Geotechnical site characterization : recent improvements to assess one-dimensional consolidation settlements

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ABSTRACT: Working on Janbu's proposals, for the assessment of one-dimensional consolidation settlement for saturated soils, and on Boulanger and Idriss soil behaviour index to assess liquefaction susceptibility, it appears that soil can be classify in three families, having each their own set of relationships.
First, it is interesting to analyse if the 400µm.D part is scattered in the 0.400µm one, or if the 400µm.D grains are in contact with each other's, D being the smaller dimension of the bigger grains.
Secondly, is introduced and analysed the interest of blue methylene values measurements. And then, having well characterised soil identification (gradation curve, blue methylene test, Atterberg limit, water content) is detailed how soils behave for each family, showing the complementary interest of cone penetration tests with induced pore water pressure measurement (CPT'u) and Menard pressuremeter test (PMT) for the first two categories.

RESUME : Travaillant sur les propositions de Janbu pour le calcul des tassements de consolidation unidimensionnelle des sols saturés et sur l'indice de susceptibilité à la liquéfaction de Boulanger et Idriss, il apparait que les sols peuvent être classés en trois familles, ayant chacune leur propre jeu de relations.
Tout d'abord, il est intéressant d'analyser si la fraction 400µm.D est disséminée dans celle 0.400µ ou si les grains 400µm.D se touchent, D étant le diamètre le plus petit des plus gros grains.
Deuxièmement, la mesure des valeurs au bleu de méthylène d'un sol est une donnée intéressante. Et alors, ayant bien caractérisé l'identification du sol (analyse granulométrique, essai au bleu, limite d'Atterberg, teneur en eau) est détaillé comment les sols se comportent dans chaque famille, en montrant l'intérêt d'essais complémentaires de type essais au pénétromètre avec mesure de la pression interstitielle (CPT'u) et essais au pressiomètre Ménard (PMT) pour les deux premières familles.

Keywords: soil identifications ; oedometer tests ; one-dimensional consolidation settlement ; cone penetration tests with induced pore water pressure measurements (CPT'u) ; Menard pressuremeter tests (PMT).

1. Introduction

Geotechnical engineers have very often to assess one-dimensional consolidation settlements under mat foundations or embankments for example.

It is a source of miscalculations the wrong parameters being used. Recent improvements have been made, using and improving Janbu's proposals.

First, we will analyse, for a given 2µm D soil, D being the smaller dimension of the greater grains – either when the grains 400µm.D are scattered in the 2 µm.400µm part, and when they are in contact with each other.

Secondly, the interest of the blue metylene test will be detailed.

And then, is presented, for each Janbu's soil family, all the relations we need in order to assess one-dimensional consolidation settlements.

When we write OD, it means soil granulometry starts at 2µm and finishes at a diameter equal to D in mm. If we write d, d is an intermediate diameter.

2. 400µm.D grains scattered or not in the 2µm.400µm part

Considering a soil, which grain sizes vary from 2µm to D, gradation curve gives the percent passing in weight at 400µm, we will write %400µ. It is the passing on which Atterberg limits are measured, and here liquidity limit W_L and plasticity index PI will be used.

Oedometer tests are very often completed on this fraction, the greater size in the oedometer apparatus being limited to h/6, h height of the tested sample (usually h/6 is equal to 3.1mm).

Looking at figure n°1, it results that the dry bulk density $\gamma_{d\text{-}O.D}$ of the O.D soil, is linked to the percent passing %400µ and to the dry bulk density of the 0.400µm fraction, through the expression :

$$\frac{1}{\gamma_{d\,0.D}} = \frac{\%400\mu}{\gamma_{d\,0.400\mu}} + \frac{1-\%400\mu}{\gamma_s} \quad (1)$$

γ_s being the average bulk density of the grains ($\approx$ 27kN/m^3).
$\gamma_{d0.400\mu}$ dry bulk density of the 0.400µm fraction.

weight	soil	volume
$\%400\mu.\gamma_{dO.D}$	voids + 0.400µm grains	$\%400\mu.\frac{\gamma_{dO.D}}{\gamma_{d0.400\mu}}$
$(1-\%400\mu)\ \gamma_{dO.D}$	400µm.D grains	$(1-\%400\mu)\frac{\gamma_{dO.D}}{}$
$\gamma_{dO.D}$	Total	1

Figure n°1 : Soil partition at 400µm

Two situations are then possible :
- the 400µ.D grains are scattered in the 0.400µ part,
- the 400µ.D grains are in contact with each others.

Let us examine the last case, through figure n°2:

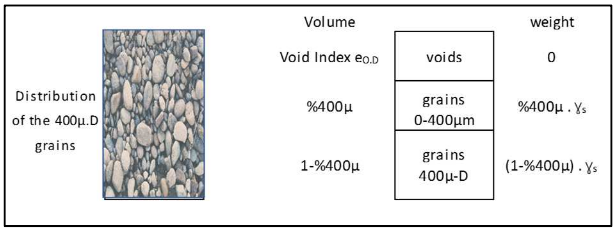

Figure n°2 : 400µ.D grains in contact

If the void index is $e_{O.D}$, the total volume of the grains being 1:
- the available volume for the void $e_{O.D}$ and for the %400µ is : $e_{O.D}$ + %400µm (2)
- the weight of the 0.400µ is : γ_s x %400µm (3)

and then the bulk density $\gamma_{d\,0.400\mu}$ is given by :

$$\gamma_{d\,0.400\mu} = \frac{\%400\mu \times \gamma_s}{e_{O.D}+\%400\mu} \quad (4)$$

We can write :

$$\%400\mu = e_{O.D}.\frac{\gamma_{d\,0.400\mu}}{\gamma_s-\gamma_{d\,0.400\mu}} \quad (5)$$

En figure n°3, we have drawn the curves %400µ as a function of bulk density $\gamma_{d\,0.400\mu}$, for different values of e_{OD} : 0.17 ; 0.2 ; 0.25 ; 0.3 ; 0.4 ; 0.6 and 0.8 (dotted line).

Moreover, the volume occupied by the voids $e_{O.D}$ and the 400µm passing must be less than the half of the total volume, if 400µ.D grains are in contact ; that implies :

$$e_{O.D} + \%400\mu m \leq 0.5\ (1 + e_{O.D}) \quad (6)$$

$$\text{And then } \%400\mu < 0.5(1-e_{O.D}) = .\frac{\gamma_{d\,0.400\mu}}{\gamma_s+\gamma_{d\,0.400\mu}} \quad (7)$$

The corresponding curve is drawn with a thick dashed line.

In a continious line, is highlighted the curve corresponding to $e_{O.D}$ equal to 0.17 being the inferior limit under which it is very rare to have bulk densities greater than 23 kN/m^3.

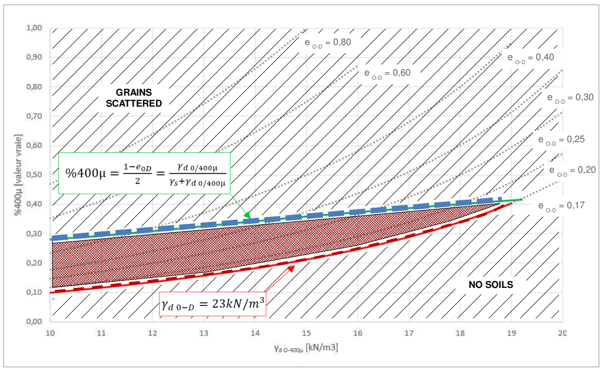

Figure n°3 : In dark zone 400µ.D grains are in contact

On figure n°3, we have three areas:
- Lower one, no points (density too high),
- Intermediate one in grey: 400µ.D grains are in contact,
- Upper zone: 400µ.D grains are scattered.

We have shown [11] that when 400µ.D grains are scattered, $\gamma_{d\,0.400\mu}$ is linked to γ_s, $VB_{0.400\mu}$, σ'_{vo} overburden effective vertical pressure and σ'_p preconsolidation pressure, through the relationship :

$$\frac{1}{\gamma_{d\,0.400\mu}} = 0{,}445 + 0{,}02 \times (1{,}37 + VB_{0.400\mu}) \times \left(4{,}2 - log(\sigma'^{\,0{,}2}_{V0}.\sigma'^{\,0{,}8}_{p})\right) \quad (8)$$

When 400µ.D grains are in contact, then $\gamma_{d\,0.400\mu}$ is probably lower than this value, due to possible arching effects through the 400µ.D grains.

$VB_{0.400\mu}$ is the blue methylene value of the 0.400µm fraction.

3. Interests of the blue methylene test

The blue methylene test is very often used in France, in soil identification, in order to caracterize fines plasticity. The test allows to quantify the quantity of dry blue methylene noted VBod, that coats the internal and external surface of the clayey minerals of 100g of o.d soils, d being an intermediate value between 2µm and D mm.

And we can write :

$$VB_{O.D} = \%d \times VB_{o.d} = \%400\mu VB_{0.400\mu} = \%2\mu\ VB_{2\mu} \quad (9)$$

For french soils, $VB_{0.400\mu}$ is well correlated to w_L and PI through the expression :

$$w_L = (1 - \%2\mu) \times 0.20 + 0.063\ VB_{0\text{-}400\mu} \quad (10)$$

$$PI = -(1 - \%2\mu) \times 0.04 + 0.045\ VB_{0\text{-}400\mu} \quad (11)$$

Knowing w_L and PI, it is possible to assess %2µ, value in percent of the passing at 2µm.

Working on soil susceptibility to liquefaction, Boulanger and Idriss have noticed that soil behaviour was linked to an index noted S_{BI} :

$$S_{BI} = \frac{1}{\left[1+\left(\frac{PI}{6,4}\right)^{8}\right]^{2}} \tag{12}$$

Figure n°4 shows the variation of 1-S_{BI} as a function of PI, Boulanger and Idriss putting forward that for 1-S_{BI} equal to zero the soil behaviour is sand like, that is for PI less than 3 and when equal to one is clay like, that is for PI greater than 8.

The corresponding values of $VB_{0.400\mu}$ for a %2µ equal to 30% are equal to respectively 1.3 and 2.4.

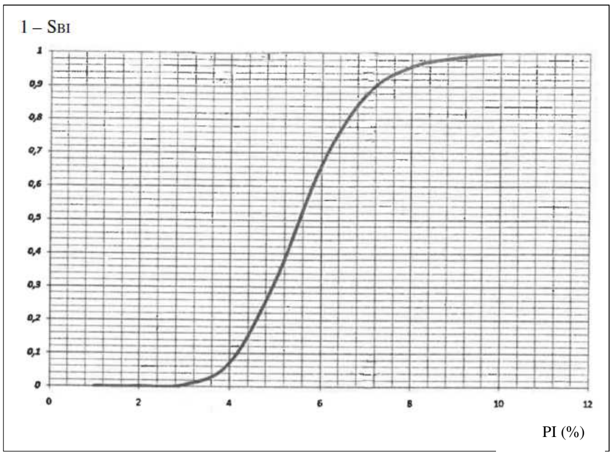

Figure n°4 : Boulanger and Idriss, soil behaviour index variation

4. Theory of Janbu extended by Gress

Janbu et al. [2] have proposed for saturated soft soils that one dimensional settlements could be assessed through the relationship:

$$\frac{d\varepsilon}{d\sigma} = \frac{1}{m\sigma r}\left(\frac{\sigma_r}{\sigma'}\right)^{1-j} = \frac{1}{Mt} \tag{13}$$

m = Janbu modulus; j = stress exponent; σ_r = 100 kPa; σ = strain; ε = deformation, Mt tangent modulus.

To extend this proposal, we suggest to write : j = S_{BI}

When, as shown in paragraph 2, 400µ.D grains are in contact one with each others, we suggest that for Janbu, these soils belong to category 1.

If, on the contrary, 400µ.D grains are scattered then the 0.400µ fraction belongs to category 1 if PI is less than 3, to category 2 if it is between 3 and 8, and to category 3 if PI is greater than 8.

And then :

- Soil category 1 : for PI < 3, we have 1 – j = 0

$$\varepsilon = \frac{1}{m\sigma_r}\Delta\sigma \tag{14}$$

- Soil category 2 : 3 ≤ PI ≤ 8
  For example when PI = 4.5 i = S_{BI} = 0.5

and then if σ'$_v$ > σ'$_p$:

$$\varepsilon = \frac{1}{5m_r}\left(\sqrt{\sigma'_p} - \sqrt{\sigma'_{vo}}\right) + \frac{1}{5m}\left(\sqrt{\sigma'_v} - \sqrt{\sigma'_{vo}}\right) \tag{15}$$

If not :

$$\varepsilon = \frac{1}{5m_r}\left(\sqrt{\sigma'_v} - \sqrt{\sigma'_{vo}}\right) \tag{16}$$

- Soil category 3 : for 1-j = 1 and if σ'$_v$ > σ'$_p$

$$\varepsilon = \frac{1}{m_r}Ln\left(\frac{\sigma'_p}{\sigma'_{vo}}\right) + \frac{1}{m}Ln\left(\frac{\sigma'_v}{\sigma'_p}\right) \tag{17}$$

With :

$$m = Ln10\frac{1+eo}{Cc} \quad m_r = Ln10\frac{1+eo}{Cs} \tag{18}$$

If not :

$$\varepsilon = \frac{1}{m_r}Ln\left(\frac{\sigma'_v}{\sigma'_{vo}}\right) \tag{19}$$

where : σ'$_v$ final effective stress (kPa) ; σ'p preconsolidation pressure (kPa) ; σ'vo initial effective stress (kPa) ; m Janbu modulus (dimensionless) ; m_r recompression modulus number (dimensionless).

5. One-dimensional consolidation settlement of category 1 and 2 soils.

Massarsch (1994) – Menard (1958) – Gress (2019)

Massarsch [6] has proposed a relationship, giving the value of m, knowing the cone tip resistance qt during a static cone penetration test :

$$m = a\frac{qt^{0,5}}{\left(\sigma r\,\sigma'_{vo}\right)^{0,25}} \tag{20}$$

qt, σ'vo in kPa, σr = 100 kPa and a being an empirical parameter, function of soil nature and it's compacity.

Gress et al. [6] have recently proposed the expression hereafter for a :

$$a = \frac{1}{\alpha_M}\frac{\sigma'_{vo}{}^{0,25}}{\sigma_r{}^{0,75}}q_T{}^{0,54} \text{ in kPa} \tag{21}$$

fitting with the values proposed by Massarsch, α_M varying here from 0.33 to 0.61 through :

$$\alpha_M = 0.33\left(2-j\right) \tag{22}$$

Then we can write m σr as :

$$M_t = m\,\sigma_r = \frac{3}{2\,\alpha_M}q_T{}^{1.04} \tag{23}$$

Moreover having noticed [7] a good correlation between q_T and Menard PMT parameters, that is : pl* net limit pressure and E_M Menard modulus, given by the relationships here after :

$$q_T = (pl^*)^{1.25} \quad E_M = (pl^*)^{1+\alpha} \text{ in kPa, with } \alpha = 0.4\frac{VB_{OD}+0.7}{VB_{OD}+1} \tag{24}$$

$m\sigma_r$ becomes then :

$$m\,\sigma_r = \frac{3}{2\,\alpha_M} E_M \quad (25)$$

K can be written for $\nu = 0.33$:

$$3K = \frac{1+\upsilon}{1-\upsilon} M_t \approx 2M_t \quad (26)$$

knowing that ((27) and (28)) :

$$M_t = \frac{(1-\upsilon)}{(1+\upsilon)\,(1-2\upsilon)} Et \quad and \quad K = \frac{Et}{3(1-2\upsilon)}$$

When 1-j = 0, then $M_t = m\sigma_r$
and the value of K becomes :

$$K = \frac{E_M}{\alpha_M} = \frac{q_T^{\ 1.04}}{\alpha_M} \quad in\ kPa \quad (29)$$

Distributed loads at soil surface on a large area, induces one-dimensional deformation given through:

$$\varepsilon_{zz} = \frac{\overline{\sigma_i}}{K} \quad (30)$$

with :

$$\overline{\sigma_i} = \frac{\overline{\sigma_{xx}}+\overline{\sigma_{yy}}+\overline{\sigma_{zz}}}{3} \quad (31)$$

6. One-dimensional consolidation settlement of category (3) soils

6.1. Soils with dimensions of grains less than 400µm

The assessment of settlements is here conducted using relations (17) and (19).

The parameters m, m_r and σ'_p are generally measured through oedometer tests, with :

$$m = Ln\,10\frac{1+eo}{Cc} \quad m_r = Ln\,10\frac{1+eo}{Cs} \quad (32)$$

where :
e_0 = initial void index ; Cc = compression index ; Cs = swelling index ; σ'_p = preconsolidation pressure.

Two major difficulties are :
- the quality of the intact samples,
- the limit of the maximum value of the grains in the sample generally fixed at 3mm $\left(\frac{19}{6}\right)$ for an oedometer test.

It is then interesting to have some correlations as :

$Cc = 0.9\,(W_L - 0.1)$ Terzaghi (1967) (33)

w_L for its real value for 0-400µm samples, or:

$$Cc = 2.7\frac{W_{SC} - 0.075}{4.2 - \log\left(\sigma'_{vo}{}^{0.2}\,\sigma'_p{}^{0.8}\right)} \quad [4] \quad (34)$$

W_{SC} water content in the overconsolidation state, expression due to Gress, derived from Herrero.

$Cs \approx 0.2\ Cc$ (35)

Preconsolidation pressure is also a very difficult parameter to measure. It is interesting to compare the laboratory results to the correlations hereafter [5]:

$$\sigma'_{vo}{}^{0.2}\,\sigma'_p{}^{0.8} = (q_T - \sigma_v)^{0.8m} = (pl^*)^m \quad (36)$$

m Mayne factor equal to

$$m = 1 - 0.28\frac{1}{1+\left(Ic/2.65\right)^{25}} \quad (37)$$

With : $Ic = 3.6\,\frac{W_L - 0.115}{W_L - 0.025}$ Ic Robertson behavior index, that is also or given through the CPT'u parameters. (38)

The value of settlement is calculated at the end of the primary consolidation at a time tp.

Finally, creep has to be taken account for:

$$\varepsilon_{zzf} = \frac{c_\alpha}{1+e_p}\log\frac{tf}{tp} \quad (39)$$

C_α creep index ≈ 0.04 Cc (40)

e_p void index at the end of the primary consolidation;
tf ≈ 10 years ; tp in year

6.2. Complete O.D soils (granulometry from 2µm to D mm)

For a O.D soils, looking at figure n° 2, we can write

$$e_{0.400\mu} = \frac{e_{O.D}}{\%400\mu} \quad (41)$$

or $e_{O.D} = \%400\mu . e_{0.400\mu}$ (42)

and then : $\Delta e_{O.D} = \%400\mu . \Delta e_{0.400\mu}$ (43)

this means that :

$Cs_{O.D} = Cs_{0.400\mu} . \%400\mu$ (44)

$Cc_{O.D} = Cc_{0.400\mu} . \%400\mu$ (45)

And : $\sigma'_{p-O.D} = \sigma'_{p-0.400\mu}$ (46)

where C_s swelling index, C_c compression index, and σ'_p preconsolidation pressure.

6.3. Conclusions

Having to assess one consolidation settlement, we have presented steps and relationshisps allowing to have relevant values of the parameters we need.

Proposed correlations are fitted to french experience, for saturated soils, having a sensitivity less than 4. For other countries, it is necessary to confront proposed values to local experience.

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