Swelling pressure of clayey soils: the influence of stress state and pore liquid composition

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Summary

The aim of this paper is to evaluate the influence of initial stress state, clay fraction (c.f. in the following), activity and pore liquid composition on swelling pressure of soils. To this aim, two clayey soils with very different c.f. and activity index have been analysed, and tendency to swell has been induced both by unloading and by exposure to water or to salt solutions. The tests were carried out on undisturbed materials as well as on reconstituted materials so as to test specimens with well known stress history. In order to evaluate the influence of test conditions, the experiments have been carried out by stress controlled and by strain controlled procedures.

In the case of the soil with the lowest c.f., the results show that swelling pressure is strongly influenced by the clay fraction. In particular, small variations in c.f. cause changes in swelling pressure similar to those caused by large variations in initial effective stress. In the case of the soil with the highest c.f., the influence of pore liquid composition – and of the composition of the liquid the soil is exposed to – is such as to obscure the influence of initial stress state. In particular, swelling pressure caused by exposure to distilled water of the material reconstituted with 1 M NaCl solution is much higher than the value of the initial mean effective stress.

The comparison between theory and experiment shows that, for both the considered soils, swelling pressure can be interpreted as osmotic pressure of the double layer-bulk solution system. The simple model derived by Bolt [1956] from the Gouy-Chapman [Gouy, 1910; Chapman, 1913] theory interprets quasi-quantitatively the behaviour of the material exposed to distilled water. Because of the approximations on which it is based, the model can only interpret qualitatively the behaviour of the material exposed to the concentrated salt solution.

1. Introduction

Swelling pressure can be defined as the pressure required to keep a soil element at constant volume, when boundary conditions are such as to induce a tendency to volume increase.

The tendency to swell can be induced by various causes, among which unloading and exposure to liquids which make the repulsive interparticle forces increase. Among other possible swelling mechanisms, mentioned by Mitchell [1993], there are salt heave resulting from temperature related crystallization of sodium sulfate [Blaser and Scherer, 1969; Blaser and Arulanandan, 1973], and expansion of sulfide minerals in shales resulting from oxidation caused by exposure to air and water [Dougherty and Barsotti, 1972].

In actual applications, swelling pressure is a very important parameter for the design of structures interacting with swelling soils and rocks. It must be evaluated in order to prevent damage to tunnels and to any stiff support of excavation surfaces, as well as in order to design safe shallow foundations, both in the case they are designed to resist differential movements and in the case they are designed to adjust to them by means of flexible construction [Abduljauwad *et al.*, 1998]. Furthermore, in order to prevent opening of cracks and fissures, high swelling pressure must be a property of materials constituting "impermeable" barriers. Finally, laboratory measurements of swelling pressure can give indications on the *in situ* stress state [Rampello, 1991].

Besides its practical importance, an analysis of swelling pressure is very important for the understanding of swelling behaviour in and by itself. In fact, as an example, by assuming that the time dependence of swelling is due only to hydrodynamic processes, the development of swelling pressure should be instantaneous in the case of ideal saturated materials. On the contrary, experimental results show that such a development can be very slow [among others: Sridharan *et al.*, 1986; Mesri *et al.*, 1994], clearly indicating the occurrence of other transient processes, among which ion diffusion.

Swelling behaviour of soils with high c.f. and high activity is usually interpreted by physicochemical models, among which: the classical Gouy [1910] – Chapmann [1913] model and Stern [1924], modified Gouy-Chapman [Carnie and Torrie, 1984], triple layer [Davis *et al.*, 1978; Hayes and Leckie, 1987] and water adsorption [Low, 1980, 1992] models. On the contrary, swelling behaviour of soils with low values of c.f. is generally analysed by purely mechanical models.

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The present paper analyses swelling pressure of two soils with different grain size and activity: the Potenza and the Bisaccia soils. The former is not a particularly "swelling soil", so, in engineering practice, the evaluation of its swelling pressure is generally not a major problem; here it has been investigated as a term of comparison with the high swelling Bisaccia clay. In particular, the aim of the comparison involving the Potenza soil is to evaluate whether, in the case of low c.f., it is possible to relate swelling pressure to purely mechanical processes. The Bisaccia clay, on the contrary, is characterised by high values of c.f. and of activity index. The experimentation has been carried out in order to evaluate the influence of chemical and mechanical factors on its swelling potential.

For both clays, the tests were carried out on undisturbed materials as well as on reconstituted materials, so as to test specimens with well known stress history. The latter materials have been reconstituted with distilled water as well as 1 M NaCl solution and have been consolidated at various stress levels. Swelling pressure has been evaluated by means of a continuous swelling equipment which works in strain controlled manner, and by means of conventional oedometers with controlled axial load.

2. Methods and results

On some specimens, swelling pressure was measured by using the GEONOR continuous oedometer swelling equipment (h – 200A) in a strain controlled manner. The apparatus (Fig. 1) consists of standard GEONOR oedometer cell and loading frame with lever arm ratio 1:10. A load gauge is secured to a screw-thread jack operated by a work drive and a DC-servomotor (15V) with reduction gearboxes. The electronics consist of one comparator box controller and two transducers (displacement and forces). By making the appropriate settings, as soon as a swelling amount of 1 μm is detected (displacement 1 in Fig. 1), the comparator box regulates the specimen height to recover initial height h_0 = 20 mm (displacement 2). Height regulation is made at a constant rate which can be chosen among a wide range of values. If high regulation rates are chosen, the curves of swelling pressure against time have a discontinuous slope.

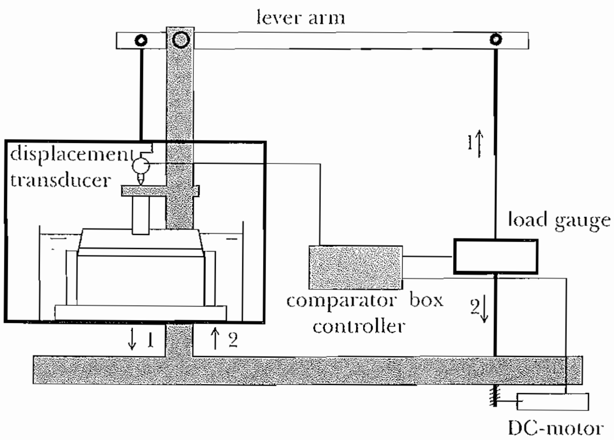

Fig. 1 - GEONOR swelling equipment.
Fig. 1 – Schema del rigonfimetro GEONOR.

2.1. *Potenza soil*

The Potenza soil is a hard soil outcropping in the hill where the Potenza town rises and in some neighbouring areas. The experiments were carried out on the undisturbed and on the reconstituted material. The former was taken from boreholes driven in two different places of the town: Gallitello and Macchia Romana. The material which was later reconstituted was taken from an open pit at Macchia Romana. Fig. 2 reports the particle size distribution curves and Tab. I reports some physical properties and the Atterberg limits. The specific gravity is G_s = 2.69 for all samples. The clay fraction is mainly composed of illite.

Tab. I – Physical characteristics of the considered Potenza materials.
Tab. I – Caratteristiche fisiche dei campioni del materiale di Potenza.

	γ (kN/m^3)	γ_d (kN/m^3)	e	S_r (%)	w_P (%)	w_L (%)
Recon. Macch. Rom.					19	32
Undist. Macch. Rom.	22.4	20.0	0.32	95	24	42
Undist. Gallitello	20.5	17.5	0.51	99	32	55

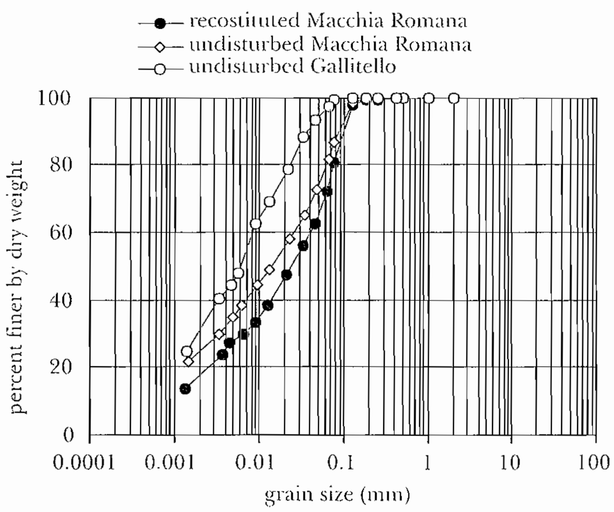

Fig. 2 – Grain size distribution curves for the investigated Potenza samples.
Fig. 2 – Granulometria dei campioni esaminati di Potenza.

The reconstituted material was prepared with distilled water at about the liquid limit. Part of it was compressed one-dimensionally and part isotropically. Fig. 3 reports void ratio against axial stress for two samples loaded in large oedometers up to axial stresses σ'_a = 300 kPa and σ'_a = 1000 kPa, and for two more samples compressed isotropically in a high pressure cell to p'_{max} = 5000 kPa and p'_{max} = 10000 kPa. The figure also reports a point relative to a specimen prepared with the fraction of the material having grain size finer than 0.074 mm (passing through sieve 200 ASTM). This material, with c.f. = 22.5 % and w_L = 36 %, was reconstituted with distilled water and isotropically compressed up to p'_{max} = 700 kPa (point E in Fig. 3).

In the equilibrium conditions represented by points A, B, C, D and E, compression was interrupted and the soil samples were removed from the apparatus in order to prepare the specimens for subsequent testing. In this phase, the physical properties could have undergone some variations, so, they were measured again. Tab. II reports, for each sample, the maximum effective axial stress $\sigma'_{a\ max}$ applied during compression, and dry unit weight γ_d, void ratio *e* and saturation degree S_r at the beginning of the new testing phase. It is worth noting that the degree of saturation of sample D, compressed at p' = 10 MPa, decreased on removal of total confining stress.

Several specimens were trimmed from the samples listed in Tab. II: a set was exposed to distilled water during the swelling pressure test,

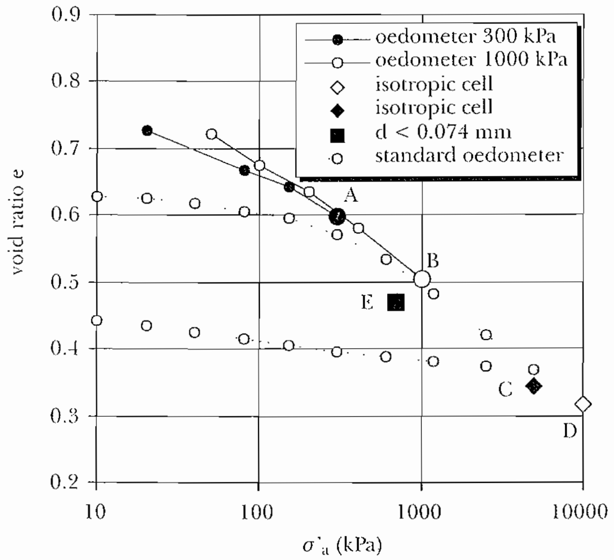

Fig. 3 – Void ratio against axial stress for the Potenza clay reconstituted with distilled water and compressed at various stress levels in one-dimensional or in isotropic conditions.

Fig. 3 – Indice di porosità dell'argilla di Potenza ricostituita con acqua distillata e compressa a vari livelli tensionali in condizioni monodimensionali o isotrope.

Tab. II – Physical characteristics of reconstituted samples of the Potenza soil consolidated at various stress levels.

Tab. II – Caratteristiche fisiche di campioni ricostituiti del materiale di Potenza consolidati a vari livelli tensionali.

Sample	$\sigma'_{a\ max}$ (kPa)	γ_d (kN/m^3)	e	S_r (%)
A	300	16.5	0.60	100
B	1000	17.6	0.50	100
C	5000	19.6	0.34	100
D	10000	20.0	0.32	93
E	700	18.0	0.47	100

another to 1 M NaCl solution. On these specimens, swelling pressure was measured by using the continuous swelling equipment in a strain controlled manner.

Fig. 4 reports the results in terms of swelling pressure against maximum mean effective stress p'_{max} (1). As expected, Fig. 4 shows that swelling pressure increases with increasing p'_{max}(2). Furthermore, at lower values of p'_{max}, the specimens exposed to distilled water and those exposed to the salt solution behave differently, whereas for higher values of p'_{max} there seems not to be a cell liquid composition influence. Finally, the figure shows that an increase in c.f. of about 4.5 % makes the swelling pressure of the specimen of sample E, consolidated at p'_{max} = 700 kPa, increase to a value similar to that obtained at 5000 kPa for the material with c.f. = 18%.

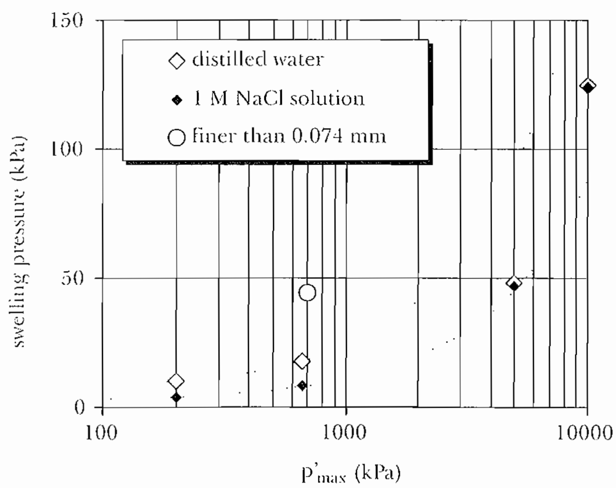

Fig. 4 – Swelling pressure against p'_{max} for the Potenza soil exposed to distilled water or to 1 M NaCl, and for the fraction finer than 0.074 mm exposed to distilled water.

Fig. 4 – Pressione di rigonfiamento in funzione di p'_{max} per l'argilla di Potenza esposta ad acqua distillata e a soluzione NaCl 1 M, e per la frazione a diametro inferiore a 0,074 mm esposta ad acqua distillata.

Fig. 5 reports plots of swelling pressure against time for specimens of samples B and D. In order to compare trends of swelling pressure and swelling, some specimens similar to those just analysed were allowed to swell in oedometer, in a bath of distilled water, under an axial stress σ_a = 1 kPa. Figs. 6 and 7 compare the time trends of swelling to that of swelling pressure for specimens of samples B and D respectively. It can be observed that the time required to reach swelling pressure equilibrium values is not very different from that needed for swelling. In the hypothesis of purely mechanical processes, specimen B, since it was saturated, should have developed swelling pressure much faster: in theory, instantaneously. MESRI *et al.* [1994] attributed the time dependence of Taylor shale swelling pressure to swelling within fissures – opened during sampling – which occurs at constant total volume. In the case under examination, it is unlikely that such a process could have occurred. One of the causes of the time dependence could be due to the inevitable salt content of the material, even when it is reconstituted with distilled water. It seems reasonable to hypothesise that when the material is exposed to distilled water, ions diffuse towards the cell liquid, thus causing an increase in repulsive interparticle forces. Furthermore, the development of swelling pressure can be in itself a time dependent process, as the analysis of the Bisaccia clay behaviour will show better.

Let us now consider the undisturbed material. Fig. 8 reports swelling pressure against time for an undisturbed Macchia Romana specimen cut from a sample taken at a depth of about 18 m from ground level. Fig. 9 reports the compression curve relative to a Gallitello undisturbed specimen taken at about 8 m. The figure shows that the curve intersects the line e = e_0 at $\sigma_a \cong$ 200 kPa. According to BRAKLEY [1973], this axial stress should be considered as swelling pressure. However, under higher values of axial stress, the material still exhibited tendency to swell. So, the value 200 kPa probably underestimates swelling pressure. Yet, this value is much higher than that obtained for the deeper Macchia Romana material. It seems reasonable to hypothesise that the differences in the behaviour of the considered materials depend on different values of c.f. and $CaCO_3$ content. In fact, the Macchia Romana mate-

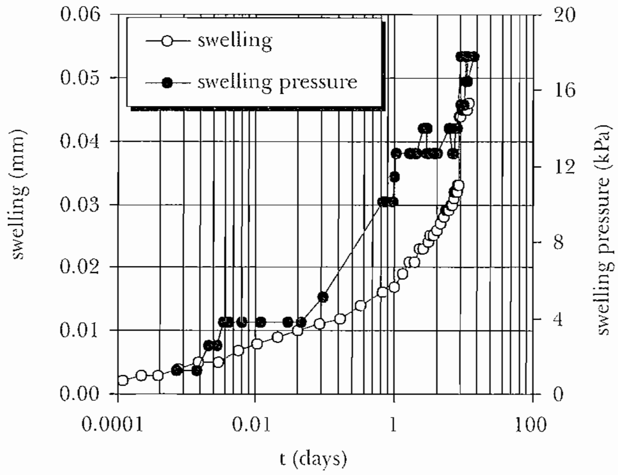

Fig. 6 – Swelling under σ_a = 1 kPa, and swelling pressure for specimens of sample B exposed to distilled water (h_0 = 20 mm).

Fig. 6 – Rigonfiamento per σ_a = 1 kPa e pressione di rigonfiamento di provini del campione B esposti ad acqua distillata (h_0 = 20 mm).

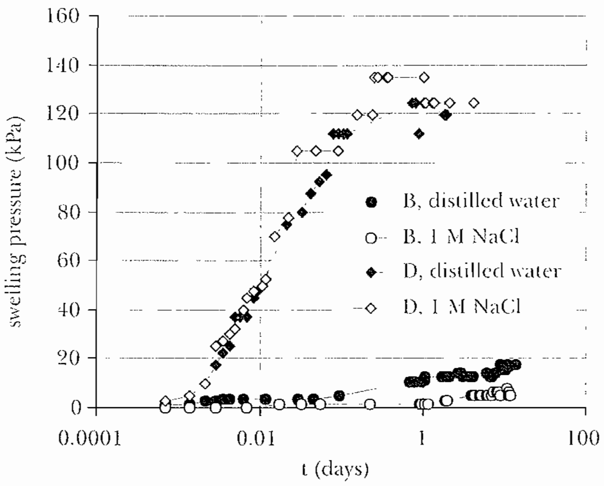

Fig. 5 – Swelling pressure against time for two specimens of sample B and two of sample D. A specimen of each couple was exposed to distilled water and the other to 1 M NaCl solution.

Fig. 5 – Pressione di rigonfiamento in funzione del tempo per due provini del campione B e due del campione D. Un provino di ciascuna coppia è stato esposto ad acqua distillata e l'altro a soluzione NaCl 1 M.

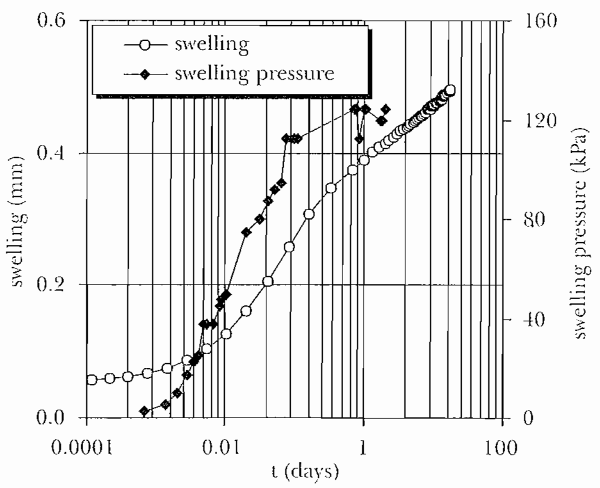

Fig. 7 – Swelling under σ_a = 1 kPa, and swelling pressure for specimens of sample D exposed to distilled water (h_0 = 20 mm).

Fig. 7 – Rigonfiamento per σ_a = 1 kPa e pressione di rigonfiamento per due provini del campione D esposti ad acqua distillata (h_0 = 20 mm).

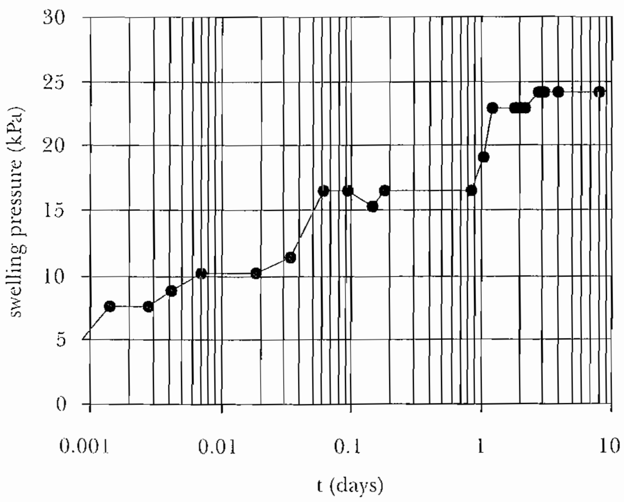

Fig. 8 – Swelling pressure against time for the undisturbed Macchia Romana material.
Fig. 8 – Pressione di rigonfiamento in funzione del tempo per il materiale indisturbato prelevato a Macchia Romana.

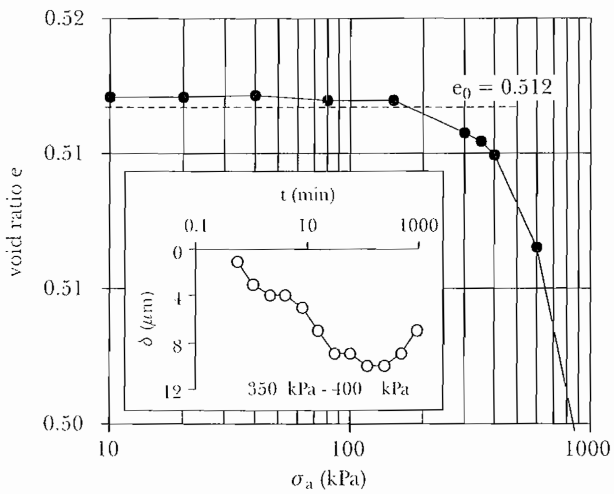

Fig. 9 – One-dimensional compression curve for the Gallitello undisturbed material and height change δ against time under an axial stress increment.
Fig. 9 – Curva di compressione monodimensionale e variazioni di altezza in funzione del tempo per un incremento dei carichi per il materiale indisturbato di Gallitello.

rial is characterised by a value of c. f. lower than that of the Gallitello material. Furthermore, the Macchia Romana sample is characterised by 22% $CaCO_3$ in dry weight, whereas the Gallitello material is characterised by 15% $CaCO_3$.

2.1.a. Influence of test procedure

In order to check the influence of test procedure on the results, swelling pressure has been evaluated also by the three different axial load controlled procedures proposed by Brackley [1973] and subsequently analysed by Sridharan *et al.* [1986]. Fig. 10 reports the results obtained by the three methods for the material of sample E. By the 1st method, the specimen is allowed to swell on addition of water, under very low value of axial stress (in the present experimentation $\sigma'_a \cong 1$ kPa). Once the specimen reaches equilibrium, it is loaded by increments and the results are plotted in terms of percent volume changes against log σ'_a. The intersection between the compression curve and the abscissa gives a value which is considered as swelling pressure. By the 2nd method, three or more specimens are loaded to different values of total axial stresses. Once equilibrium has been reached, water is added into the cells. This causes consolidation of some specimens and swelling of others, depending on the value of external loads. In a representation like that of Fig. 10, according to Brakley, the equilibrium points lie on a straight line. The intersection between this line and the abscissa provides a value of pressure which, probably, if applied at the beginning of the test, would not have caused volume changes. So, this pressure can be interpreted as swelling pressure. By the 3rd method, once water has been added to the cell, swelling is controlled by small increments of axial stress. The intersection of the $\Delta V/V_0 - \log\sigma_a$ curve with the abscissa provides the third value of swelling pressure.

Fig. 10 shows that the three values of swelling pressure vary in a large range, clearly indicating a strong influence of test procedure. Sridharan *et al.* [1986] discussed the relative convenience of each method and gave an explanation of the differences among the results. With respect to these methods, the strain controlled method provides a value of swelling pressure which better abides by the definition. The comparison among the results show that

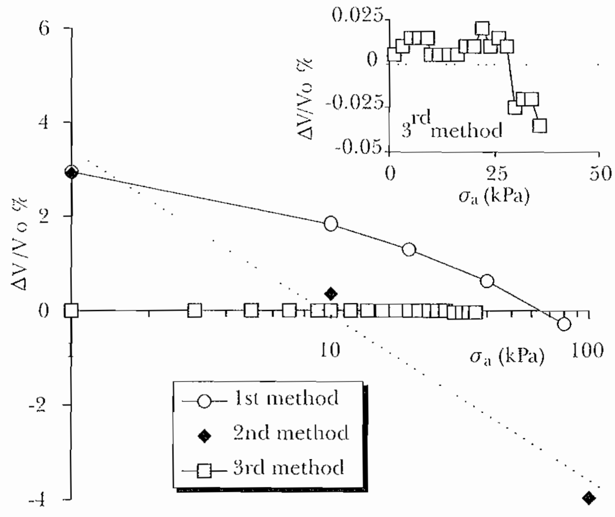

Fig. 10 – Results of tests carried out by using the three Brakley methods on specimens of sample E.
Fig. 10 – Risultati di prove condotte con i tre metodi di Brakley su provini del campione E.

the value 44 kPa of swelling pressure obtained by the strain controlled method (reported by Fig. 4) lies in the range 29 kPa – 65 kPa between the 3rd and the 1st Brakley methods respectively. Reasonably, such a value is lower than that of the 1st method because of the much smaller hysteresis loop. The third method provides a low value of swelling pressure because, on unloading, inevitable imperfections of the specimen cause small settlements which make the compression curve intersect the abscissa, independently of the swelling characteristics of the material. In fact Figs.9 and 10 show that, after the intersection, the specimens tested by this method still exhibit tendency to swell.

2.2. *Bisaccia clay*

The Bisaccia clay has been studied by many authors [among others: CICOLELLA and PICARELLI, 1990; FENELLI and PICARELLI, 1990; PICARELLI and URCIUOLI, 1993; PICARELLI et al., 2000]. It is a very active smectitic clay whose behaviour is strongly influenced by physicochemical processes [DI MAIO, 1996; DI MAIO and ONORATI 2000a; 2000b; 2000c; PICARELLI et. al., 2000]. The material used for the present experimentation was in part taken from a borehole and in part from an open pit west of the Bisaccia hill. The former was undisturbed, the latter, remoulded by sampling, was reconstituted in laboratory. Fig. 11 reports the grain size distribution curves for the material which was reconstituted and for the undisturbed samples. Tab. III shows the large variability of physical characteristics with sample distance from ground level. It can be observed that the liquid limit, evaluated by using distilled water, varies in the range 83% – 128%. In the case of the material which was reconstituted, the liquid limit was evaluated by using distilled water and 1 M NaCl

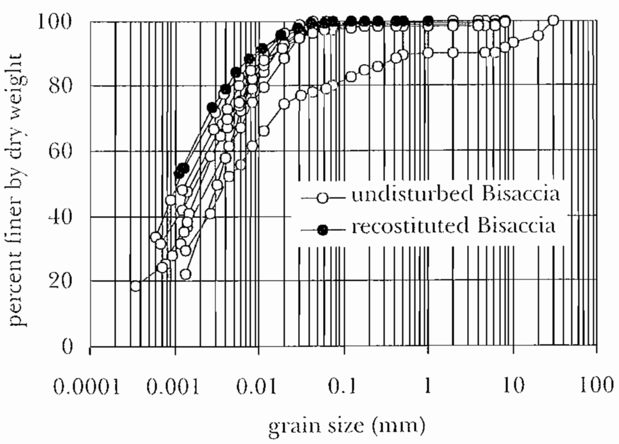

Fig. 11 – Grain size distribution curves for the investigated Bisaccia clay.
Fig. 11 – Curve granulometriche di campioni dell'argilla di Bisaccia.

Tab. III – Physical characteristics, specific surface A_S and average particle spacing $2d$ of the Bisaccia clay at various depths from ground level.
Tab. III – Caratteristiche fisiche, superficie specifica A_S e distanza interparticellare media 2d dell'argilla di Bisaccia a varie profondità dal piano campagna.

depth (m)	γ (kN/m³)	γ_d (kN/m³)	w (%)	w_L (%)	A_S (m²/g)	$2d$ (Å)
2.5	18.5	13.9	33	103	150	44
9.6	20.7	17.5	18	95	135	27
13.1	19.9	16.5	21	128	195	22
20.8	19.4	16.8	16	118	176	18
21.3	21.2	18.0	18	103	150	23
23.0	23.2	20.9	11	83	114	19
23.4	22.3	19.8	14	89	125	22
25.5	20.9	16.9	24	92	129	36
28.5	19.1	16.4	17	97	140	24

solution. It was found to be 94% in the former case and 40% in the latter.

The reconstituted material was prepared by mixing part of the clay with distilled water and part with 1 M NaCl solution. Fig. 12 reports the *e* – log σ'_a curve relative to a specimen of the Bisaccia clay (specimen *s*) which was reconstituted with distilled water and compressed in oedometer up to 712 kPa while immersed in a bath of distilled water. Once the equilibrium was reached, water

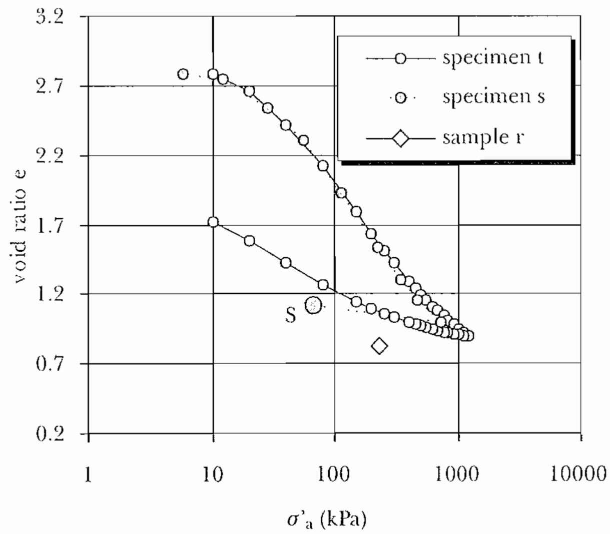

Fig. 12 – One-dimensional e-logσ_a curves and swelling pressure (point S) of the Bisaccia clay reconstituted with and immersed in distilled water.
Fig. 12 – Curve e-logσ_a monodimensionali e pressione di rigonfiamento (punto S) dell'argilla di Bisaccia ricostituita con, ed immersa in, acqua distillata.

was removed from the cell, the specimen was removed from the oedometer and it was placed in the swelling apparatus. This required about 20 minutes, during which the specimen underwent a small increase in volume, probably due to water adsorption from the saturated porous stones. Point S in Fig. 12 represents the equilibrium conditions in terms of void ratio against swelling pressure. For comparison, the figure also reports the compression and swelling curves for specimen *t* of the same material which underwent one-dimensional loading and unloading. Point S lies below the swelling curve relative to specimen *t*, whereas, in theory, it should lie above it, on the swelling curve relative to p'_{max} = 712 kPa [WARKENTIN and SCHOFIELD, 1962]. Secondary swelling of specimen *t* on one hand, and stress relaxation of specimen *s* on the other hand can reasonably account for such a result. In fact, specimen *t* was unloaded by small decrements of axial load and, for each decrement, secondary swelling was permitted for some days. Furthermore, Fig. 13, which reports swelling pressure against time for specimen *s*, shows that at about 10 days from the beginning of the test, swelling pressure exhibited a tendency to decrease. A similar phenomenon has been observed almost in all the strain controlled tests on reconstituted normally consolidated samples. It is worth noting that MESRI *et al* [1978] explained swelling behaviour of Duck Creek, Crab Orchard, Cucaracha and Bearpaw shales, by assuming that unloading in one-dimensional conditions had caused passive failure. For the material under examination, passive failure due to unloading was never observed even for large overconsolidation ratio. In particular it was not observed on specimen *t*, nor on specimen *s*.

Fig. 14 reports the results relative to two specimens prepared from a sample reconstituted with a 1 M NaCl solution and compressed in the triaxial cell to p'_{max} = 230 kPa (sample *r* in Fig. 12). A specimen was exposed to distilled water in the course of swelling pressure measurement and the other to the salt solution. The figure shows a large difference between the equilibrium values. When comparing these results to those of Fig. 13, it can be observed that, notwithstanding the lower initial stress level, the specimen reconstituted with the salt solution and subsequently exposed to water exhibits a value of swelling pressure about 500% higher than that relative to the specimen reconstituted with and exposed to distilled water. Furthermore, the time of the process is highly dependent on the composition of both the pore liquid and the liquid the clay is exposed to. In particular, the time required by the specimen prepared with and exposed to the salt solution is much shorter than that relative to the specimen exposed to distilled water. The procedure used in reconstituting the former specimen was such as to minimise ion exchange and ion diffusion. So, in this case, the time required to reach equilibrium is intrinsic to the process. In the case of the specimen reconstituted with the salt solution and exposed to distilled water, it seems reasonable to hypothesise that the process length is due to the slow ion diffusion

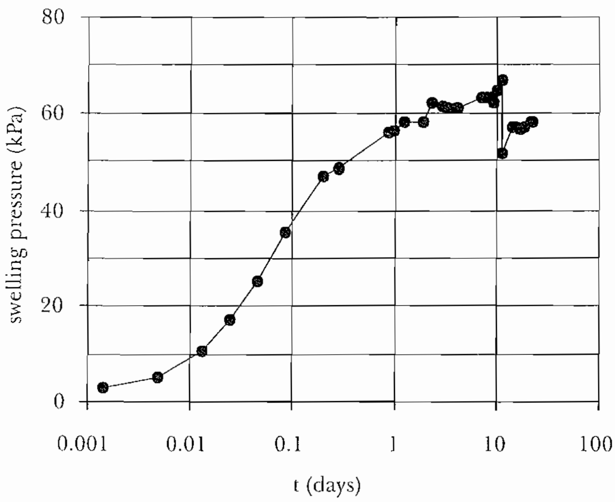

Fig. 13 – Swelling pressure against time for specimen *s* reconstituted with and immersed in distilled water.
Fig. 13 – Pressione di rigonfiamento in funzione del tempo per il provino s dell'argilla di Bisaccia ricostituita con, ed immersa in, acqua distillata.

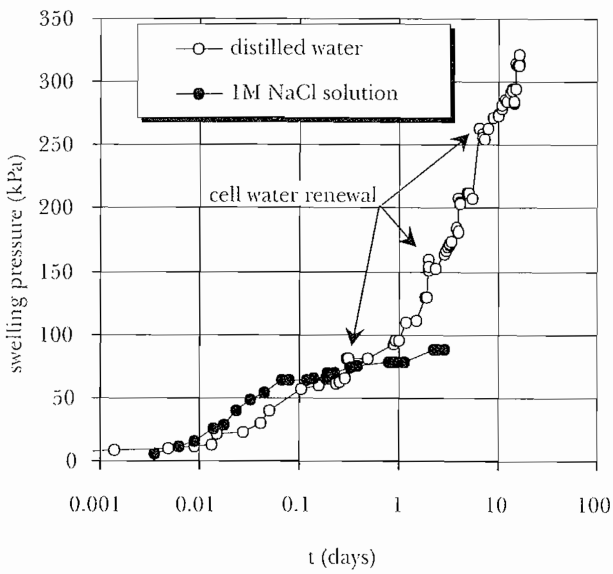

Fig. 14 – Swelling pressure against time for two specimens of the Bisaccia clay reconstituted with 1 M NaCl solution and isotropically compressed to 230 kPa. A specimen was exposed to the same solution and the other to distilled water.
Fig. 14 – Pressione di rigonfiamento in funzione del tempo per due provini dell'argilla di Bisaccia ricostituiti con soluzione NaCl 1M. Un provino è stato esposto alla stessa soluzione e l'altro ad acqua distillata.

from the pores to the cell water caused by ion concentration gradients. As ions diffuse, the repulsive interparticle forces increase and, consequently, swelling pressure increases.

The influence of the composition of the liquid the clay is exposed to is even stronger in the case of the undisturbed material, as shown by Fig. 15 which reports swelling pressure against time for two undisturbed specimens of a sample taken at a depth of 21 m below ground level. The specimen immersed in a bath of distilled water exhibited a value of swelling pressure as high as 930 kPa. On the contrary, the specimen exposed to 1 M NaCl solution reached a value of about 60 kPa. Under the conditions indicated by the arrow, the cell solution of the latter specimen was substituted with distilled water. This caused a large increase in swelling pressure. It is worth noting that such increase is due *only* to variations in physicochemical conditions.

Once the equilibrium had been reached, the specimen exposed to distilled water was placed in a conventional oedometer. It was tested in stress controlled manner, with small increments of external load, by using the 3rd Brakley method. Fig. 16 shows that the compression curve intersects the line $e = e_0$ several times. Notwithstanding an overall volume decrease, the specimen exhibited a tendency to swell until about 930 kPa, a value very close to that obtained by the strain controlled method. Fig. 17 reports the complete compression and swelling curves for the very same specimen in order to show its high swelling potential.

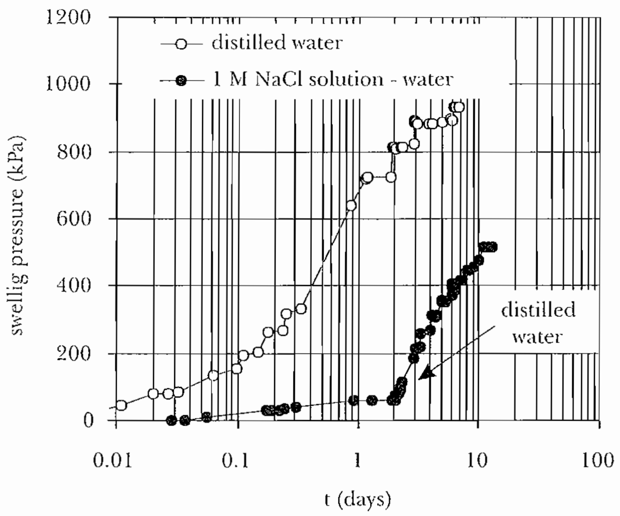

Fig. 15 – Swelling pressure against time for two undisturbed specimens of the Bisaccia clay (sample C7), one exposed to distilled water and the other to a salt solution and afterwards to water (c.f. = 39%; w_L = 103 %; w_P = 32 %; h_0 = 20 mm).
Fig. 15 – Pressione di rigonfiamento in funzione del tempo per due provini indisturbati dell'argilla di Bisaccia (campione C7), uno esposto ad acqua distillata e l'altro a soluzione NaCl 1M.

All the other undisturbed specimens underwent tests by stress controlled procedure. The results are expressed in terms of ranges of values whose lower and upper limits are, respectively, the maximum value of axial stress under which the specimens exhibited tendency to swell and the minimum value under which only consolidation occurred. Fig. 18 reports swelling pressure ranges against depth from ground level for undisturbed specimens exposed to distilled water or to 1 M NaCl solution. The analysis of data reported in Fig. 18 and Tab. III shows that the variability of physical characteristics and the clay-water chemical interactions are such as to obscure the influence of the field stress state.

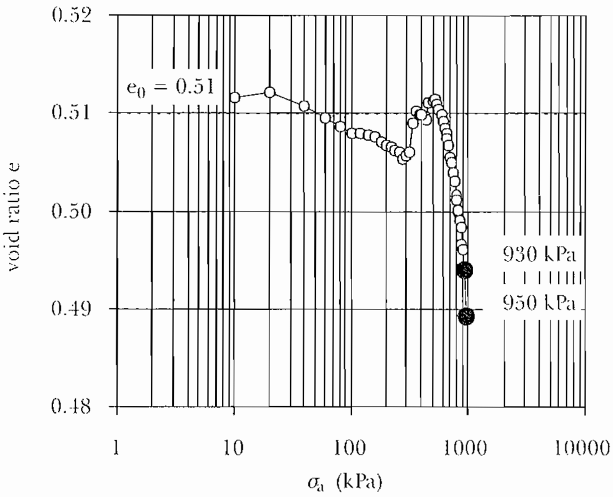

Fig. 16 – Swelling pressure of an undisturbed specimen of sample C7 evaluated by the 3rd Brakley method.
Fig. 16 – Pressione di rigonfiamento di un provino indisturbato del campione C7 valutata con il terzo metodo di Brakley.

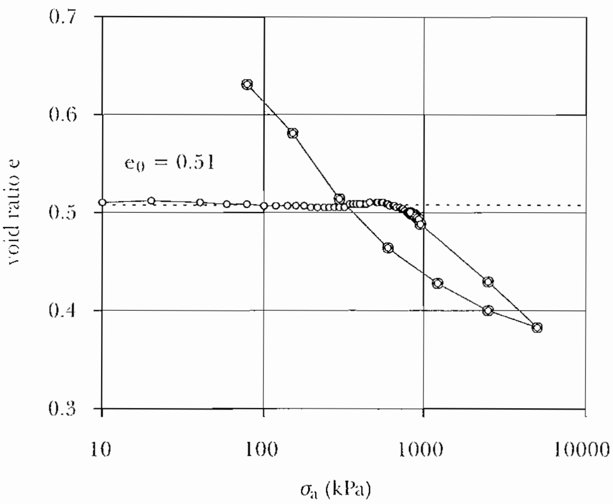

Fig. 17 – Compression and swelling curves of a specimen cut from sample C7 and exposed to distilled water.
Fig. 17 – Compressione e rigonfiamento di un provino del campione C7 esposto ad acqua distillata.

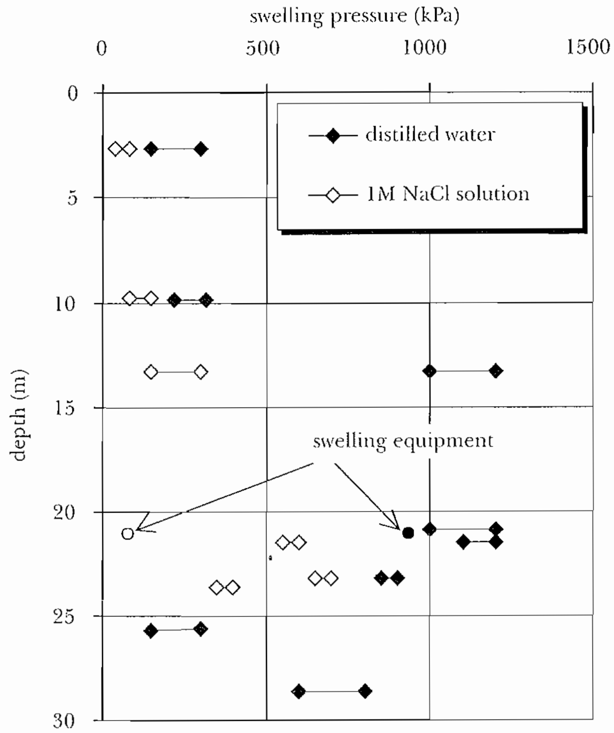

Fig. 18 – Ranges of swelling pressure against depth from ground level for undisturbed Bisaccia clay exposed to distilled water or to 1M NaCl.

Fig. 18 – Pressione di rigonfiamento in funzione della profondità dal piano campagna per provini indisturbati dell'argilla di Bisaccia esposti ad acqua distillata o a soluzione NaCl 1M.

3. Analysis of the results

The above results show that swelling pressure is noticeably influenced by c.f., mineral composition and pore liquid composition. The influence is very strong in the case of the very active Bisaccia clay, and it is much lower, but not negligible, in the case of the Potenza soil. So, it is reasonable to try and interpret the behaviour of both soils by using models which take into account physicochemical processes.

Swelling pressure can be considered as the difference between the osmotic pressure in the central plane between two particles and the osmotic pressure in the equilibrium bulk solution. An equation that allows for the evaluation of osmotic pressure in terms which are convenient for geotechnical purposes was derived for saturated clay by Bolt [1956][3].

By solving the equation, it is possible to relate void ratio to swelling pressure, for given values of the other parameters (see also Mitchell, 1993, where all the procedure followed is clearly explained).

The relationship is highly dependent on A_S. For the considered material, A_S has been evaluated empirically as suggested by Farrar and Coleman [1967], from the liquid limit w_L:

$$w_L(\%) = 19 + 0.56\,A_S \qquad (1)$$

where A_S is expressed in m^2/g.

In the case of the Potenza material, the following values have been calculated for A_S: 23 m^2/g for the reconstituted material, 41 m^2/g for the undisturbed Macchia Romana sample, 64 m^2/g for the undisturbed Gallitello sample and 30 m^2/g for sample E.

For the other parameters in (4), the following values have been assumed: $\nu = 1$ (monovalent ions), $\beta = 10^{15}$ cm/mmole (valid at normal temperature); $x_0 = 1/\nu$ Å (valid for illite); $G_s = 2.69$.

Fig. 19 reports the curves of void ratio against swelling pressure relative to the above specified four values of specific surface, at ionic concentration = 10^{-3} M. These curves can be considered as representative of distilled water because for $M \leq 10^{-3}$ the curves are very close to each other. The figure also reports the experimental points relative to undisturbed and reconstituted specimens of the Potenza soil exposed to distilled water. It can be observed that each experimental point is close to the curve at equal A_S, with the exception of the Macchia Romana undisturbed specimen, probably because of its high $CaCO_3$ content.

Fig. 20 reports the experimental results relative to the reconstituted specimens exposed to distilled water and to 1 M NaCl solution and, for comparison, the theoretical curves at various molarity relati-

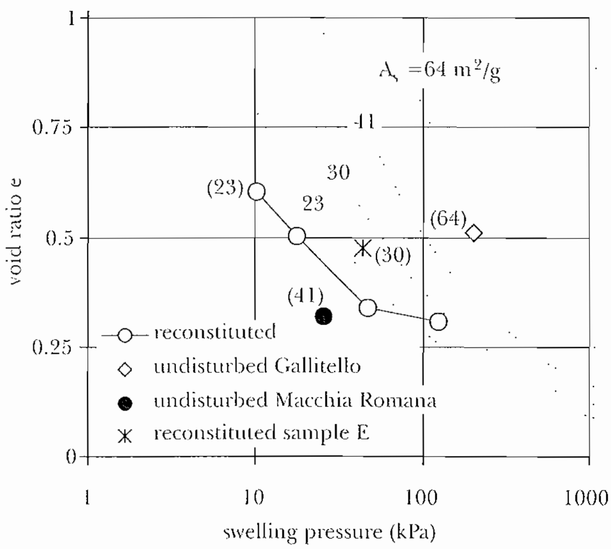

Fig. 19 – Comparison between experimental results relative to the Potenza clay and the results of the double layer model at low ion concentration for given values of A_s; the number between brackets is the specimen specific surface.

Fig. 19 – Confronto fra risultati sperimentali relativi all'argilla di Potenza e risultati del modello del doppio strato a basse concentrazioni ioniche e per i valori di A_s calcolati; fra parantesi è riportata la superficie specifica dei provini.

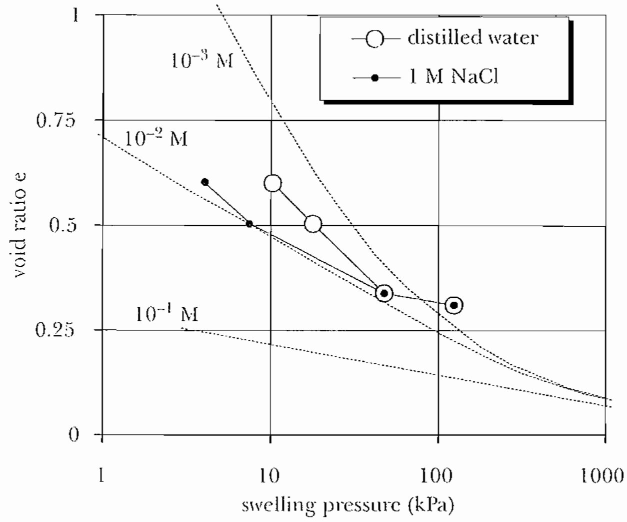

Fig. 20 – Comparison between experimental results relative to the reconstituted Potenza clay and the results of the double layer model for A_s = 23 m^2/g and for various ion solution molarity.
Fig. 20 – Confronto fra i risultati sperimentali ottenuti per l'argilla di Potenza ricostituita ed i risultati del modello del doppio strato per A_s = 23 m^2/g e varie molarità della soluzione ionica.

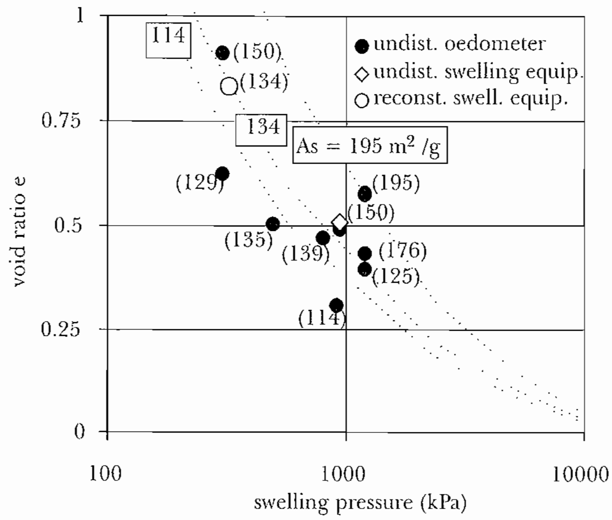

Fig. 21 – Comparison between experimental results relative to the undisturbed Bisaccia clay and the results of the double layer model, at low ion concentration (10^{-3} M) and for three values of A_s.
Fig. 21 – Confronto fra i risultati sperimentali relativi all'argilla indisturbata di Bisaccia ed i risultati del modello di doppio strato, a basse concentrazioni ioniche (10^{-3} M) e per tre valori di A_s.

ve to A_S = 23 m^2/g. The maximum molarity which has been considered is M = 0.1 because for higher values the model fails. In fact, it is well known that Gouy-Chapman approximation to the Poisson-Boltzmann equation is applicable for 1:1 electrolytes up to 0.1 M. Also the van't Hoff relationship is no longer valid for concentration higher than 0.1 M. For this reason, the only aim of the comparison of Fig. 20 is to show that the convergence of the experimental curves relative to distilled water and to the salt solution is predicted by the model, although for higher values of swelling pressure.

Fig. 21 reports experimental data and expected patterns as predicted from the Gouy-Chapman theory for the Bisaccia clay. Patterns have been obtained for 10^{-3} M case, and refer to three values of specific surface. In particular, A_S = 114 m^2/g and A_S = 195 m^2/g are, respectively, the minimum and the maximum values that can be predicted for the undisturbed samples (Tab. III), whereas A_S = 134 m^2/g is the value predicted for the reconstituted material. For the other parameters, the following values have been assumed: $\nu = 1, \beta = 10^{15}$ cm/mmole; $x_0 = 4/\nu$ Å (valid for montmorillonite); G_s = 2.73.

The experimental points refer to the upper lismit of the swelling pressure range evaluated for the undisturbed material. The point relative to the undisturbed specimen which underwent strain controlled test is also reported. The point relative to the material reconstituted with 1 M NaCl solution and exposed to distilled water lies on the theoretical curve relative to its A_S, whereas the point (67 kPa, 1.12) relative to the material reconstituted with distilled water, is very far from curve at and it is doesn't appear in the figure. The Bisaccia clay fraction is mainly constituted by smectites. Furthermore, the typical aggregation of smectites in water is edge-face. Hence, a reasonable explanation of the difference between theory and experiment, in the case of the material reconstituted with distilled water, probably is that neither the reconstitution procedure nor the applied load nor the time of compression were such as to cause parallel particle orientation. On the contrary, such an orientation is typical of smectites formed in concentrate electrolytes.

Notwithstanding some exceptions, the results show that theory and experiment agree. An analogous agreement was found by MADSEN and MÜLLER-VONMOOS [1985; 1989] for a Jurassic opalinum shale with a specific surface between 130 m^2/g and 140 m^2/g.

It is worth noting that according to many authors, in the case of pure clays, the model is applicable for interparticle distances larger than 10 molecular diameters of the liquid [ISRAELACHVILI and MCGUIGGAN, 1988; GÜVEN; 1992], which is, in the case of water, about 30 Å. For interparticle distances lower than that, other interparticle forces, among which surface hydration forces, can be no longer ignored [LOW, 1980; 1992]. LOW [1980] found an empirical relation between swelling pressure and some clay characteristics such as water content, specific surface and average interparticle distance. In particular he analysed 34 Na-smectites and found that their behaviour was well described by the empirical equation:

$$P_S + 1 = B\exp(\alpha m_c/m_w) \qquad (5)$$

in which: α and B are constants, m_c and m_w are the mass of the clay and the mass of water, and P_S is expressed in atm.

For most of the Bisaccia samples the average interparticle distance $2d$ seems to be lower than 30 Å (Tab. III). However the Low relationship does not interpret experimental results, as shown by Fig. 22, in which the experimental points are clearly dispersed and cannot be interpolated by a straight line. This is probably due to the fact that the Bisaccia clay is not homogeneous. In particular, its smectite content varies greatly from sample to sample and hence α and B cannot be considered as constant.

4. Conclusions

This paper has shown that, in the case of the reconstituted Potenza soil, an increase in c.f. of about 4.5 % makes the swelling pressure of the material consolidated at p'_{max} = 700 kPa increase to a value similar to that obtained at 5000 kPa for the material with c.f. = 18%. In the case of the undisturbed Potenza soil, the influence of $CaCO_3$ seems to be very high. The reconstituted Bisaccia clay is strongly influenced by pore liquid composition and by the composition of the liquid the clay is exposed to. As far as the undisturbed material is concerned, the influence of clay-water physicochemical interaction and the extreme variability in grading and mineral composition obscure the influence on swelling pressure of the field stress state.

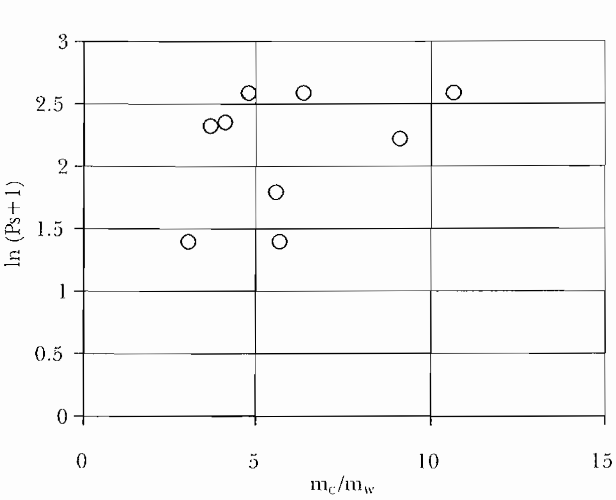

Fig. 22 – Relation between $\ln(\pi+1)$ and m_c/m_w for the undisturbed Bisaccia clay.

Fig. 22 – Legame fra $\ln(\pi+1)$ e m_c/m_w per l'argilla indisturbata di Bisaccia.

For both soils, the interpretation of swelling pressure as the osmotic pressure of the double layer-bulk solution system is generally satisfactory. It is interesting to observe that, in the case of reconstituted materials, Bolt's model [1956] interprets satisfactory the behaviour of the Potenza soil reconstituted with and exposed to distilled water and the behaviour of the Bisaccia clay reconstituted with a concentrated salt solution and exposed to distilled water. This probably depends on the fact that face-face particle arrangement, which is a hypothesis of the model, is obtained in water for illite and in concentrated salt solution for smectite. As expected, the model interprets only qualitatively the behaviour of the material exposed to concentrated salt solutions.

In the case of the Bisaccia clay, the importance of physicochemical processes is such that one of the problem with this clay is to understand what kind of liquid should be used in laboratory. By using distilled water, overestimated values of swelling pressure are obtained. In order to obtain more realistic values, it is important to use a liquid equal to the one the clay is – or is supposed to come – in contact with.

Acknowledgements

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Note

(1) In the case of the one-dimensionally consolidated specimens, the value of p'_{max} was evaluated by applying Jakey's relation to estimate the lateral earth pressure coefficient at rest $K_0 = 1 - \sin\varphi'$, with φ' = 30° as obtained by CU triaxial tests.

(2) The two dotted curves in Fig. 3 are the semilogarithmic representations of the linear relations between the two points at p'_{max} = 200 kPa and those at p'_{max} = 667 kPa. It can be observed that in the case of distilled water the relationship between swelling pressure and p'_{max} is not linear, whereas, in the case of 1 M solution, only one point is out of the linear regression.

(3) The equation has been derived under the following assumptions: validity of the Gouy-Chapman model, parallel flat clay particles, validity of van't Hoff's relation which, in terms of interparticle region and equilibrium bulk solution becomes:

$$\Pi = RT\Sigma(c_{ic} - c_{i0}) \qquad (2)$$

where π = osmotic pressure, R = gas constant; T = absolute temperature, c_{ic} = ion concentration in the central plane of ion specie i, c_{i0} = equilibrium solution concentration of ion specie i; and validity of the relation:

$$e = G_S d A_S \gamma_w \qquad (3)$$

where d = half the particle spacing and A_S = specific surface. Bolt [1956] reported the values of the two groups of variables:

$$\nu\sqrt{\beta c_0}\left(x_0 + \frac{e}{G_s A_s}\right), \quad and \quad \log\frac{P_s}{RTc_0} \qquad (4)$$

where ν = exchangeable cation valence, $\beta = 8\pi F/1000\,DRT$; c_0 = ion concentration in bulk solution, x_0 = parameter depending on clay surface density of charge ≅ $4/\nu\beta\Gamma$, P_s = swelling pressure, Γ = surface density of charge, F = Faraday's constant, D = dielectric constant.

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Influenza dello stato tensionale e della composizione del liquido interstiziale sulla pressione di rigonfiamento dei terreni argillosi

Sommario

Questo lavoro si propone di valutare l'influenza sulla pressione di rigonfiamento dei terreni di stato tensionale preesistente, frazione argillosa (c.f. nel seguito del testo), attività e composizione del liquido interstiziale. A tale scopo, sono stati analizzati due terreni molto diversi fra di loro per contenuto in minerali argillosi e indice di attività. La tendenza al rigonfiamento è stata indotta sia mediante scarico tensionale che mediante esposizione a liquidi diversi da quello interstiziale, tali da far aumentare le forze di repulsione interparticellare. Le prove sono state eseguite sui materiali indisturbati e, allo scopo di analizzare provini con storia tensionale nota, sui materiali opportunamente ricostituiti. Per valutare l'influenza delle procedure sperimentali, le prove sono state eseguite sia a deformazioni che a carichi controllati.

Nel caso del materiale a minor c.f., i risultati mostrano che la pressione di rigonfiamento è molto influenzata dalla frazione argillosa. In particolare, piccole variazioni in c.f. causano variazioni di pressione di rigonfiamento paragonabili a quelle provocate da notevoli variazioni dello stato tensionale efficace iniziale. Nel caso del terreno a maggior c.f., l'influenza della composizione del liquido interstiziale e del liquido a contatto con la superficie esterna del materiale è tale da oscurare del tutto l'influenza dello stato tensionale iniziale. In particolare, l'esposizione ad acqua distillata di provini ricostituiti con soluzione 1 M NaCl induce pressioni di rigonfiamento il cui valore è molto maggiore del valore della tensione efficace media iniziale.

Il confronto fra i risultati sperimentali ed i modelli teorici mostra che per entrambi i terreni la pressione di rigonfiamento può essere interpretata come pressione osmotica del sistema doppio strato - liquido interstiziale. Il semplice modello di BOLT [1956] interpreta semi-quantitativamente il comportamento del materiale esposto ad acqua distillata. A causa delle approssimazioni su cui è basato, il modello fornisce soltanto una rappresentazione qualitativa del comportamento del materiale esposto a soluzioni saline concentrate.