Available at www.scientevents.com/proscience/

ScientEvents

ProScience 6 (2018) 24-32

digilabs

ProScience

Conference Proceedings

3rd International Conference on
Applied Mineralogy & Advanced Materials - MMS2018

Stiff clay masses: pore water salinity, geotechnical properties and system energy

R. Pellicani[1,4], I. Argentiero[1], M.D. Fidelibus[2], S. Fiore[3], G. Spilotro[1,4]

[1]*Dept of European and Mediterranean Cultures, Basilicata University, Matera, (Italy)*
[2]*Dept of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Bari, (Italy)*
[3]*National Research Council CNR IMAA, Tito Scalo, PZ (Italy)*
[4]*National Research Council CNR IREA, Bari (Italy)*

Abstract

Natural soils are characterized by grain size and mineralogical assortments that derive from the history of sediment: original rocks, selective transport phenomena, chemico-physical interactions with the environment and, in particular, with ground- and surface waters. The deformation response to external loads is defined with different and contemporary mechanisms by the solid skeleton and the clay component. In both cases, mineralogy defines the behaviour at the micro and nano scale. The coarse component responds with a work of elastic (conservative) and non-elastic deformation (re-arrangement or crushing of soil particles or components). Almost a century of studies of the inner structure of clays allows to assimilate it to a capacitor, whose dielectric is the DDL and the filler between the plates, electrically negatively charged. This kind of system is conservative from the energetic point of view and the inner capacity of energy storage depends from the mineralogical type of the clay, and from the dielectric type, which in turn depends on water having variable concentration of dissolved ions. Clay swelling should be regarded as a typical energy release phenomenon, which depends from the soil type and from the previous energy stored. It is relevant to note that the energy release can be triggered either by load confinement changes, or by changes of border environmental conditions, such as the salinity and chemistry of interacting groundwater, or their concentration by severe sun driven capillarity.
The paper shows results of the behaviour of clayey soils sampled in several contexts in the blue clays from the Bradanic foredeep (southern Italy), emphasizing the role of geomorphological and hydrogeological context on the salinity and chemical composition of clay pore waters and on the geotechnical and swelling behaviour of this very common kind of soils. The pore water salinity has been tested after high pressure squeezing on soil samples and the energy balance has been evaluated

ISSN: 2283-5954© 2018 The Authors. Published by Digilabs
Selection and peer-review under responsibility of MM2018 Scientific Committee
DOI:10.14644/mms.2018.005

by means of one-dimensional confined compression tests. For the tested soils, the physical parameters and swelling capabilities are strictly relate to the pore water salinity (and chemical composition).

1. Introduction

Expansive clays are worldwide widespread and known for their damaging behaviour, able to induce severe strains or displacements and destructive stress fields on soil interacting with structures in surface or in subsurface.

Swell potential is normally related to the final volume in free swell tests, or to the pressure developed in no-swell tests (ASTM Standards (D4546-96), 1997; Alyaqoub et al., 2017; Basma et al, 1995; Fattom et al., 2000). Such results lead to a rating of clay minerals swelling capabilities. Swelling (and shrinking) is due to the ability of some clay minerals to absorb water between the layers, resulting in repulsive forces and structural expansion. Smectites are considered as the swelling clay minerals par excellence, whereas illite, kaolinite and chlorite are not swelling minerals. However, also weathered illite and chlorite can swell if their crystalline structure is defective.

Damages on buildings easily evidence that in the swelling process of a clay-rich soil a work is performed against external (mainly gravitational) forces and that this work should derive from the previous stored energy, of conservative type from evidence. In this respect, the damage potential should be primarily assessed based on the total energy stored in a volumetric soil unit. In other words, if some clay minerals swell more than others, soils with less swelling minerals but that have stored more energy from the work of external loads, can produce greater damages. Previous research (Fidelibus et al., 2018) have well related the energy stored in clayey soils to the geological and hydrogeological history of the stratigraphic deposits, the overburden or changes in groundwater level, the environmental conditions of exposure to fluids with salinity different from that of the native pore waters and the relative importance of exposure to wet/dry climate. So, the evaluation of the past and present or expected climate could become relevant in the evaluation of swelling damages potential.

Two examples of swelling damages are reported in Figs. 1 and 2. They relate to buildings founded on blue stiff fissured marine clays of Pleistocene, which fill a wide tectonic trough (the Bradanic foredeep) in the southern Italy. Fig. 1 shows the floor lifting of a private house in Matera (context 4 in Fig. 3), while Fig. 2 evidences the effects of clay swelling on a hospital long building in Taranto (context 9 in Fig. 3; Spilotro et al., 1995). The main clay minerals in these sediments are illite and kaolinite with some interstratified smectite-illite phases (Ciaranfi et al., 1971; De Marco et al, 1981; Garavelli et al., 1974). The whole region represented in Fig. 3 is characterized by a semi-arid climate.

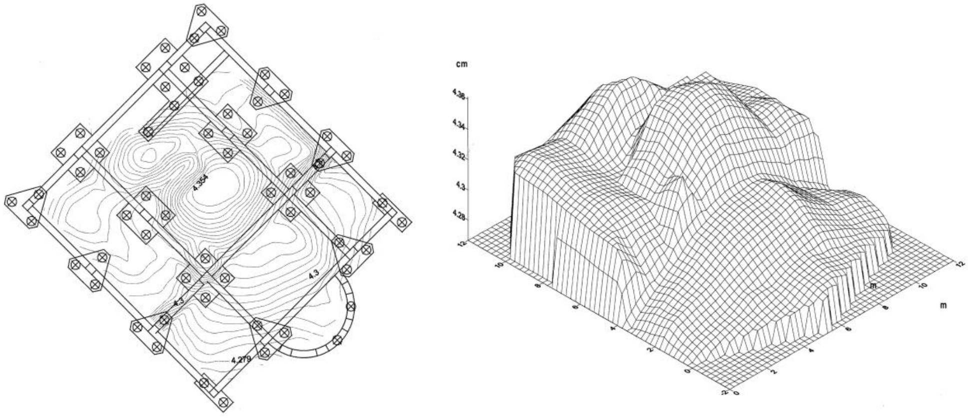

Fig. 1. Plan and DEM of a floor lifting in a private house in Matera (Basilicata, Southern Italy), from clay swelling

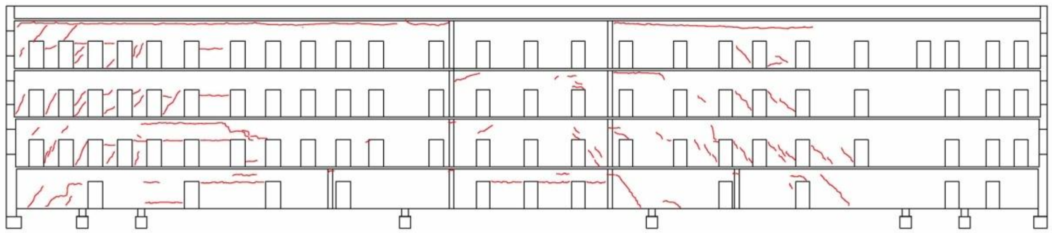

Fig. 2. Cracks on the masonry of a long public (Hospital) building in Taranto (Puglia, Southern Italy) from foundations differential heave on swelling blue clays

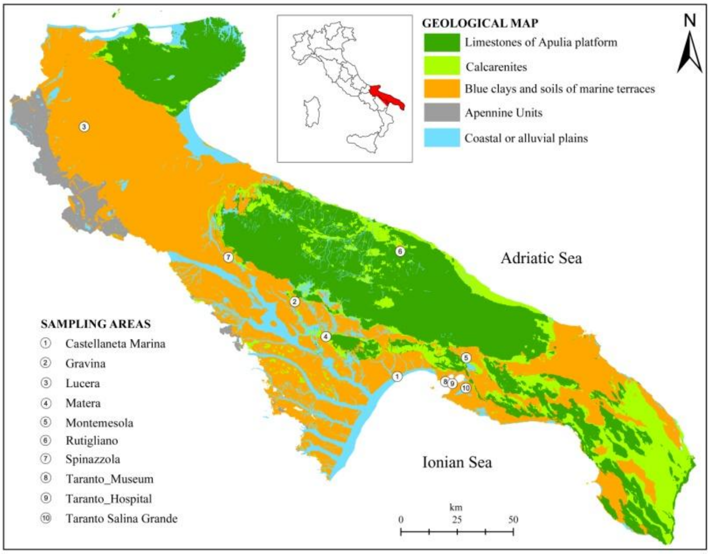

Fig. 3. Geolithological simplified map of Southern Italy with sampling areas (from Fidelibus et al., 2018, modified)

2. Clay-rich soils and energy storage

The crystal structure of clay minerals and their behaviour at micro and macro scale have been investigated for several decades from different mineralogical, geotechnical, and engineering points of view (Gouy, 1910, and many others). One of the most debated issue is the role of the interstitial fluid salinity under an external stress field, since it controls the volumetric equilibrium of a clay sediment (i.e. the soil stiffness and the compression work) (Olson, 1971; Siddiqua, 2014; Sridharan et al., 1982). The main difficulty in assessing such a role lies in the fact that the process involves many chemico-physical factors, which assign a great complexity to the system. However, an extreme simplification should be possible: the saline interstitial fluid in a clay mineral system is strictly related to the fluid in the DDL, which acts as the dielectric in a capacitor composed of two-faced crystals (both electrically negatively charged) (Tayloret al, 1986).

An electrical field, whose intensity depends on the electric charge and on the properties of the dielectric, is then generated. Such electric field is conservative, and it is associate to a stored energy, which is the balance between the positive work (external loading or hot climate driven capillarity and drying) and the negative work (swelling and heave). The system, really more complex also for the presence of non-conservative works, can be represented by a spring of fixed stiffness coupled with a charged capacitor, of variable spacing and dielectric between the plates. This system is energetically conservative and can store energy of deformation to give back it as soon as the external force weakens or the dielectric changes (Fig. 4).

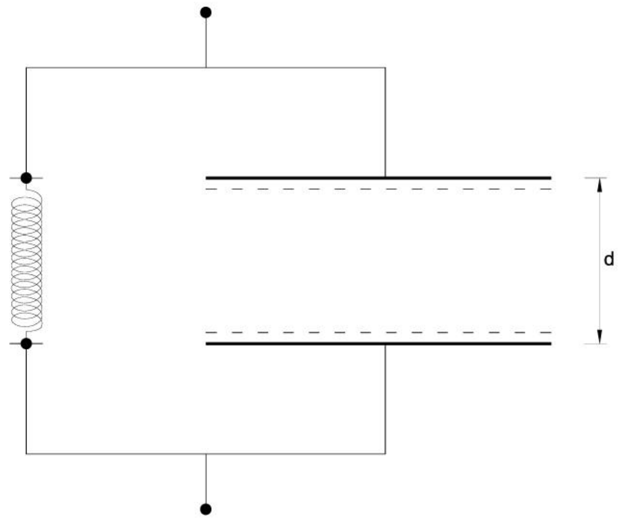

Fig. 4. Mechanical and electrostatic coupled model of a clay rich soil. External loads or thermal stresses modify the internal conservative energy stored in the system. Note that crushing or rearrangement of soil particles introduce also not conservative works

The energy stored in this system is

$$U = U_m + U_{el} = 1/2\ K_m * d\^{}2 + 1/2 * K_{el}*d/e_r$$

where U_m is the mechanical energy, U_{el} is the energy stored in the electrostatic system, K_m is the mechanical stiffness of the spring, K_{el} is the equivalent electrostatic stiffness of the system, d is the one-dimensional geometrical variation of the whole system, e_r is the relative permittivity of the dielectric inside the DDL.

It should be noted that the energy of the system depends not only by d, i.e. the results of strain achieved by the soil under external loads or by drying, but also from e_r, which is strictly related to the salinity of native waters interacting in geological times with environmental groundwater; e_r from saltwater is greater than the unity. In the sampling area #10 (Fig. 3) squeezed pore water has a threefold salinity compared to the native saltwater of marine origin.

Osmotic effects, naturally or man-made induced by differences in both the chemical components and their concentration between the pore water and free water in the discontinuities and on the border of the clayey masses, may be relevant in determining their geotechnical behaviours (Barbour et al., 1989; Bolt, 1956; Mitchell, 1973). Marine clays incorporate native interstitial salt water having high concentration of dissolved ions, mainly sodium and chlorides (Sayles et al., 1975). This generates, in the dielectric spaces, a lower electrical field compared to an identical situation but with a lower salt concentration of the interstitial water. In nature, turning between the two types of interstitial water is very common, being driven by ion diffusion processes (and their thermodynamics constraints) like in surface freshwater interacting with saline interstitial water of marine clays. These latter, either by the overburden of younger sedimentary deposits, but mainly by very strong capillary forces activated by surface drainage and evapotranspiration from sun and dry wind (Fidelibus et al., 2018), undergo strong volumetric reduction, which can be recovered with work production (well known as the swelling of the stiff clays) if pore waters interact with freely circulating waters of different salinity. Relationships between salinity, type of squeezed water and geotechnical properties of blue stiff clays occurring in the Bradanic Trough (Southern Italy, Fig. 3) (Ricchetti et al., 1979), confirms the previous statements. As a matter of fact, the measurements of the work released by these marine clays (after ionic diffusion in fresh water) has been extensively tested in the oedometer apparatus (which allows one dimensional volumetric variation) (Fig. 5).

The process changes the dielectric properties and the energy stored inside the diffuse double layer. This explain why stiff marine clays can exhibit a sudden work against the gravitational force due to overburden or a foundation by swelling or, more rarely, ensuing different border conditions, a settlement under relatively insignificant heads. These phenomena have been evaluated, up to now, in terms of swelling pressure. However, a better understanding can be gained using energetic terms: this part of the clay soil system is energetically conservative. External contribution of energy, work of overburden or sun driven capillarity and long exposure to border low salinity waters can modify the concentration of pore-waters, thus affecting the DDL geometry. Swelling and shrinkage of clays, and their volumetric and geotechnical implications, should be also regarded as variations of the electrostatic and mechanical internal energies of the system.

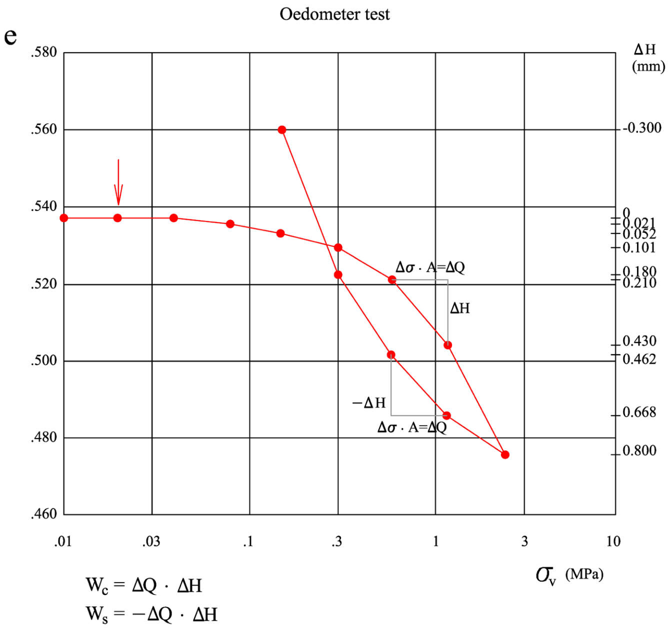

Fig. 5 Typical graph of an oedometer test with incremental or decremental work during loading or unloading cycle. Sample of a swelling stiff blue clay from site # 4 in fig. 3

3. Border hydrological conditions and soil profiles

Relationships between salinity, type of squeezed water, groundwater salinity profiles and geotechnical properties of blue stiff clays occurring in the Bradanic Trough (Southern Italy) have been extensively tested (Fidelibus et al., 2018). In particular, 53 samples taken from 10 sites (Fig.3) were analysed by means of classification and recognition tests, resistance to axial compression and confined compression. Part of these samples (30) was subjected to squeezing to obtain samples of interstitial waters (Reeder et al., 1998; Sacchi et al, 2001) up to a load of 20 MPa; the extracted fluids were subjected to chemical analysis. The results of the tests can be synthetized in Fig.6, which shows the relationship between the dry density (Gd) and Wc 0, 12, i.e. the work in an oedometer test performed in compression on swelling (Sw) and non-swelling (NSW) samples. From the engineering geology point of view it is clear the geological-environmental conditioning: the dry density and salinity of the squeezed interstitial waters are strictly related each other through the intensity of the overburden and the long-time freshwater stands. More in detail, a high salinity of pore waters matches with high dry density and, as revealed by oedometer tests, high stored energy; it results from strong consolidation by loads or capillarity saving native saltwater salinity, with no interaction with freshwater. The natural environments that host this situation are non-flat clay exposure (contexts #1, #4, #5 and #9 in Fig. 3); the interstitial water salinity in the context #10, a natural salt pad feed by marine water and under perennial evaporation, is about three times that of present seawater.

Conversely, marine clays that underwent long-time interaction with freshwater, show a lower interstitial salinity, and are characterized by lower dry density and lower stored energy (lower swelling potential). This situation arises also at significant depths under flat surfaces and permeable covers, hosting perennial freshwaters (contexts #2, #3, #6 and #7 in Fig. 3); the fresh water diffusion in a marine clay mass after geological persistence has been detected in the context #2 (Fig. 7).

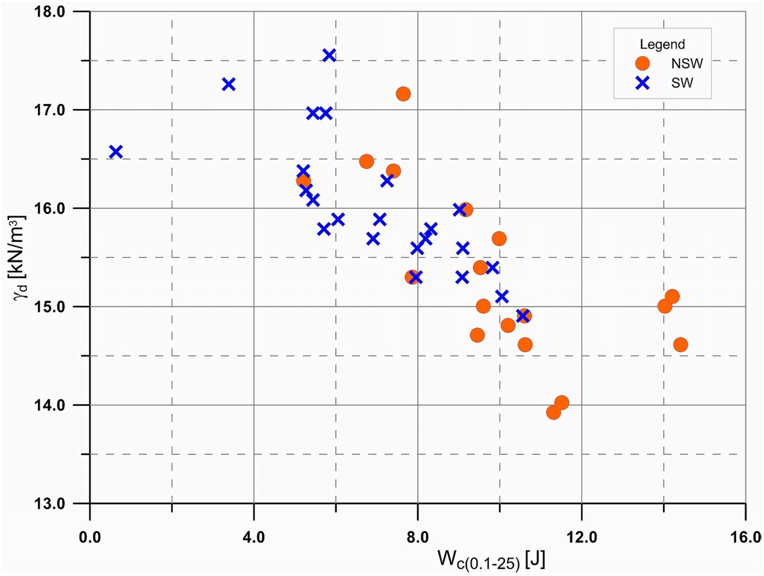

Fig. 6. Experimental relationship between dry density and compression work in oedometric test on swelling and non-swelling samples (from Fidelibus et al., 2018, modified)

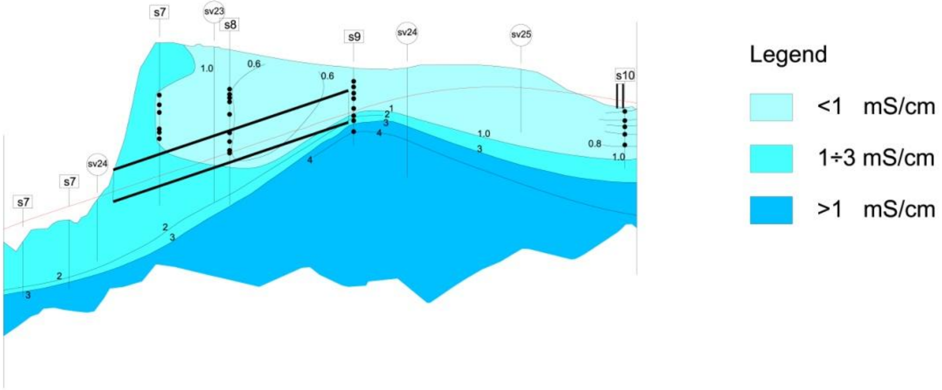

Fig. 7 Groundwater conductivity field in a clay mass under a freshwater aquifer hosted in a sandy terrace near Gravina (context #2 in Fig. 3)

4. Conclusions

A clay soil system should be viewed as energetically conservative in respect of the external contribution of energy: the work from overburden or from sun driven capillarity and long exposure to border low salinity waters can modify the concentration of pore-waters, thus affecting the DDL geometry inside the clay mineral arrangement. Swelling and shrinkage of clays, and their volumetric and geotechnical implications, should be regarded as variations of electrostatic and mechanical energies of the system. So in terms of swelling potential (almost always damaging) should be relevant the energy release capability, which in turn, depends from the previous total stored energy, function of the type of clay mineral and of the intensity of external (mechanical or thermal) contributions during the geological life of the sediments. Specific geomorphological environments can lead to effective stress variations, but also to changes (by dilution, concentration or water-rock interaction) of the chemical composition and salinity of the native interstitial saltwater, so affecting the inner clay mineral structure (part of the dielectric inside the DDL) and thereafter the energy stored and the geotechnical properties. Sudden changes of salinity in the border aquifers or in clay fissures, and variations of climate condition can lead to huge swelling with big energy releases also in not smectitic clayey sediments.

References

ASTM Standards (D4546-96) Standard test methods for one-dimensional swell or settlement properties of cohesive soil. ASTM standards annual book, 1997.

Alyaqoub T.H., Parol J., Znidarcic D. (2017). Experimental investigation of volume change behaviour of swelling soil. *Appl. Clay Sci.*, 137, 22-29. doi:10.1016/j.clay.2016.11.018.

Basma A.A., Al-Homoud A.S., Malkawi A.H. (1995). Laboratory assessment of swelling pressure of expansive soils. *Appl. Clay Sci.*, 9, 355–368.

Barbour S.L., Fredlund D.G. (1989). Mechanisms of osmotic flow and volume change in clay soils. *Can. Geotech. J.*, 26, 551-562.

Bolt G.H. (1956). Physico-chemical analysis of the compressibility of pure clays. *Geotechnique*, 6 (2), 86-93.

Ciaranfi N., Nuovo G., Ricchetti G. (1971). Le Argille di Taranto e di Montemesola. Studio geologico, geochimico e paleontologico. Boll. Soc. Geol. Ital., 90, 293-314.

De Marco A., Moresi M., Nuovo G. (1981). Le argille di Taranto e di Montemesola: caratteri granulometrici, Mineralogici e chimici. Rend. Soc. It. Mineralogia e Petrologia, Milano, 37 (1), pp 241- 266.

Fattom M., Barakat S. (2000). Investigation of three methods for evaluating swelling pressure of soils. *Environ. Eng. Geosci.*, VI (3), 293–299.

Fidelibus M.D., Argentiero I., Canora F., Pellicani R., Spilotro G., Vacca G. (2018). Squeezed interstitial water and soil properties in Pleistocene blue clays under different natural environments. *Geosciences 2018,8,89;* doi:10.3390/ geosciences8030089.

Garavelli C., Nuovo G. (1974). Le argille di Montemesola: dati mineralogici e chimici, Rend. Soc. It. Mineralogia e Petrologia, Milano, XXX (2), pp 611 – 642.

Gouy G. (1910). Sur la constitution de la chargeélectrique à la surface d'un electrolyte. *J. Physique Ser.*, 4 (9), 457-467.

Mitchell J.K. (1973). Chemico-osmotic effects in fine-grained soils. ASCE J. of the Soil Mech. and Found. Division, 99, 307-322.

Olson R.E., Mesri G. (1971). Mechanisms controlling the compressibility of clays. *J. Am. Soc. Civ. Engrs*., 96, SM6, 1853-1878.

Reeder S., Cave M.R., Entwisle D.C. (1998). Trick, J.K. Extraction of water and solutes from clayey material: a review and critical discussion of available techniques. BritishGeologicalSurvey. Technical Report WI/98/4C, 60 pp.

Ricchetti G., Scandone P. (1979). Inquadramento geologico regionale della fossa Bradanica. *Geol.Appl. e Idrogeol*., XIV, p III, 489 – 492.

Sacchi E., Michelot J.L., Pitsch H., Lalieux P. (2001). Aranyossy, J.F. Extraction of water and solutes from argillaceous rocks for geochemical characterisation: Methods, processes, and current understanding. *Hydrog. J*., 9(1):17-33, doi: 10.1007/s100400000113.

Sayles F.L., Manheim F.T. (1975). Interstitial solutions and diagenesis in deeply buried marine sediments: results from the Deep-Sea Drilling Project. *Geoch. Cosmoch. Acta*, 39, 103-127.

Siddiqua S., Siemens G., Blatz J., Man A., Lim B.F. (2014). Influence of pore fluid chemistry on the mechanical properties of clay-based materials. *Geotech. Geol. Eng*., 32, 1029-1042.

Spilotro G., Fidelibus M.D. (1995). Sea level changes and salt content in the pore water. Proc. of XI ECSMFE, the Interplay between Geotech. Eng. and Eng. Geol., Copenhagen, 1, 259-264.

Sridharan A., Jayadeva M.S. (1982). Double layer theory and compressibility of clays. *Geotechnique,* 32, 133-144.

Taylor R.K, Smith J.T. (1986). The engineering geology of clay minerals: swelling, shrinking and mudrock breakdown. *Clay minerals,* 21, 235-260.