# Assessment of Carillo's Theory for Improved Tunis Soft Soil by Geodrains

## Évaluation de la théorie de Carillo pour les sols mous de Tunis améliorés par géodrains

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ABSTRACT: This paper presents an experimental study carried out on undisturbed cored samples of Tunis soft soil extracted at 17.25 m depth at the lagoon of Sejoumi. Three types of oedometer tests had been performed: first type was a standard test on Tunis soft soil, the second was an oedometer test on the same soil improved by a prefabricated vertical drain Mebradrain 88 (Mb88) type and the third test is similar to the second test in which vertical drainage was prevented. Then, the assessment of Carrillo's theory is studied by quantifying the effect of radial and vertical consolidation from the observed global degree of consolidation of improved Tunis soft soil specimens by geodrains.

Résumé: Ce papier présente une étude expérimentale réalisée sur des échantillons intacts du sol mou de Tunis prélevés à 17,25 m de profondeur de la marécage de Séjoumi. Trois types d'essais oedométriques ont été effectués : le premier est un test standard sur le sol mou de Tunis, le second était un essai oedométrique sur le même sol amélioré par un drain vertical de type MebraDrain 88 (MB88); le troisième test est similaire au deuxième test dans lequel seulement le drainage radial a été favorisé . Ensuite, l'évaluation de la théorie de Carrillo est étudiée en quantifiant l'effet de la consolidation radiale et verticale sur le degré de consolidation global.

## 1. INTRODUCTION

Considerable attention has been recently devoted worldwide to the problem of building structures on highly compressible saturated soils and to the development of soil improvement techniques for increasing stability, reducing settlements, and accelerating consolidation of soft soils.
Prefabricated verticals drains (PVD) with preloading method was considered the most used improvement technique to accelerate the consolidation of soft soils and, consequently, to increase their bearing capacity.
The commonly used consolidation theory for designing PVD's is the unit cell model, e.g., Barron (1948), Hansbo (1981) and Terzaghi (1943). Because the solutions considering both vertical and radial drainage are complicated, those most used in practice ignore the effect of vertical drainage, such as Barron's theory. Barron (1948) developed solutions for two types of boundary conditions at the surface of improved soil such as: (i) "free vertical strain," resulting from a uniform distribution of vertical load, and (ii) "equal vertical strain", which results from imposing the same vertical deformation. However, in some cases, the vertical drainage by PDV has a considerable effect on the degree of consolidation of improved soil; Terzaghi (1943) suggested the well known simple method for one-dimensional (1D) vertical consolidation condition.
Furthermore, for most cases in practice, the soil is not homogeneous, and the deformation of PVD improved soil does not occur in 1D condition. Carrillo's theoretical solution (1942) is used to combine the vertical and radial drainage effects to predict the global degree of consolidation *U*:

$$(1 - U) = (1 - U_r)\,(1 - U_v) \qquad (1)$$

$U_r$ and $U_v$ are respectively the radial and the vertical average degree of consolidation.
Theoretically speaking, Carillo's formula (Eq 1) is only valid for instantaneously applied loading.
The consolidation of soft soil is related to the dissipation of excess pore pressure generated by the surcharge load. For radial consolidation problem with centered vertical drain in oedometer cell, the governing differential equation of excess pore pressure is (Parakash et al, 1996):

$$\frac{\partial(\Delta u^r)}{\partial t} = C_r\left(\frac{\partial^2(\Delta u^r)}{\partial r^2} + \frac{1}{r}\frac{\partial(\Delta u^r)}{\partial r}\right) \qquad (2)$$

$C_r$ is the coefficient of radial consolidation of soft soil and $\Delta(u^r)$ =Δu(r, t) is the excess of pore pressure at radius r and time t.
Solution of equation (2) that uses the condition of equal vertical strain without smear effect is given by (Barron, 1948):

$$U_r = 1 - \exp\left(-\frac{8T_r}{F(n)}\right) \qquad (3)$$

The smear zone is defined as the remolded zone of soil immediately adjacent to the drain. F(n) is a Barron's function given by :

$$F(n)=\left(\frac{n^2}{n^2-1}\right)\ln(n)-\left(\frac{3n^2-1}{4n^2}\right) \qquad (4)$$

"n" is the drain spacing ratio given by:

$$n=\frac{D}{d_w} \qquad (5)$$

D and $d_w$ denote the equivalent diameters of unit cell and of PVD, respectively.
$T_r$ is the dimensionless time factor of consolidation due to radial drainage is written in function of time t:

$$T_r=\frac{C_r\times t}{D^2} \qquad (6)$$

.

For vertical consolidation problem, the differential equation of one-dimensional consolidation for the excess pore pressure is written (Terzaghi, 1943):

$$\frac{\partial(\Delta u^z)}{\partial t}=C_V\left(\frac{\partial^2(\Delta u^z)}{\partial z^2}\right) \qquad (7)$$

$\Delta(u^z)$ = $\Delta u$ (z, t) is the excess of pore pressure depending of the depth z and time t;

$C_v$ is the coefficient of vertical consolidation.
Solution of the differential equation (7) is the vertical degree of consolidation $U_v$ as follows:

- $U_v$ < 50 %:

$$U_V=2\sqrt{\frac{T_V}{\pi}} \qquad (8)$$

- $U_v$ > 50%:

$$U_V=1-\frac{8}{\pi^2}\exp\left(-\frac{T_V\pi^2}{4}\right) \qquad (9)$$

$T_v$ denotes the time factor of vertical drainage:

$$T_r=\frac{C_V\times t}{H^2} \qquad (10)$$

H is the drainage distance that is equal half of the thickness of specimen.

## 2. STUDIED SOIL

Tunis soft soil specimens used in this study were obtained from the Sejoumi's lagoon at depth of 17.25 m. The extracted sample is grey coloured, it has a characteristic smell and contains shell debris. From grain size analysis performed by hydrometer and sieving in accordance with standards NFP 94-056 and NFP 94-057, (AFNOR, 1995), it was found that Tunis soft soil presents 85 % of particles with dimension less than 80 µm, it also includes a high fraction of silt.

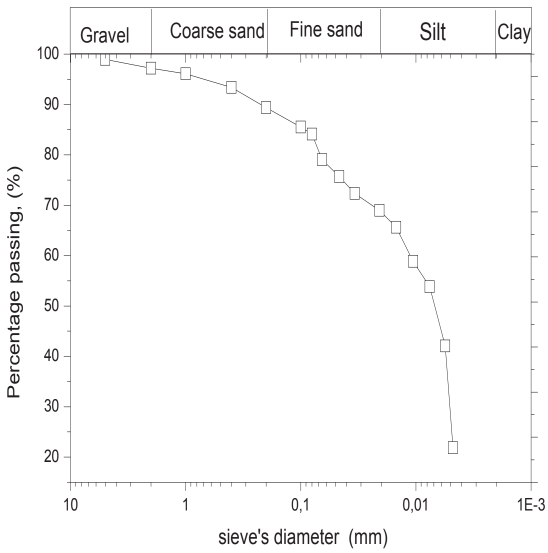



Figure 1. Gradation curve of Tunis soft soil

## 3. CONSOLIDATION TESTS

Three series of consolidation tests were carried out on the Tunis soft soil in oedometer cells . These tests involved applied increments of vertical load to the specimen and measurements of the settlement. For each increment of loading, the decrease of the thickness of the sample versus time is recorded. Duration of the applied increment of load depends on the soil and its consolidation characteristics.
The range of applied stress depends on the range of effective stress which is needed in the consolidation analysis of the studied. When the primary consolidation at prescribed load level is completed (200 kPa) the sample is unloaded in one or several steps until the increment of load of 25 kPa is dismounted and the swelling of specimen can be measured. The applied vertical load is doubled at each increment until reaching the maximum required load (50, 100, 200,400,800 kPa). The specimen is again unloaded. At the end of the test, the sample is careful removed and its thickness and water content are measured.
Series 1 (VD): It corresponds to a standard oedometer test performed according to NF P94-90-1 standard (French Standard, 1997). This test is carried out on a cylindrical sample of saturated soil with 70 mm diameter and 19 mm thickness. The soil sample is enclosed in a metal ring and is placed on a porous stone. The loading cap has also a porous stone, so the sample is sandwiched between two porous stones at the top and bottom of the sample to allow vertical drainage (VD).When preparing the sample, filter papers are placed between the soil and the porous stones. The sample is then placed in the consolidation cell and the unit cell. Water is added into the cell around the sample, so the sample remains saturated during the test.
Series 2 (RD): It corresponds to an oedometer test performed on Tunis soft soil improved by a single geodrain (Mebradrain 88) of sizes (thickness = 0.5 cm, width = 1cm and length= 19 mm). In these tests only

radial drainage (RD) is allowed, vertical drainage is prevented by mean of an impervious membrane which covers the porous stone at the top and the bottom levels of the specimen.

Series 3 (V&RD): It corresponds to an oedometer test performed on Tunis soft soil improved by a single of geodrain (Mebradrain 88) type sized as that used in series 2. In these tests the vertical drainage radial drainage are allowed.

Results of the three series of tests presented in Figure 2 show the variation of void ratio e in function of the effective stress plotted in the logarithmic scale for loading-unloading – reloading sequences for three series of tests.

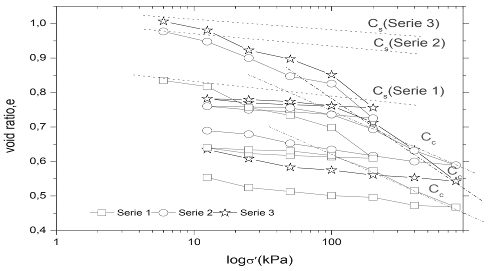



Figure 2. Oedometer curves obtained from three experimental series

Compression $C_c$ and the swelling $C_s$ indices, obtained from the three series of tests (VD, RD and VR&D) were determined from oedometer curves and summarized in table 1. Notice that the compression index obtained from series 3 (VR&D) is roughly the double of that recoded in series 1 (VD) and 2 (RD). This can be explained by the allowed vertical and radial drainage paths from which follows enhanced consolidation of the compressible soil. From Table 1, it is understood the swelling is only attributed to vertical infiltration of water with sample unloaded.

Table 1: Values of compression and swelling indices

| Serie of tests | 1 : VD | 2 : RD | 3 : V&RD |
|---|---|---|---|
| $C_c$ | 0.16 | 0.16 | 0.30 |
| $C_s$ | 0.022 | 0.022 | 0.023 |

## 4. STUDY OF THREE DIMENSIONAL CONSOLIDATION:

### 4.1 Coefficients of consolidation:

Coefficients of vertical and radial consolidation Cv and Cr are determined from the evolution in time of settlement for each increment of loading (from 50 to 800 kPa). From the results obtained for series 1 and 2: Cv and Cr were determined by the logarithmic method; which use the plot of thickness of sample versus the logarithmic of time: log (t) (Casagrande, 1938).

### 4.2 Coefficient of permeability

Vertical and radial hydraulic conductivities (permeability coefficients kv and kr) are determined by the variable head permeability test. In fact, oedometer apparatus (in series 1 and 2) is equipped with a conventional measuring device (tubes connected to the base of the specimen). The measurements are performed for different levels of applied load form 100 kPa to 800 kPa (100, 200, 400 and 800 kPa).

Figure 9 shows opposite variations of the ratios Cr/Cv and kr/kv when the consolidation stress varies from 100 to 800 kPa. In this range, ratio Cr/Cv varies from 36 to 12 and ratio kr/kv varies from 4 to 12. Obtained results show that the assumption made e.g. Cr/Cv = kr/kv is only valid at high levels of consolidation stress (Jia and Chai, 2010).

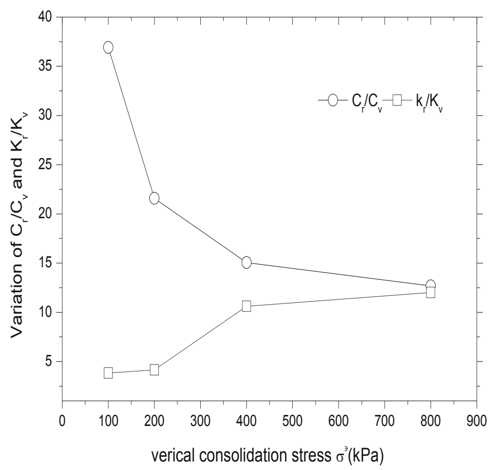



Figure 3. Ratios $k_r/k_v$ and $C_r/C_v$ versus consolidation stress

### 4.3 Degree of consolidation:

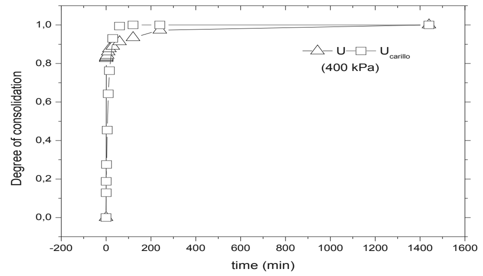
In this paper, the global degree of consolidation U(t) is predicted by two methods. The first one uses the measured settlement at different levels of applied load in series 3 (case of vertical and radial drainage, VR&D):

$$U(t) = \frac{s(t)}{s_\infty} \quad (11)$$

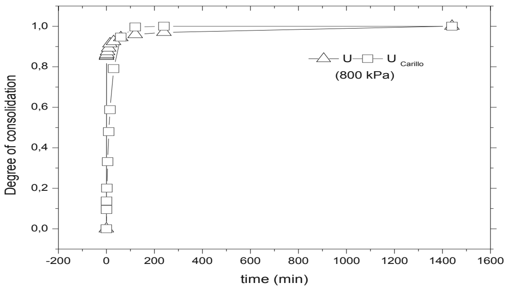
s(t) and $s_\infty$ denote respectively the settlements at given time and at the end of consolidation.

The second method consists in calculating U by the Carillo's equation (1). The radial degree of consolidation Ur is estimated from the experimental results of series 2 (case of radial consolidation RC) and equations (7) and (9). The vertical consolidation Uv is obtained from recorded results in series 1 (case of vertical consolidation VC) by using equation (2).

Figures 4a and 4b illustrate the variation of global degree of consolidation U in function of time for vertical consolidation stress of 400kPa and 800 kPa.



(a)



(b)

Figure 4. Variation of global degree of consolidation

For applied loads (100, 200, 400 and 800 kPa), it is noted that the degree of consolidation as predicted by the Carillo's theory reaches 100% for a time less than 24 hours, while the degree of consolidation U, estimated from equation (11) by using measurements of serie 3 results, reaches 100% in 24 hours.

One can also remarks that by using the Carillo's theory a lower degree of consolidation which starts from 10% is obtained, however when using measurements of in series 3 simple approximate methods, higher degrees of consolidation starting from 70% are obtained. Comparing between recorded and predicted global degree of consolidation U, it follows that the evolution of U predicted by the Carrillo's theory are overestimated with respect to that deduced from recorded settlement from series 3. The final global consolidation degree U is identical by using the two methods.

CONCLUSION

This paper presented an experimental study conducted on Tunis soft clay, in which three types of oedometer tests were executed: a standard oedometer test; an oedometer test on specimen soil improved by an element of geodrain and test a similar test to the second one by preventing the vertical drainage. From measurements coefficients of permeability $k_v$ and $k_r$ were determined by the variable head permeability test. In addition, coefficients of vertical and radial consolidation $C_v$ and $C_r$ were determined from the evolution in time of settlement at different levels of consolidation stress. Comparison between the ratios $k_{r/}$ $k_v$ and $C_{r/}C_v$ demonstrated that equality between the two ratios only happens at high level of stress consolidation, contrarily to the common assumption made in previous studies. Predictions of the global degree of consolidation showed that the Carillo's theory leads to overestimated results with respect to predictions from recorded settlements. Further, the effect of vertical and radial consolidations from the observed global consolidation of improved Tunis soft soils was discussed.

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