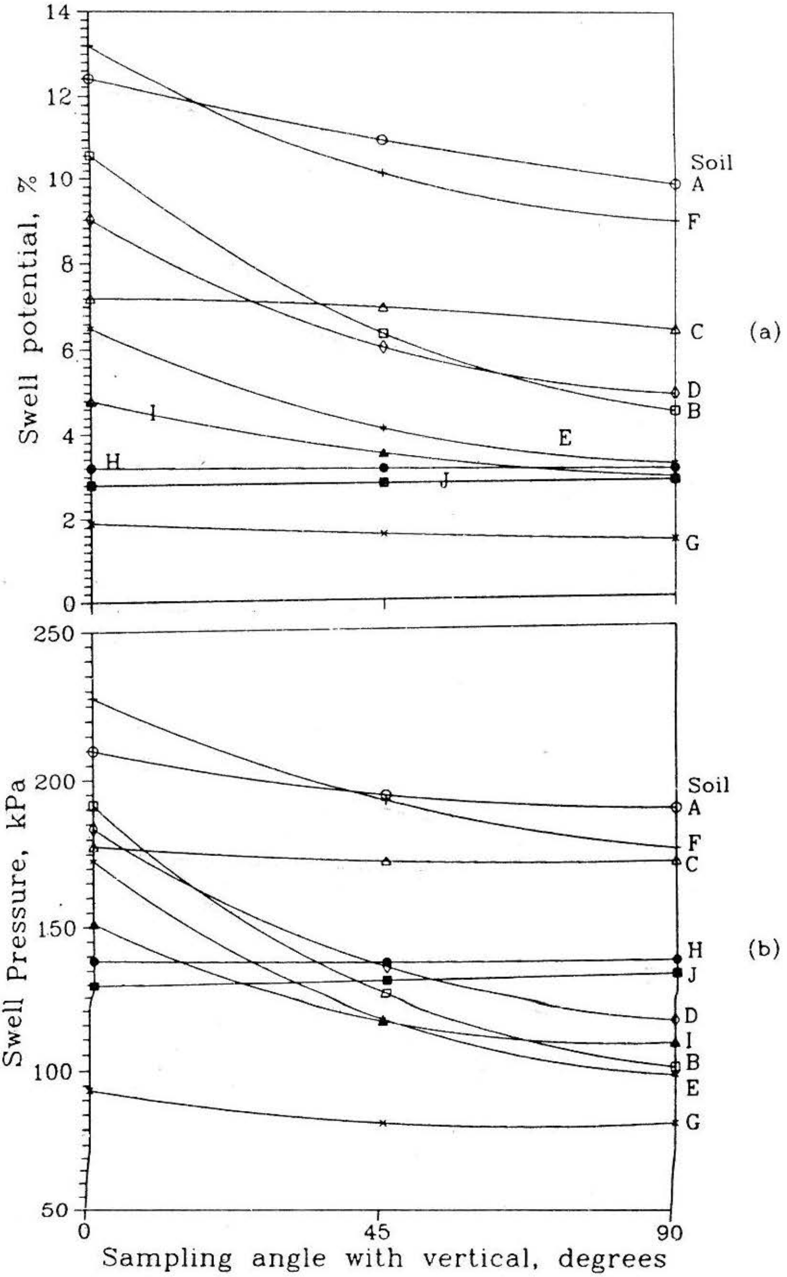

FIGURE 4 : Variation of a) Swell Potential b) Swell Pressure with Sampling Angle

where SP = swell potential in percent p = swell pressure in kPa and subscripts "v", "i" and "h" representing respectively vertical, inclined (45 degrees) and horizontal (90 degrees). As can be noted, these indices relate the inclined and/or horizontal swelling parameters to the vertical one. Figure 5 depicts the values of the anisotropic indices for all test soil with sampling angle. Additionally, this figure clearly shows the soil J is isotropic with respect to swell potential and swelling pressure (I_s and $I_p = 1.0$). On the other hand, soil B shows the most anisotropic behaviour among the studied soils (Is and $I_p < 1.0$). This result could be explained through the image analysis of the clay microstructure. Generally, the soils utilised in this study have common trends in microstructural formation. Upon studying the scanning electron microscope (SEM) of soil B (shown in Fig. 1) one may suggest that the decrease in swelling characteristics with sampling angles is consistent with the clay microstructure. The vertical sample (shown in Fig. 1a) has a rather smooth fabric characterised by a high degree of orientation on the surface. For the 45° inclined sample (shown in Fig. 1b), the structural element orientation is relatively high and becomes even higher and more turbulent for the 90° sample (Fig. 1c). This observation may be attributed to the disintegration of structure along the bedding as the sampling inclination increases resulting in correspondingly lower water absorption and thus producing lower swelling ability.

Effect of Soil Properties on Swell Anisotropy

As was observed in earlier sections, some soils possess swell anisotropy while others do not. In order to assess the variables that affects swell anisotropy, two basic soil properties that influence swelling behaviour were considered namely clay activity and liquid limit (Seed, 1962; Basma, 1993). Additionally, the stress history of the soils, as defined by the overconsolidation ratio OCR was also considered as a possible parameter affecting swell anisotropy. This latter property was considered because most researchers suggest that it could greatly affect anisotropic properties of clays (Jacobson, 1955; Saada, 1973; Lo et al., 1977; Clough and Hansen, 1981; Mitachi and Fujiwara, 1987).

The influence of the aforementioned properties on swell anisotropy was investigated by plotting the swell anisotropy indices (Eqns. 2 to 5) versus these properties as shown in Figs. 6 and 7. The former figure clearly illustrates the significant effect of OCR on swell anisotropy where as the latter figure suggests that neither activity nor the liquid limit seem to have any effect on it. Moreover, and as can be noted from Fig. 6, the swell anisotropy indices are about unity for soils with $OCR \leq 2.0$. This result demonstrates that normally and lightly overconsolidated clays are isotropic with respect to swell. As OCR increases beyond 3.0, the anisotropic indices decrease with the smallest values occurring at $OCR = 9.5$ (soil B). The

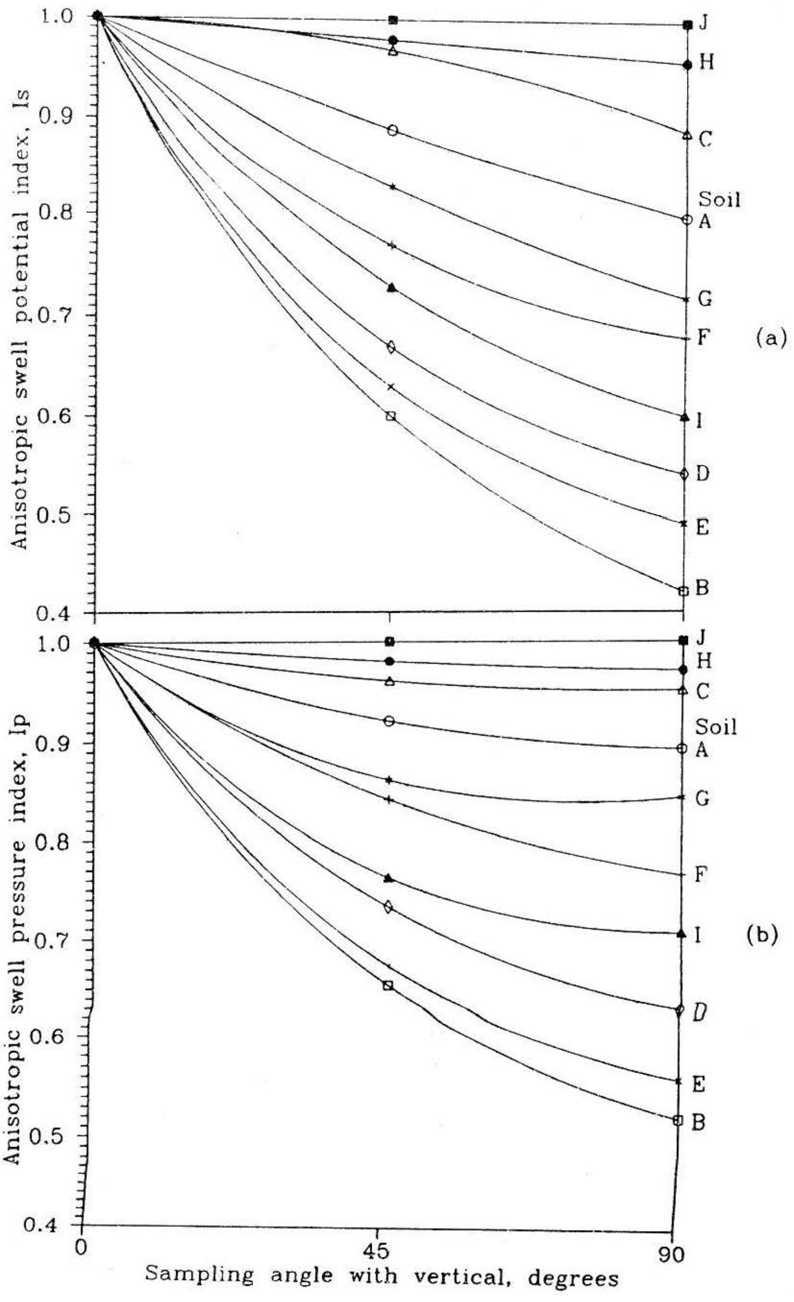

FIGURE 5 : Variation of a) Anisotropic Swell Potential Index b) Anisotropic Swell Pressure Index with Sampling Angle

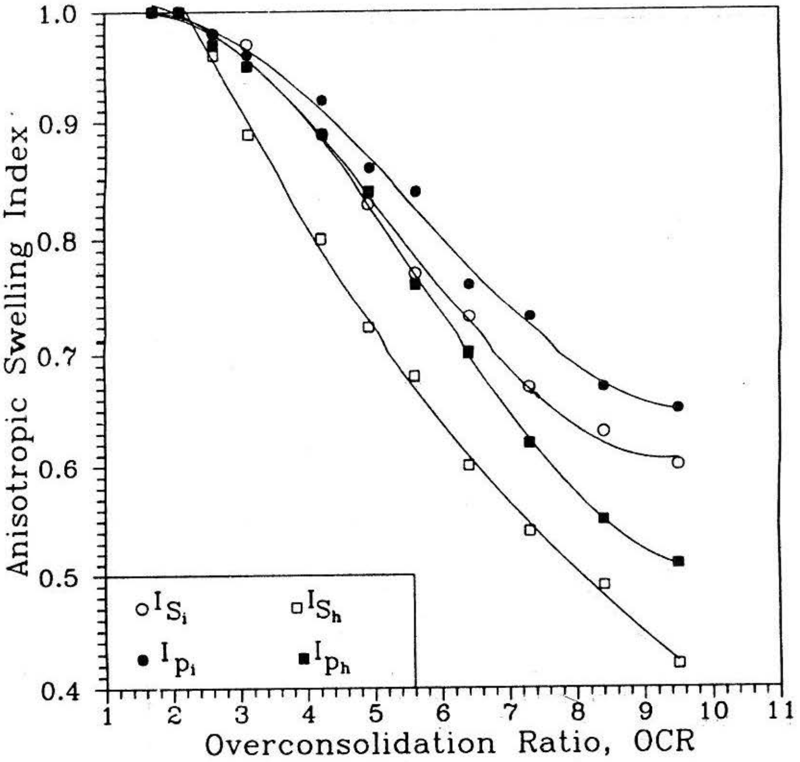

FIGURE 6 : Variation of Swell Anisotropic Indices with Overconsolidation Ratio

estimated values at this point were :

a) For swell potential

$I_{S_i} = 0.60$ and $I_{S_h} = 0.42$

b) For swell pressure

$I_{p_i} = 0.65$ and $I_{p_h} = 0.51$

This result conclusively illustrates that overconsolidated clays tend to exhibit anisotropic swelling behaviour. For normally consolidated clays one may explain this fact in terms of the particles orientation which may be regarded as flocculated. This implies that the particles exist in various directions and they can be regarded as uniformly distributed. As the soil becomes overconsolidated to some degree (as the case with soil B in Fig. 1) the particles tend to develop more orientations in a single direction mainly the vertical one (Mitchell, 1976). This, consequently, increases the swell

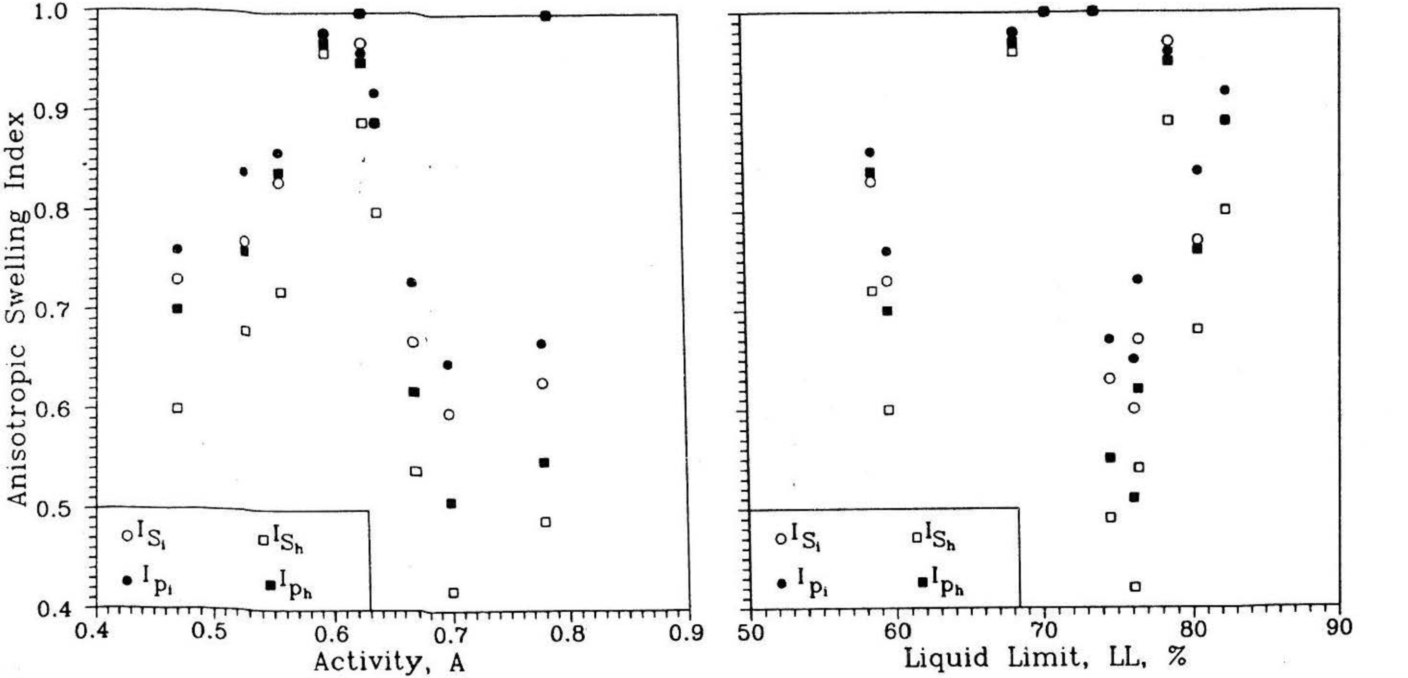

FIGURE 7 : Variation of Swell Anisotropic Indices with Clay Activity and Liquid Limit

anisotropy in the soil. It is worthy to note that similar results were reported for anisotropy in undrained shear strength and compressibility.

Conclusions

Based on the results of this study and for the soils considered herein the following conclusions about swell anisotropy can be made :

i) Anisotropy in swelling characteristics exist in some clays. The results indicated that both swell potential and swelling pressure in the vertical direction are greater than in the horizontal and inclined directions.

ii) Scanning electron micrographs clearly showed a continuous rearrangement of particles with sampling angle. This led to higher structural element orientation due to the disintegration of structure along the bedding resulting in correspondingly lower water absorption thus reducing swelling ability.

iii) Swell anisotropy depends on the stress history of the soils. Isotropic behaviour was observed in soils with OCR ≤ 2.0. As OCR increases beyond a value of 3.0 anisotropy becomes more evident. Consequently, it was deduced that superficial clay deposits experience swell anisotropy. Clays at greater depths behaved rather isotropically.

iv) Activity and liquid limit, which usually influence expansion of clays, were found to have no effect on swell anisotropy.

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