Study of the behavior of Tunis soft clay

Mnaouar Klai¹ · Mounir Bouassida¹

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Abstract The paper reviews research investigations conducted on Tunis soft clay that is classified as problematic soil. Results obtained from an experimental study carried out on undisturbed Tunis soft clay specimens are presented and interpreted. On the basis of experimental results, the paper discusses which constitutive law can describe at best the observed behavior of Tunis soft clay. The elastoplastic behavior modeled by the hardening soil model is then justified upon the validation of numerical results of oedometer and triaxial tests carried out on undisturbed soft clay specimens. Stage construction of embankment built of Tunis soft clay was analyzed by the FE code Plaxis 2D. This case study well illustrated the need for practicing ground improvement techniques to neutralize the inherent long-term settlement induced in soft clay.

Keywords Behavior · Characterization · Hardening · Numerical · Simulation · Soft clay · Settlement

List of symbols

W_L	Liquid limit
W_P	Plastic limit
I_c	Consistency index
I_p	Plasticity index
C_c	Compression index
C_s	Swelling index

σ'_p	Pre-consolidation pressure
C'	Drained cohesion
φ'	Drained friction angle
λ	Slope of virgin compression line
κ	The slope of unloading–reloading line
e_0	Initial void ratio
k_h and k_v	Horizontal and vertical hydraulic conductivity, respectively
ν	Poisson's ratio

Introduction

The soil profile of Tunis City mainly consists of a layer located between 3 and 20 m depth constituted by grayish sandy clay, which is at the origin of the contamination observed on several constructions built on this ground. This soil commonly called the Tunis soft clay (TSC) is very problematic because of the difficulty to extract undisturbed specimens for performing laboratory tests. Besides, performing in situ tests sometimes leads to unrealistic data due to its very low stiffness compared to that of expanded membrane to measure the limit pressure during pressuremeter tests.

Bouassida [1] reported the difficulty in predicting the undrained cohesion of TSC from in situ vane shear tests due to unreasonable interpretation of these results. In parallel, the use of reconstituted TSC to avoid disturbance of specimens does not reflect the actual behavior of in situ soil [7]. An overview on geotechnical parameters of TSC and related correlations were suggested by [4]. In this paper, a comparison was made between the characteristics of reconstituted and undisturbed TSC.

Relevant contribution on numerical modeling of TSC was proposed by Tounekti et al. [10]. Those authors

✉ Mounir Bouassida
mounir.bouassida@fulbrightmail.org
Mnaouar Klai
m_klai@yahoo.fr

¹ Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, LR14ES03 - Ingénierie Géotechnique, BP 37 Le Belvédère, 1002 Tunis, Tunisia

assessed the validity of soft soil model (SSM) as suitable constitutive law for the remolded Tunis soft clay after comparisons between numerical results (simulation of oedometer and triaxial tests) and measurements during performed tests in laboratory. Numerical predictions of the behavior of two geotechnical infrastructures have been proposed adopting the SSM for TSC [10].

This paper focuses on the study of behavior of TSC as observed from experimental investigation conducted in laboratory. A set of identification tests, oedometer and triaxial tests has been performed on samples extracted during geotechnical campaigns conducted in Tunis City. From experimental data the soil parameters of hardening soil and modified cam clay constitutive laws are determined and then used as input data to simulate oedometer and triaxial tests. The validation of those constitutive models was discussed based on comparison between experimental and numerical results [8]. As continuation of this latter, the prediction of an embankment behavior is here investigated using stage construction scheme.

Geotechnical investigations: sampling and laboratory tests

In the urban area of Tunis City two bore holes namely BH1 and BH2 spaced of 10 m were executed at the “Avenue de la République”. Cored specimens namely CS1 and CS2 have been extracted, respectively, at 7.5 and 9.5 m depths by a double rotary driller of external diameter 101 mm.

- BH1 soil profile shows an upper fill layer of 7 m thickness overlaying the Tunis soft clay layer of about 18 m thickness. Three undisturbed cored specimens (specimen 1, specimen 2, and specimen 3) have been extracted at depths of 7.55, 9.85 and 18.35 m, respectively.
- BH2 soil profile shows a similar formation as that observed in BH1. Thickness of the upper fill layer is 2.5 m. Two cored specimens (specimen 4 and specimen 5) have been extracted at depths of 3.75 m and 7.75 m, respectively.

Undisturbed samples are cored in PVC tubes of 101 mm external diameter, logged in the rotary driller gently penetrated within soft clay layer at displacement rate of about 10 mm/min. Extracted PVC tubes are then placed in wood boxes and transported from the site to laboratory so that shocks are prevented.

In laboratory, undisturbed soil specimens are extracted by penetrated thin cutting shoe in the direction of in situ extraction. Therefore, soft soil specimens are ready for laboratory tests from extracted cutting shoe. Laboratory tests have been carried out at the soil mechanics laboratory of the Higher Institute of Technological Studies of Rades (Tunis). The soil identification tests included: grain size distribution (sieve and hydrometer), total unit weight, specific gravity, Atterberg limits and content of organic wastes (OM). The second group of tests included oedometer tests (compressibility and consolidation), consolidated undrained (CU) triaxial tests and consolidated drained (CD) triaxial tests.

Experimental results

Identifications tests

As part of soil identification wet sieve and sedimentation analyses were performed on five undisturbed soft clay specimens. Grain size distributions show the average minimum fines content (grain size <0.08 mm) is about 87 % [6]. Table 1 summarizes the identification parameters of the five undisturbed soft clay specimens.

The classification of saturated Tunis soft clay is highly plastic silt with very low consistency. For undisturbed soft clay specimens, which contain wastes of shell, Atterberg's limits values are lower than those obtained for the reconstituted Tunis soft clay [1].

Several useful properties also help in a better identification of soft clays. Indeed, chemical tests for the determination of content of organic wastes and the calcium carbonate, respectively, provide useful information about the compressibility and strength [5].

The percentage of organic content recorded for reconstituted Tunis soft clay was about 3.12 %. Undisturbed soft clay has a higher organic content than the

Table 1 Identification parameters of undisturbed Tunis soft clay

Specimen no.	Specific gravity	Unit weight [kN/m ³]	W_L	I_c	I_p
1	2.62	17.4	46	0.31	19
2	2.50	16.1	50	0.50	5
3	2.53	18	51	0.72	9.5
4	2.32	17.6	65	0.50	15
5	2.39	16.9	79	0.50	29

reconstituted soft clay which confirms its low compressibility of about 10 %.

Oedometer tests

Referring to Table 2 undisturbed soft clay specimens no. 1, no. 2, no. 3, no. 4 and no. 5 extracted at average depth of 8.5 m is classified as under consolidated. The pre-consolidation stress of tested specimens is lower than the effective vertical stress at extraction depth that varied from 52 to 180 kPa. Compression and swelling indices indicate that undisturbed Tunis soft clay has lower compressibility and swelling than those of reconstituted soft clay [7]. Meanwhile recorded values of compression index are in accordance with those initially reported by Touati et al. [9] from other geotechnical investigations data conducted on Tunis soft clay undisturbed specimens, i.e., $0.4 \leq C_c \leq 0.6$.

CU and CD triaxial tests

The drained friction angle of tested specimens is found in the range of $\phi' = 19.2^\circ$ – 23.7° . The drained cohesion is not very significant since it does not exceed 5 kPa (Table 3). The inherent over-consolidation of tested specimens is more likely attributed to the applied consolidation stress during triaxial test (up to 300 kPa) which largely exceeds the in situ effective overburden stress at depth of extracted specimens (less than 20 m).

Table 2 Oedometer characteristics of undisturbed Tunis soft clay

Specimen no.	C_c	C_s	σ'_p (kPa)
1	0.43	0.057	12
2	0.485	0.056	25
3	0.35	0.057	17
4	0.385	0.057	14
5	0.384	0.057	14

Table 3 Shear strength parameters of undisturbed Tunis soft clay

Specimen no.	C_{cu} (kPa)	C' (kPa)	ϕ' ($^\circ$)
1	7.53	5.0	22.7
2	8.49	4.0	23.7
3	8.67	5.1	20.8
4	7.79	3.6	19.2

Justification of the hardening soil model (HSM) for Tunis soft clay

Zimmermann et al. [11] recommended the adoption of the standard HSM for normally consolidated soft clays. Relationships between the parameters of the HSM are as follows:

$$E_{ur}^{ref} = 3E_{50}^{ref} \quad v_{ur} = 0.35 \quad P^{ref} = 100 \text{ kPa} \quad K_0^{nc} = 1 - \sin \phi' \\ R_f = 0.9 \quad \sigma_f = 0 \quad m = 1 \quad \psi = 0.$$

The HSM is selected to simulate the behavior of Tunis soft clay since it is capable to account for the increase in stiffness due to consolidation stress. Such parameter is essential for the modeling of foundation that extends to relatively deep soil layers for example underneath an embankment. From recorded experimental data the input parameters of HSM adopted for Tunis soft clay layer are presented in Table 4.

Numerical investigation is performed to simulate the oedometer and triaxial tests carried out on TSC specimens. Aside from the HSM, the modified cam clay (MCC) model is also considered to characterize the TSC for the purpose of numerical predictions. Table 5 presents the geotechnical parameters of the modified cam clay model considered for undisturbed specimens extracted at the Avenue Mohamed V at depths from 3 to 20 m.

Note that λ and κ are proportional to compression and swelling indices, respectively [6].

Simulation of observed behavior of TSC

The simulation of oedometer and triaxial tests is conducted by using the software Plaxis V9.2D in axisymmetric condition due to the cylindrical geometry of tested specimens and applied loading.

Oedometer tests

Numerical computations are run by Plaxis software with the assumed HSM and the MCC model input parameters. Quarter of the specimen is considered for numerical simulation due to the geometrical and loading symmetries (radius equals 17 mm; height equals 35 mm). Figures 1

Table 4 Hardening soil model parameters of Tunis soft clay

Specimen no. (depth in meters)	E_{oed}^{ref} (kPa)	E_{50}^{ref} (kPa)	C' (kPa)	ϕ' ($^\circ$)
1 (7.2–7.9)	1337	1672	5.0	22.7
2 (9.5–10.2)	1186	1482	4.0	23.7
3 (18–18.7)	1643	2054	5.1	20.8
4 (3.3–4.0)	1494	1867	3.6	19.2

Table 5 Parameters of modified cam clay model considered for the Tunis soft clay

λ	e_0	κ	C' (kPa)	ϕ' (°)	v	$k_h = k_v$ (m/day)	γ_{sat} (kN/m ³)
0.21	1.55	0.024	13	20.8	0.35	$1.73 \cdot 10^{-6}$	17.4

Fig. 1 Predicted behavior of TSC modeled by the HSM and MCC model and experimental measurements from oedometer tests (specimens 4 and 5) **Fig. 2** Predicted behavior of TSC modeled by the HSM and MCC model and experimental measurements from oedometer test (specimen 1)

and 2 compares experimental data with numerical simulation results obtained by the HSM and MCC model. Figures 3 and 4 show experimental and numerical results predicted by the HSM.

Fig. 3 Predicted behavior of TSC modeled by the HSM and MCC model and experimental measurements from oedometer test (specimen 2) **Fig. 4** Predictions by the HSM of TSC behavior compared with data from oedometer test (specimen 3)

Interpretation of results

From Figs. 1, 2, 3 and 4 it is noted that the numerical prediction by the HSM during the primary consolidation phase is overall in accordance with the observed behavior on tested specimens.

Fig. 5 Experimental and numerical results during shear loading of CU triaxial test (specimen 4)

Fig. 6 Experimental and numerical results during shear loading of CU triaxial test (specimen 5)

Fig. 7 Modeling of embankment on soft soil

In turn, significant difference is noticed between experimental data and the numerical predictions obtained by the modified cam clay model that overestimates the predicted decrease in void ratio.

During the unloading–reloading phase of Figs. 1, 2, 3 and 4 (on the right of slope C_s), the numerical prediction by the MCC model slightly underestimates the swelling of specimens, whilst the HSM shows a good agreement with experimental measurements.

The overestimated consolidation by the MCC model is essentially owed to the parameters λ and κ which represent, respectively, the slopes of the oedometer curve both in consolidation and during unloading–reloading phases of the specimens of Tunis soft clay.

Triaxial tests

Figures 5 and 6 show the numerical predictions of deviatoric stress versus axial strain, as predicted by the HSM, for various isotropic consolidation stresses as well as experimental measurements during the shear phase of CU triaxial tests performed on specimens 4 and 5.

The observed behavior during shear loading is overall in fair agreement with numerical results predicted by the HSM. This leads to the conclusion that the adopted failure parameters (C' and ϕ') are quite representative of the observed behavior of undisturbed TSC specimens. Using Plaxis software (version 9.2) the simulation of observed behavior of those specimens subjected to oedometer and triaxial tests showed that the HSM predictions are in good agreement with measured data rather than predicted results obtained by the MCC model [6]. For this reason the HSM can be considered to model the TSC for the prediction of behavior foundations built on Tunis soft clay and subjected to vertical loading.

Table 6 Mohr–Coulomb model parameters

Parameters	Embankment	Sand
γ_{unsat} (kN/m ³)	20	19
e_{ini}	1	0.5
E_{ref} (kN/m ²)	4000	30,000
ν	0.3	0.3
E_{oed} (kN/m ²)	4038.462	40,380
C_{ref} (kN/m ²)	15	5
G_{ref} (kN/m ²)	1153.846	11,540
ϕ	20	30

Table 7 HSM parameters for soft clay

Parameters	
γ_{sat} (kN/m ³)	17
e_{ini}	1.2
E_{50}^{ref} (kN/m ²)	1664
ν	0.3
$E_{\text{oed}}^{\text{ref}}$ (kN/m ²)	1332
C' (kN/m ²)	3.6
$E_{\text{ur}}^{\text{ref}}$ (kN/m ²)	9892
ϕ	19.2
$k_x = k_y$ (m/day)	1.74E−4
P^{ref} (kN/m ²)	100
m	1
K_0^{nc}	0.69
R_f	0.9

Embankment on compressible soft clay

This structure illustrates typical conditions of the expressway linking Tunis City and the La Goulette suburb.

The geotechnical profile includes an embankment of thickness 2 m, resting on a saturated soft clay layer of thickness 6 m overlaying rigid impervious bedrock (Fig. 7). The plane strain modeling is adopted for studying the behavior of this embankment using stage construction option. The Mohr–Coulomb model is adopted for the embankment material and the HSM model is adopted to model the behavior of soft clay (Tables 6, 7).

Two stages construction were planned; for each the placement of 1 m thickness of embankment material is scheduled. As explained by Bouassida and Hazzar [3] such procedure enables the increase in undrained cohesion from partial consolidation because of very short waiting time of first load level (thickness embankment = 1 m).

The stage construction of embankment is presented in Fig. 8. The option of primary consolidation is active to follow up the evolution of pore pressure during 3 years. Figure 7 shows the thickness of the soft clay layer $h = 6$ m, embankment dimensions ($a = 5$ m; $b = 10$ m; $h_r = 2$ m) and $L = 30$ m.

Prediction of settlement under the embankment axis is 11.8 cm, whilst at the toe of embankment it is equal to 1 cm (Fig. 8). It is noted that the consolidation settlement becomes almost stabilized after 250 days upon the

Fig. 8 Variation of settlement versus time under embankment axis

commencement of stage loading. It follows an induced differential settlement between the axis and toe of embankment which compromises the stability of any load structure whenever applied at the upper side of embankment. In such situation, the need for stone columns or sand compaction pile techniques is quite helpful to significantly decrease, in allowable limit, the differential settlement under the embankment, adding to the acceleration of consolidation provided by the reinforcing columns that act like vertical drains because of enhanced drainage property of their constituent material [2].

Conclusion

This paper discussed the behavior of Tunis soft clay as observed during an experimental investigation carried out on undisturbed specimens. Then, the simulation of performed oedometer and CU triaxial tests, using Plaxis 2D software has been considered. Two constitutive behavior laws were tested to model the Tunis Soft Clay: the hardening soil and modified cam clay models (HSM and MCC). Comparisons between numerical results from the simulation of oedometer and triaxial tests favored the adoption of the HSM for TSC in order to predict the behavior of structures founded on typical soil profile comprising the soft clay layer and subjected to vertical loading. The study of the behavior of an embankment built on compressible Tunis soft clay showed the need to schedule a stage construction procedure.

References

1. Bouassida M (2006) Modeling the behaviour of soft clays and new contributions for soil improvement solutions. Keynote Lecture. In: Proc. 2nd Int. Conf. On Problematic Soils. December 3–5th 2006. Pétain Jaya, Salengro, Malaysia. Editors Bojan, Pinto & Jefferson, pp 1–12
2. Bouassida M (2016) Design of column-reinforced foundations. J. Ross Publishing, FL, USA, p 224. ISBN 978-1-60427-072-3
3. Bouassida M, Hazzar L (2008) Comparison between stone columns and vertical geodrains with preloading embankment techniques. Proceedings of the 6th international conference on case histories in geotechnical engineering, Arlington, 11–18 August 2008, Paper No. 7.18a
4. Bouassida M, Klai M (2012) Challenges and improvement solutions of Tunis soft clay. *Int J Geomate* 3(1):296–305
5. Das BM (2006) Principles of geotechnical engineering, 6th edn. Thomson, Ontario
6. Klai M (2014) On the behaviour of Tunis soft clay—application to the study of foundations' stability (in French). Defended 16 Oct. 2014. National Engineering School of Tunis, Tunisia
7. Klai M, Bouassida M (2009) Comparison between behaviour of undisturbed and reconstituted Tunis soft clay. In: 2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering, 28–30 May 2009, Near East University, Nicosia, North Cyprus
8. Klai M, Bouassida M, Tabchouche S (2015) Numerical modelling of Tunis soft clay. *Geotech Eng J SEAGS AGSSEA* 46(4):87–95
9. Touati L, Bouassida M, Van Impe W (2009) Discussion on the Tunis soft clay sensitivity. *Geotech Geol Eng J* 27:631–643
10. Tounekti F, Bouassida M, Klai M, Marzougi I (2008) Etude expérimentale en vue d'un modèle de comportement pour la vase de Tunis. *Rev Fr Géotech* 122(1):25–36
11. Zimmermann T, Truty A, Podles K (2010) Numerics in geotechnics and structures. Elmeppress international, Lausanne