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Discussion on Tunis Soft Soil Sensitivity

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Abstract In Tunis City, the sensitivity of the marine deposits at shallow depth ($z = 0$–20 m) varies significantly. The influence of the process of the leaching out of Tunis soft soil on its geotechnical parameters is a focal point in this research. This process leads finally to moderate levels of sensitivity for Tunis clays since it appears to happen in a two steps with increasing sensitivity. The "hard water" leaching out and the dispersive action of organic matter (humus) lead unexpectedly to higher but still moderate level of sensitivity as measured on many Tunis sites. These sensitivity variations result from the combination of leaching out with hard ground water and high content of organic matter. This sensitivity attracted our attention and remains of high interest for the study of the behaviour of the Tunis soft clay.

Keywords Activity · Deposit process · Leaching out · Sensitivity · Shear strength · Tunis soft clay

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1 Introduction

Research studies aiming at describing the properties of sensitive clays have been conducted since the forties, mainly in Sweden, Norway and Canada (Bjerrum 1954; Talme et al. 1966; Leroueil et al. 1983). Quick clays refer to clays with a structure collapsing completely at remoulding thereby reducing the shear strength to almost zero. Rosenqvist (1946) suggested that the engineering properties of quick clays are due to leaching out of the salt content in marine clays. Marine deposits, in their post deposition phase, are not influenced by salty water only; the leaching out by "hard water" is actually the predominant factor to discuss.

Several classifications for clays including the sensitivity aspect have been proposed (Rosenqvist 1953; Sôderblom 1969; Mitchell 1976). Sôderblom (1974), (1983) has suggested that the quick clay behaviour only applies for soft cohesive soils having a minimum sensitivity of 50. It is generally accepted that the sensitivity increases linearly with increasing liquidity index. The mineralogy and grain size distribution are not sufficient to explain the difference between such a "real" quick clay and clays having low sensitivity.

The sensitivity greatly increases in case of very low salinities. Leaching out experiments conducted by Torrance (1974) on Norwegian marine clays demonstrated that the major changes in Atterberg limits, in remoulded shear strength and in sensitivity do occur after the salinity has been reduced to a value smaller than 2 g/l.

Houston and Mitchell (1969) then Quigley (1979) have conveniently summarized the factors which affect sensitivity, i.e., the factors which produce high peak strength and a low remoulded strength.

Brand and Brenner (1981) showed that all sediments with "quick" behaviour are young from the geological view point, and that most of them are marine deposits. A compilation of several analyses from different parts of the Champlain sea soft deposits, conducted by Lebuis et al. (1983), indicated that high sensitivity corresponds to high concentration of Na^+ and K^+. In addition and as a geo-engineering consequence, the kinematics and the final shape of a sliding in clay is largely governed by its sensitivity; as noticed from many land slide studies. The presence of quick clays, its leaching out and especially the excess pore pressures induced stepwise during retrogressive flake type sliding should be thoroughly taken into account in this respect (Van Impe and De Beer 1984; Hight et al. 1987). The influence of sensitivity on compressibility is another important issue (Skempton and Northey 1952; Skempton 1970a, b; Leroueil et al. 1983; Burland 1990; Cotecchia and Chandler 2000).

Bjerrum (1954) had reported that activity, liquid limit, peak and remoulded shear strength, all decreasing as the salt content of the clay drops down. The plateau of Tunis is basically a marine/alluvial deposit formation of the recent quaternary (Holocene). Clays and mud are deposited in mixed environments of latchstring, alluvial, fluvial and marine origins [which explains their high content in silt and in organic matter (OM)].

In a first work Kaâniche et al. (2000) performed a geotechnical and geological analysis of Tunis soft soil; these physical parameters were addressed especially for Tunis soft clay by Touiti et al. (2007). Since the first attempts interest in the sensitivity of the Tunis clays grew continuously.

The objective of this paper is to understand the development of sensitivity in the Tunis soft soil by investigating, the geological origin, the processes of post-deposition as well as the mineralogy of Tunis soft soil. In addition, the survey of the physical and mechanical parameters as well as comparison with other sensitive clays will also be undertaken.

2 Geological and Geotechnical Aspects of Tunis Clay

The ancient Tunis City was built on a depression surrounded by hills. The old town was established in the southern side, and the new residential suburbs now are located in the north. The plateau is identified as an important deposit of the recent Quaternary age, including sandy levels and overlaid by anthropogenic formation. The recent quaternary is resting on clayey to sandy-clay layer of ancient Quaternary. This latter represents the rigid stratum of Tunis City.

The alluvial sedimentation in the Tunis estuary can be associated with simultaneous intensive subsidence (Piementa 1959). These lagoon depressions, at the level of Sebkhet-Essijoumi and the Lake of Tunis, are generally filled with mud of the recent Quaternary and of clayey sand or silt sand of the riverbeds. Divergent displacements of the riverbeds of Medjerda and Méliane during the recent Quaternary are the consequence of a synchronous upward block displacement of the region of Tunis (Ben Ayed 1986; Boutib et al. 1997). Thereafter, the soft deposits were filled up to create the zones of urban extensions with anthropogenic formations of thickness varying between 1 and 8 m. This geological and geotechnical situation requires deeper study in order to determine the mechanical features of the Tunis soft soil.

The analysis of geotechnical and electronic atlas maps and the geological profiles deduced from the geotechnical and geological information system (GGIS) performed by Kaâniche et al. (2000) permitted the subdivision of Tunis City in four homogeneous zones: I, II, III and IV.

The soil of the Tunis plateau (zone I) is composed of three important formations: the embankments, the muddy complex and the sandy-clay complex which is assumed to be rigid stratum.

The thickness of embankments varies from 1 to 8 m. Due to the presence of versatile materials; their geotechnical characteristics are very heterogeneous.

The muddy complex deposit is linked to the evolution of the Tunis Lake during the recent Quaternary. Analysis of data from the GGIS shows that, the grey sandy mud was deposited, in a continental environment, directly on the rigid stratum which constitutes the deep mud layer. Than, the marine environment favoured deposit of grey and greenish sandy mud, of gray silt mud and of blue-grey mud, which represents the width-deep mud. Finally, a lagoon environment caused the deposit of superficial black and grey mud.

The shallow mud layer represents the main focus of this paper. It corresponds to the foundation level of modern buildings in Tunis City and some older areas at the western side. This mud layer is covered all over by the above stated embankments. This formation includes the first twenty meters of the Tunis mud complex, which is characterized by high compressibility and very low strength. For this reason a thorough study of such soft clay is needed.

3 Sensitivity

The sensitivity, S_t, is basically defined as the ratio of the undisturbed shear strength by the remoulded shear strength of the clay, at the same water content. Normally consolidated clays very often exhibit values of sensitivity 1–4 and in some cases up to 8. Heavily over-consolidated clays are considered insensitive ($S_t = 1$).

Several classifications of clays with respect to sensitivity have been proposed, Rosenqvist (1953), Sôderblom (1969), and Mitchell (1976). The classification proposed in this paper is presented in Table 1.

The diagram (Fig. 1), which has been presented by Mitchell (1976), was only intended for rough estimation of sensitivity. It is based on average values from several normally consolidated clays in Norway, UK, USA and Canada. This classification has been used to assess the sensitivity of soft clays, which may reach values of 30. Leroueil et al. (1983) have suggested the existence of a relation between compression index Cc and initial void ratio e_0 and the sensitivity S_t (Fig. 2). Applying Leroueil's and Mitchell's diagrams to Tunis soft clays reveal high levels of sensitivity.

Table 1 Classification of soils based on their sensitivity, S_t

S_t	Classification
1	Insensitive clays
1–4	Slightly sensitive clays
4–8	Medium sensitive clays
8–30	Very sensitive clays
>30	Quick clays

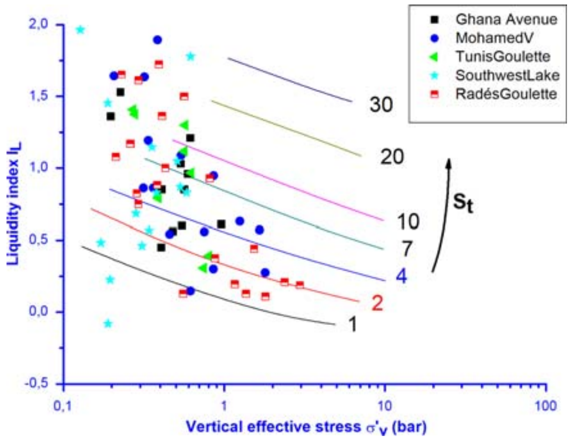

Fig. 1 Sensitivity of various Tunis soft clays according to Mitchell's diagram (1976)

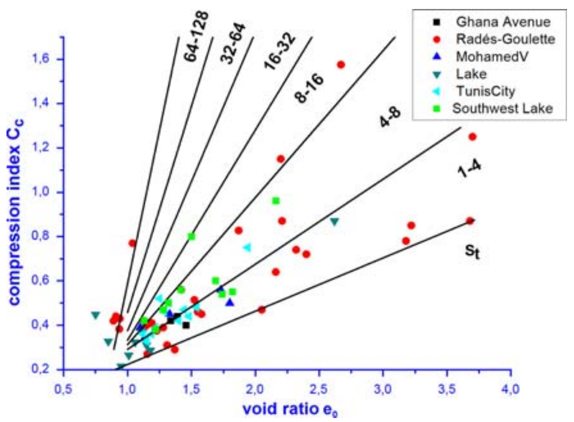

Fig. 2 Sensitivity of various Tunis soft clays according to the diagram of Leroueil et al. (1983)

4 Factors Contributing to Sensitivity

Difference between quick clays and clays of lower sensitivity is made by the relation between water content, limit of consistency, and soil activity. As example, Talme et al. (1966), showed that very sensitive clays and clays having normal sensitivity may have the same type of mineralogy while the difference in sensitivity is attributed to the microstructural, physical and chemical conditions of water.

The factors contributing to sensitivity (Quigley 1979) are respectively: high water content (equal or higher than liquid limit), high specific area of soil grains, high zeta potential (expanded double layers) due to high monovalent cation adsorption (Na^{+}, K^{+}) relative to divalent cations (Mg^{2+}, Ca^{2+}), low salinity, high active organic matter content, low smectite content and low deposition speed.

4.1 Leaching Out

The post depositional process of leaching out is potentially one of the most important events in the chemical history of soft clays. Leaching out is a process that removes substances such as dissolved salt ions (Ca^{2+}, Mg^{2+}, Cl^{-}, Na^{+}, CO_3^{2-}, K^{+} etc.) from parts of the soil skeleton.

During this process, the water content remains approximately constant (Skempton and Northey 1952), while the liquidity index (LI) increases and the remoulded undrained strength decreases (Fig. 3).

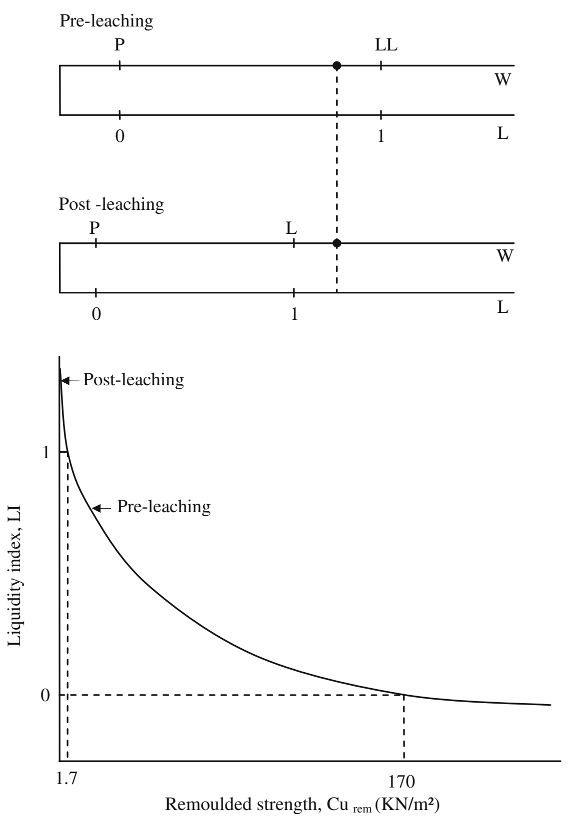

Fig. 3 Changes in liquidity index and remoulded strength, caused by leaching

When clay particles are deposited in sea water with a high ion concentration, the electrical double layer will be smaller and the particles will move closer to each other. Then attractive forces will dominate and may cause the particles to flocculate and thereby create clay with a higher void ratio. In fact, the clay deposited in salt water is composed of large aggregates. When the salt in such a clay is leached out, there will be low ions concentrations in pore water and larger electrical double layer (skeleton structures were kept unchanged but the links were broken). Then, when this clay is remoulded particles cannot be re-connected into large aggregates again. The void ratio and water content remain constant; however the water retaining capacity of the clay, which is reflected in the liquid limit, is reduced.

Leaching out does not only cause a decrease in stiffness but it also reduces the undrained shear strength (Fig. 3). Consequently, the process of leaching out is one of the factors leading to the development of very sensitive clays. The remarkable increase in compressibility is attributed to the large reduction in water holding capacity (liquid limit) which occurs at leaching out processes and the resulting decrease in water content if the clay is subjected to a stress level close to its original pre-consolidation stress (Fig. 4).

The presence of more permeable seams in Tunis soft soil, such as sand and silt seams, greatly enhances the possibility of leaching out. Also the water content of Tunis soft soil rising beyond its liquid limit is a characteristic of leaching out. Figure 5 illustrates the process of leaching out of Tunis soft soil.

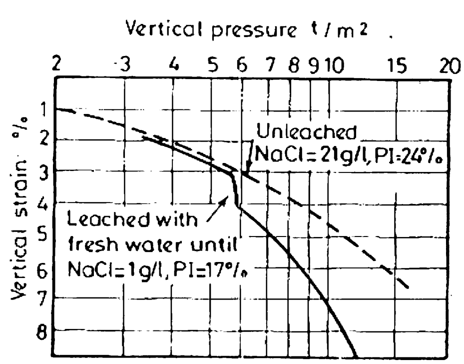

Fig. 4 Experimental evidence of leaching effects (from Bjerrum 1967)

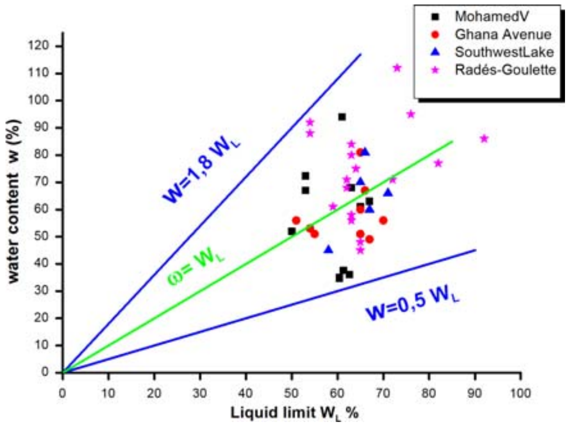

Fig. 5 Water content versus the liquid limit of the Tunis soft clay

4.2 Physical Properties of Tunis soft Soil Contributing as Well to its Sensitivity

The difference between very sensitive clays and clays of low sensitivity is enhanced as well by specific relations between water content, limit of consistency and the soil activity. As example Talme et al. (1966), showed that the very sensitive clays and clays having a normal sensitivity may have the same type of mineralogy while the difference in sensitivity is attributed to the micro structural, physical and chemical conditions of water.

4.2.1 Water Content and Consistency Limit

Water content higher or equal to the liquid limit is one of the factors contributing to the sensitivity. The water content of Tunis soft clay ranges from 0.5 W_L to 1.8 W_L. In Goulette-Radès and Mohamed V sites, water content is generally larger than the liquid limit, and liquidity index is then greater than 1 (Fig. 5; Table 2).

4.2.2 Very Slow Geological Deposition of Tunis Soft Clay

The fact is that lower sensitivities resulted from rapid deposition in active water while higher sensitivities do correspond mainly to slow deposition in dormant water.

Table 2 Liquidity index of the Tunis soft soil

	Radès-Goulette	Tunis-Goulette	Mohamed V	Ghana avenue	South West Lake
LI	1.59 [0.19–3.92]	1.22 [0.39 to 1.41]	1.10 [0.15 to 2.22]	0.89 [0.45 to 1.53]	0.92 [0.22 to 1.78]

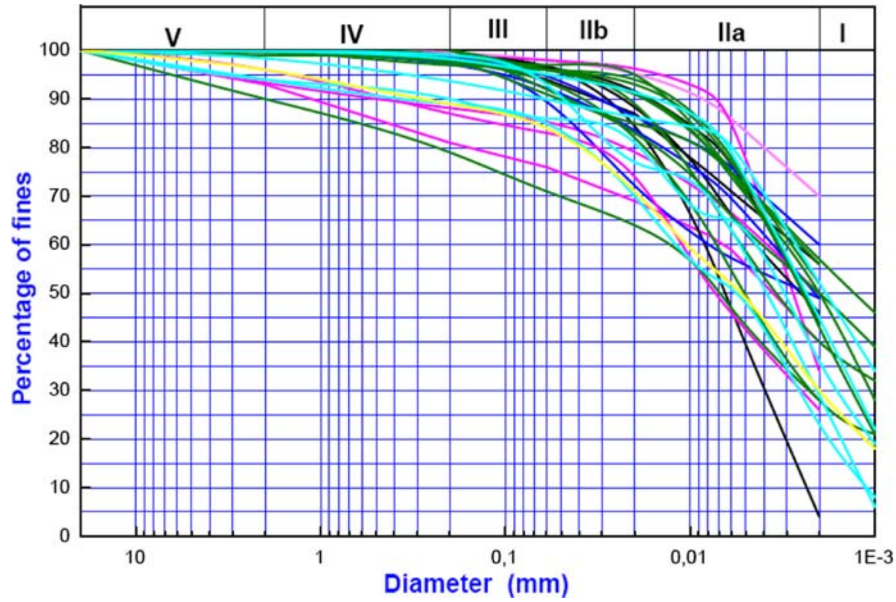

Fig. 6 Grain size distribution of Tunis soft clays (depth <20 m)

The grain size distribution curves of Tunis soft soils have generally hyperbolic facies illustrating the deposition in lake water conditions i.e., slow deposition in dormant water (Fig. 6). Slow rates of sedimentation are associated with soils of lower density and higher void ratio and water content. Low density values and high water content of the Tunis soft soil can be confirmed from the trends depicted in Fig. 7.

4.2.3 Activity and Smectite Content

The "activity" mainly depends on the ionic exchange capacity and the specific area of clay minerals as well as on the content of organic colloids (Hansbo 1975). Skempton (1953) and later Mitchell (1976) noticed that difference in activity (A_c) may be mainly due to the different clay minerals (illite, kaolinite, montmorionnite and chlorite).

Bjerrum (1967) compiled values of the clay content and the corresponding plasticity index for several natural Norwegians clays (Fig. 8). The activity of quick clays remained normally less than 0.5.

The Tunis soft soil is classified as low-active (Fig. 8) and its sensitivity varies between extreme values corresponding to Toyen sensitive clay and Studenterlunden normal clay in Oslo. Tunis soft clay salt concentration varies from 6 to 27 g/l. After Bjerrum's classification comparison of various types of sensitive clays with Tunis soft clay shows that the latter has various levels of sensitivity (low to high, Fig. 8) according to the data obtained from different investigated sites in Tunis City.

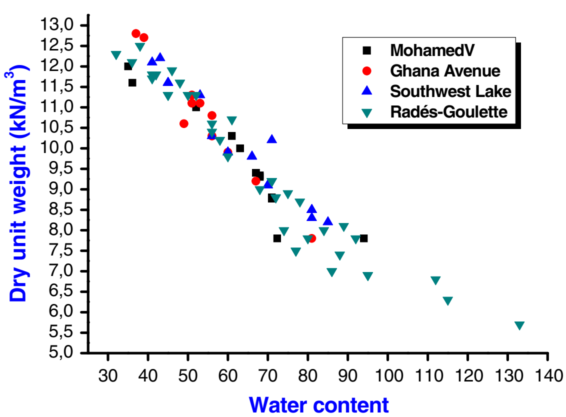

Fig. 7 Dry density versus water content of the Tunis soft clay

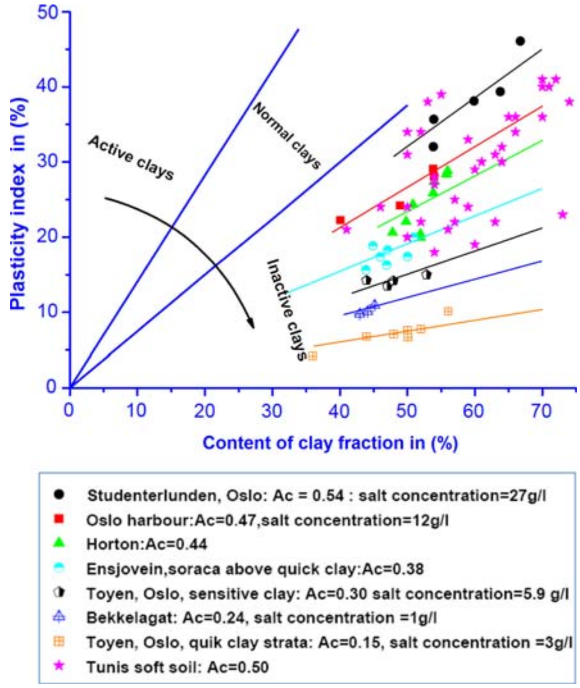

Fig. 8 Activity of Norwegian clays (Bjerrum 1954) and Tunis soft clay

Soft clays having the potential to become quick clays do not contain more than a few percent of swelling minerals of the smectite type (Rosenqvist 1978). Clay minerals of six muddy samples from Tunis City were identified by X-ray diffraction. All samples were investigated as air dried powders and ethylenenglycol solvated. An estimation of the contained clay minerals quantities was performed following the procedure proposed by Tributh and Lagaly (1991). The very low montmorionnite contents fall in the range of 0 to 5.5% (Table 3).

The observed low activity for Tunis soft clay can be explained by its low content in swelling minerals as a predominant factor.

Table 3 Quantitative analysis of clay minerals for Tunis soft soil

Samples	1	2	3	4	5	6
Montmorrillonite (%)	0.7	0	2.8	5.5	3	0
Chlorite (%)	2.4	13	1.3	3	3.4	4.6
Kaolinite (%)	24.2	32	37.6	39.4	31.8	29.3
Illite (%)	68	52	50.7	35	51	58.6

4.3 pH Level

Tunis clay is soft calcareous clay. Calcareous particles in the clay act as neutralizing acid agents (Eq. 1). Most natural soils have a pH of about 5.5–8.3 (Van Impe 2003). Thus the potential of hydrogen ions (pH) of soft clay in Tunis is over seven (alkaline).

$$CaCo_3 + 2HCl \rightarrow CO_2 + H_2O + Ca(Cl)_2 \quad (1)$$

Table 4 gives an overview of the pH zero point charge (pH_{ZPC}) for various minerals. As can be seen, the values for quartz, illite, kaolinite and chlorite are less than seven, indicating that in Tunis soft soil, these minerals act as a cation exchanger (Eq. 2). Then the particle surface will be more negatively charged (Fig. 9).

$$pH > pH_{ZPC} \Rightarrow MOH + OH^- \rightarrow MO^- + H_2O \quad (2)$$

4.4 Active Organic Matter and Carbonates Contents

There are two types of organic matter, free (not transformed) and active organic matter, which is mainly composed of humic colloids.

Table 4 pH_{ZPC} values of various minerals (Stumm and Morgan 1981)

Mineral	pH_{ZPC}
Quartz	1–3
Illite	6.5
Kaolinite	1–4.6
Montmorrillonnite	<2–3

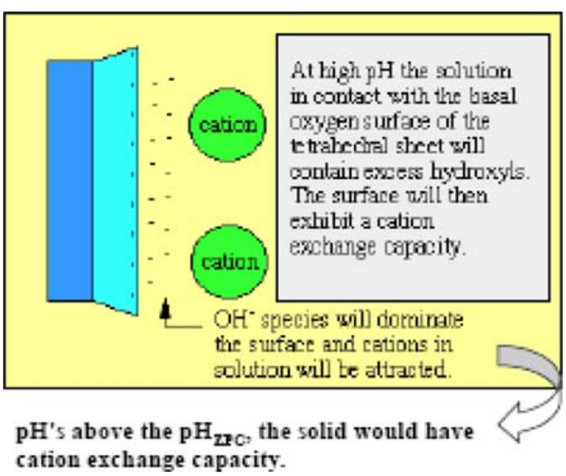

Fig. 9 The surface of the clay particle at high pH values (Schroeder 2002)

Free organic matter plays a role only at the level of soil fabric; by increasing the void ratio and decreasing dry density. The humic colloids (HC), with high negative charge, increase with the degree of degradation (Millar et al. 1965). The HC have high capacity of ionic exchange (150 to 300 meq/100gr), Bunzl (1974). When bonding positive ions such as Ca^{2+}, they contribute to the increase of the degree of sensitivity.

The organic and carbonates contents of six muddy samples extracted from the city of Tunis (Table 5) were determined using respectively the Ann method and calcimetry method. These tests were performed in the mineralogy laboratory of the college of science of Tunis. The fraction of organic carbon was determined by oxidizing the organic matter existing in the 63 μm passing fraction of muddy samples, in a balloon provided with an ascending cooling agent. The oxidizer is sulfona-chromic mixture boiled during 5 min. The bichromate excess is determined by measuring the content of Mohr salt (ferrous sulphate). The organic content (OC) is calculated as:

$$\%OC = \%Carbon_{organic} \times 1.724 \quad (3)$$

where the factor 1.724 is an average coefficient, generally admitted by pedologists, and it is owing to the fact that the organic matter contains an average of carbon of about 58% (Vidaly 1977).

The percentage of the humic fraction (active OM) of Tunis mud varies from 0.7 to 6.5% based on experiments (Table 6) and from 1 to 17% according to collected data published in technical reports related to several construction projects in Tunis City.

The carbonates content is determined by the calcimetry method which is a fast method. The method consists in attacking the fraction of soil that is less than 63 μm by the hydrochloric acid and drying at to 50°C. Measuring the amount of the emitted carbon dioxide at the time of the attack by the hydrochloric acid, the $CaCO_3$ content is deduced (Bouassida and Boussetta 2007).

Besides, the sedimentological study of a deposit sampled at eight meters depth in "Ghana Avenue "(Fig. 10) showed a high abundance of carbonate. This fraction is mainly formed by Mollusc fragments (Gibula, Nasser, Cardium) which belong to the fraction with more than 500 μm, by the Foraminifera (Millioles, Elphidium crispum, Ammonia beccarii) and by algae as calcareous concretions.

Table 5 Geotechnical properties of the Tunis clay samples

Samples	γh (kN/m^3)	γd (kN/m^3)	γs (kN/m^3)	Grain size distribution			Atterberg Limits		ω	Oedometer			
				% >5 mm	% <2 mm	% <0,08 mm	W_L(%)	Ip(%)		e_0	Cc	σ'p (kPa)	Cv (E-08 m^2/s)
1	16.2	12.3	26.5	1	97	93	68	43	32	1.07	0.32	96	1.47
2	16.4	11.3	26.5	0	99	89	65	38	45				
3	13	07	26.5	0	99	98	92	51	86	2.67	1.58	74	0.55
4	18.7	14.7	26.5	0	100	99	68	43					
5	15.4	11	25.4	12	–	75	43	17	40	1.15	0.36	–	–
6	–	–	–	–	–	–	–	–	–	–	–	–	–

Table 6 Organic content (OC) of the Tunis clay samples

No	Samples	Carbon (%)	OM (%) (fraction <63 μm)
1	Radès-Kheireddine Channel (27.3–28.0)	0.47	0.81
2	Radès-Kheireddine Channel (30.10–30.8)	0.70	1.21
3	Radès-Goulette-Liaison route North (5.20–8.70)	3.98	6.86
4	Goulette-Kheireddine Channel (18.6–19.3)	0.66	1.14
5	South Lake area ($Z = 4$ m)	1.72	2.97
6	Goulette harbor	1.57	2.71

Furthermore, the organic matter (plants) is mainly composed by remnants of roots and leaves of *POSIDONIA OCEANICA* which affect the dynamics of sediments by acting as a trap enriching the sediments with carbonate.

Indeed the organic matter allows the proliferation of fauna (Nassa, Risso, Turritelia) whose shells induce the enrichment of sediments in carbonate.

Figure 10 *also shows that* the deposits of the Holocene in Tunis City occurred in marine environment. In conclusion, Table 7 and Fig. 10, explains the high Tunis soft soil carbonates content by the abundance of shells.

The grey black to grey green color of Tunis Soft Clay (reduced iron) illustrates the abundance of organic matter (OM) in the pore water. The alluvial deposits leached out under Ca^{2+} conditions are a sign of high active OM content as well. In fact, the cations Ca^{2+} maintain neutrality at the surface of the clay particle by bonding (neutralizing the charge) both the clay particle and the acidic functional group of the organic matter (COO^-) (Theng 1979).

Theses amounts of active organic matter act as dispersive agents and trigger the development of thicker double layers, hence higher electrokinetic potential and higher sensitivity.

High sensitivity of some Tunis soft soils is thus governed, not only by the leaching out process but mainly by the action of active OM in the small particle fraction.

5 The Proposed Classification

Based on the classifications suggested by Mitchell (1976) and Leroueil et al. (1983), variable results are obtained for Tunis soft clay (Figs. 1, 2). Indeed, the organic matter can be of great importance in the development of highly sensitive clay. The dispersing agents are important for very sensitive Swedish marine clay which contains more than 5% OM. However, the OM is irrelevant to the very sensitive Norwegian marine clay with levels lower than 0.5% (Christoulas et al. 1987).

The abundance of active OM in various clay sites in Tunis City contributed to the development of high sensitivity in these clays. For example, via the vane test a sensitivity of 13.5 was obtained for a clay

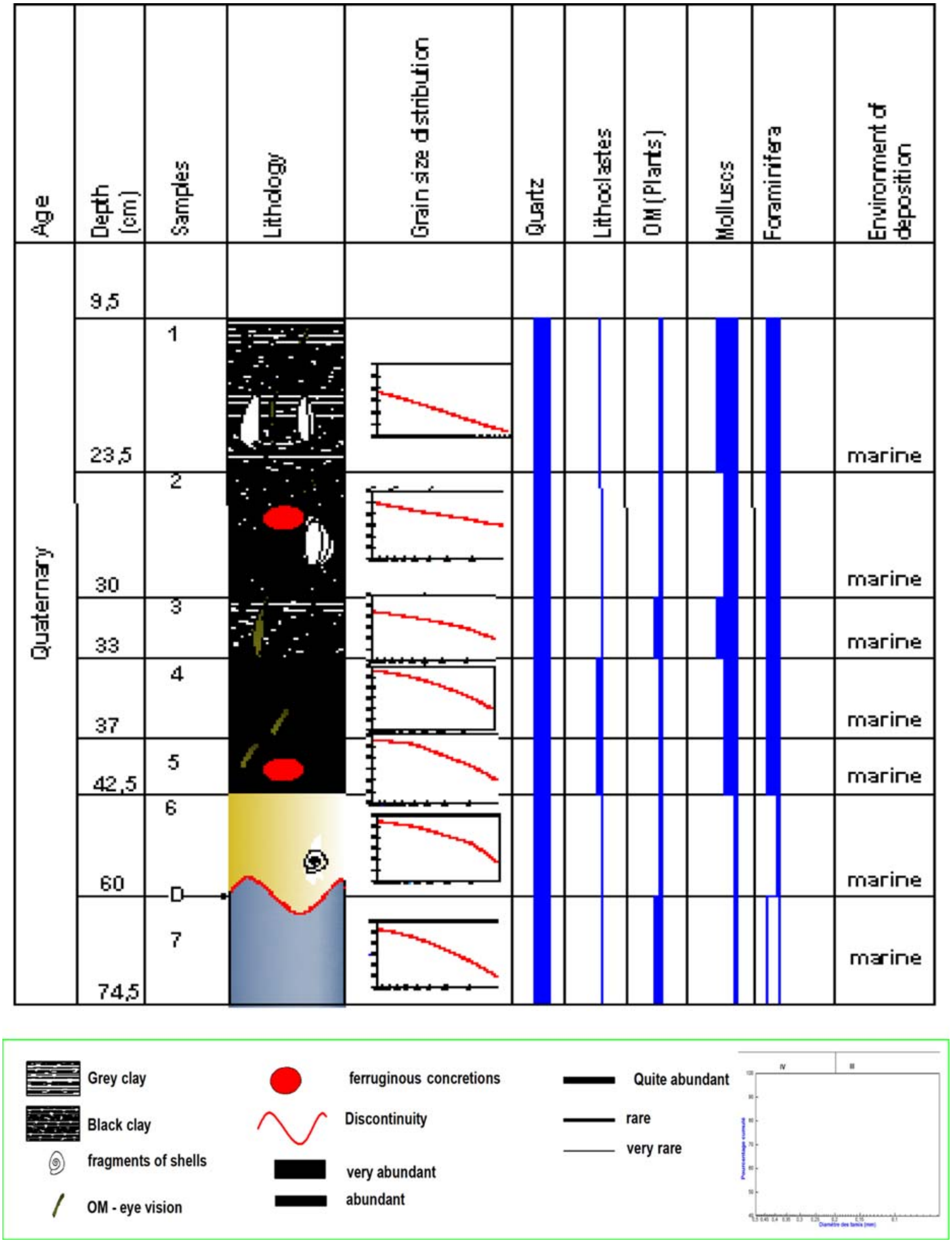

Fig. 10 Mineralogical study of the Ghana Avenue cored samples

Table 7 Carbonates contents of the Tunis soft samples

No (samples)	% $CaCO_3$ in (fraction <63 μm)	% $CaCO_3$
1	32	28.8
2	36	31
3	28	26.6
4	24	23
5	33	31.7
6	30	–

sample extracted from the Ghana Avenue site at six meter depth. Indeed, according to the Rosenqvist classification, this clay sample is considered as quick clay.

Nevertheless the effective stress path (esp) related to the clay sample does not correspond to that of a quick clay (Fig. 11a). In fact, in the case of quick clays, as soon as the friction angle Φ'_{mob} reaches a critical value Φ'_{crit}, a marked increase in pore pressure is noticed and the esp direction abruptly changes (Fig. 11b). Thus, it was imperative to find a specific classification for Tunis soft clay (Table 1).

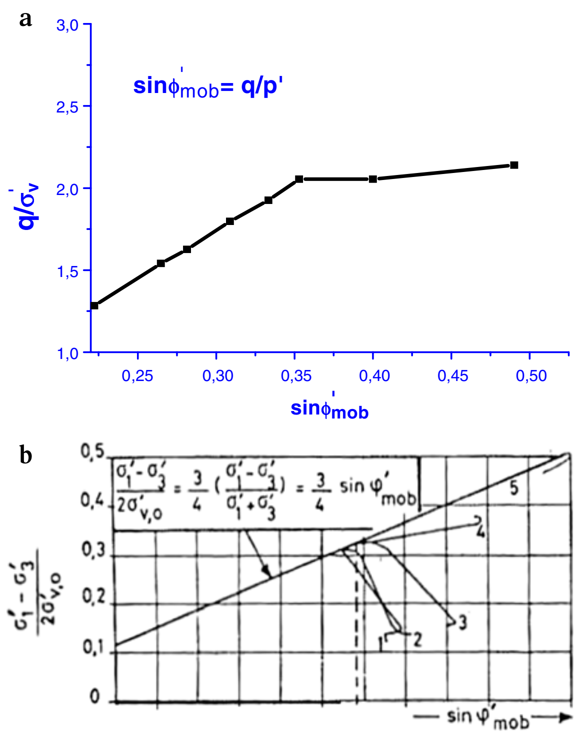

Fig. 11 **a** Effective stress path (esp) of a very sensitive Tunis clay. **b** Effective stress path (esp) of Norwegian quick clays (soil 1, 2 and 3), (Van Impe and De Beer 1984)

6 Examples of Measured Sensitivity

From the collected data, Tunis soft soil sensitivity values range between 2.66 and 22 (Tables 8, 9). According to our proposed classification, the Radès soft soil consequently should be considered as medium to very sensitive clay while the Ghana

Table 8 Measured values of sensitivity at Radès site (Tunis)

C_u (vane test)	C_{ur} (vane test)	Sensitivity (S_t)
17.9	4.3	4.2
21.5	2.4	9.0
21.5	9.0	2.4
14.1	2.4	5.9
39.7	3.3	12.0
12.0	3.0	4.0
16.0	6.0	2.7

Table 9 Measured values of sensitivity at Ghana Avenue (Tunis)

C_u (vane test)	C_{ur} (vane test)	Sensitivity (S_t)
30.0	8.0	3.8
22.0	4.0	5.5
20.0	5.0	4.0
8.0	2.0	4.0
9.0	2.0	4.5
8.0	2.0	4.0
13.0	3.0	4.3
18.0	3.0	6.0
21.0	3.0	7.0
07.0	2.0	3.5
12.0	2.0	6.0
11.0	2.0	5.5
19.0	3.0	6.3
22.0	5.0	4.4
27.0	2.0	13.5
09.0	2.0	4.5
10.0	2.0	5.0
12.0	2.0	6.0
05.0	1.0	5.0
11.0	0.5	22.0
18.0	2.0	9.0
18.0	4.0	4.5
12.0	2.0	6.0

Table 10 Strength and index profiles of Ghana Avenue (Tunis)

Depth (m)	Description of soil	γh (kN/m³)	γd (kN/m³)	Grain size distribution			L_I	Water content	Atterberg Limits W_P	W_L	Undrained shear strength (kPa)	Residual shear strength (kPa)
0–4	Fill: clayey and gravely sand	–	–	–	–	–	–	–	–	–	–	–
4	Black soft silty clay with high shell content	–	–	–	–	–	–	–	–	–	40	3
5		14.2	07.8	40	40	20	1.53	81	35	65	20	9
6		16.7	11.1	24	34	42	0.56	51	33	65	17	5.7
8		17.1	11.3	43	35	18	0.85	51	28	55	17	6
10	Plastic grey clay with shells	15.4	9.2	25	40	30	1.03	67	35	66	–	–
11		18	13	30	45	25	0.61	38	24	47	–	–

Avenue soft soil can be considered as rather medium sensitive clay (Table 10).

7 Principles of Soft Clay Oedometric Behaviour Applied to Tunis Soft Soil

Skempton and Northey (1952) and Burland (1990) suggested that, in terms of normalized values, the laboratory compression curves for reconstituted clays are similar. From the intrinsic compression line (ICL), Burland (1990) defined the void ratio index I_v:

$$I_v = \frac{e_0 - e^*_{100}}{e^*_{100} - e^*_{1000}} \quad (4)$$

e_0: current void ratio e^*_{100} and e^*_{1000} void ratios for specimens with overburden stress of 100 and 1,000 kPa respectively.

Using Eq. (4), Burland re-plotted most of Skempton's original data for the in situ conditions of normally consolidated clays, and also added other data. These in situ conditions defined the sedimentation compression line (SCL). The gap between the intrinsic compression line (ICL) and the sedimentation compression line (SCL) represents the structure imparted to the soil during one-dimensional normal compression. Skempton (1952) and Burland (1990) found clays of lower sensitivity to be plotted closer to the ICL and those of higher sensitivity to be plotted beyond this line.

Based on results of Skempton and Northey (1952), Cotecchia and Chandler (2000), one may note that the compression curves of the undisturbed samples of Tunis clay present various sensitivities depending on the site. As examples, Fig. 12 shows the compression curve of Radès-La Goulette site is located above the NCL of Horten (Norway) with sensitivity of 17. The compression curve of Tunis North Lake clay is between those of Horten (Norway) and that of Torslanda, with sensitivity around 6. The compressive curve of the Tunis-Goulette clay is closer to the NCL of Gosport-Deep clay with a sensitivity of 2–4.

Taking into account the influence of sensitivity, Cotecchia and Chandler (2000) assumed that due to this sensitivity, the viscous behaviour is outspokenly extensive and goes beyond the normal time periods in civil engineering projects i.e., infinity of sedimentation compression curves (SCC). It means that the SCC do show a specific contour for each value of sensitivity; it also would imply that the SCL introduced by Burland (1990) is the SCC corresponding to a mean sensitivity of about 5.

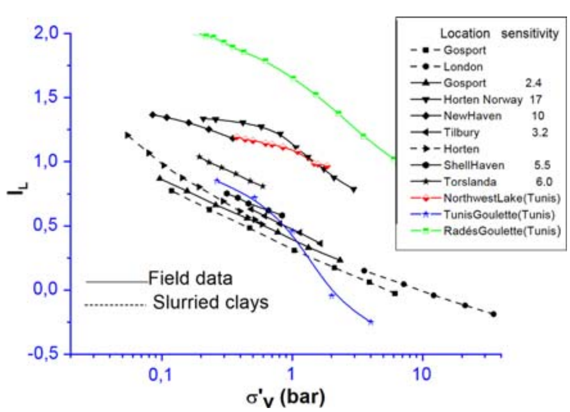

Fig. 12 In situ states of normally consolidated clays and oedometer data for reconstituted clays

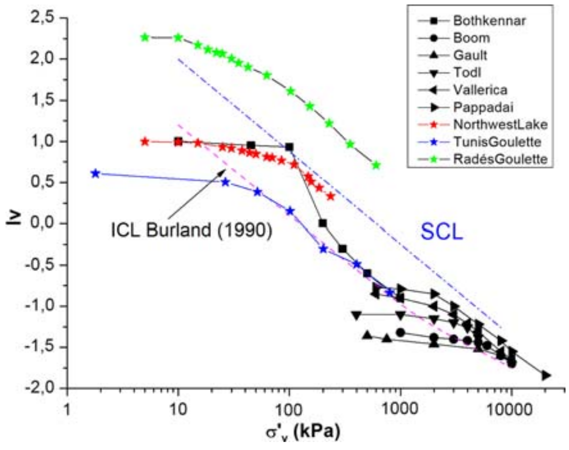

Fig. 13 Adopted one dimensional compression data for a variety of natural clays and the Tunis soft clay

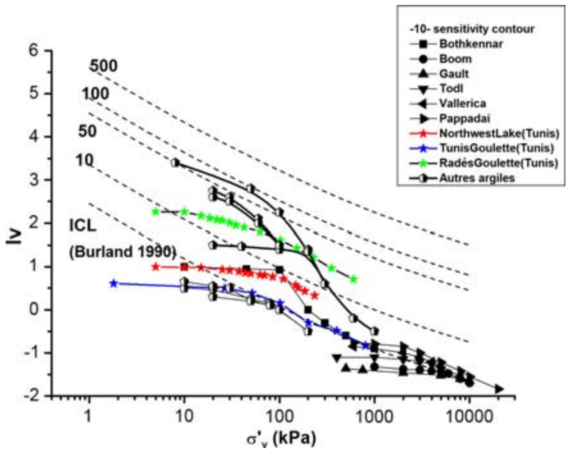

Fig. 14 Compressive behavior for deep-ocean sediments, terrestrial clays and the Tunis soft soil

The various compression curves recorded for Tunis soft clay (Figs. 13, 14), show a sensitivity of the order of 20 for the site of Radès-Goulette (above the SCL), and of the order of 8 for the North Lake site.

Strain levels at collapse depend on the type of soft soil structure. Indeed, for soft soil, sampled from Radès-Goulette and North Lake only partial collapse occurred. Their compressive curves show some initial convergence with the ICL after yield, while at higher stresses it tends to be parallel to the ICL rather than to join it. However, for samples from Tunis-Goulette, total collapse is observed by superposition of compressive curve and the ICL after yield.

8 Conclusion and Recommendations

The marine environment deposition of Tunis soft soil during the quaternary age and the abundance of non swelling minerals (quartz) led to a low electro-kinetic potential resulting in flocculated structure.

Tunis soft soil leached out, however, afterwards with "hard" ground water (cations Ca^{2+}) leading finally to pore water with a high concentration of polyvalent ions and therefore with limited possibilities of highly sensitive clay development. At locations where Tunis soft soil was in contact with active organic matter (acting in dispersive, bonding cations at clay particle surface thus increasing negative charges at the particle surface), the double layers around the particles were expanding. The electro-kinetic potential became higher, implying larger repulsive forces between particles. After remoulding of such type of soft soil, these forces will prevent flocculation of the clay particles. This reduces remarkably the remoulded shear strength and therefore greatly increases the sensitivity of the clay leading to high sensitivity of many of Tunis soft soils.

The levels and the origin of high sensitivity in Tunis soft soils were pointed out. These variations result from a combination of leaching out with hard ground water and high content of organic matter.

It is recommended to focus more on the latter aspect especially when discussing the stiffness behaviour of these clays.

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