Geotechnical Aspects of Underground Construction in Soft Ground – Yoo, Park, Kim & Ban (Eds)

Relevant relations in order to better assess preconsolidation pressure values for the design of underground constructions in soft ground

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ABSTRACT: Geotechnical design of underground constructions in soft ground needs a good knowledge of the variation of preconsolidation pressure variation with depth. Having very oftenly too rare values given by oedometer tests on good undisturbed samples, we will develop ways to cope with this lack of information, using different layers physical properties and results of in situ tests like CPTu PMT and vane tests.

1 INTRODUCTION

Of course the best way to have relevant preconsolidation pressure values, is through oedometer tests on undisturbed samples. Here, we have at least two problems. The first one is to have good soft soils samples, especially at great depth. The second one is due to soft soils containing some gravels. It will be always necessary to have a sound examination of values given by the laboratory tests, in comparison with the results of physical properties and the results of in situ tests, in order to check their relevance.

For example, in Paris La Défense site, it was necessary on very plastic clays, sampled at a depth greater than 60 meters to also measure dry density through probe and neutron probe, measuring total density and volumic water content, in order to consolidate samples at corresponding void index (e = 0,82) under a pressure equal effective vertical stress value ($\sigma'_{vo} = 750$ kPa) in order to have primary consolidation oedometric parameters fitting with in situ tests and obtain relevant settlement assessments. PMT tests at the same depth were giving very high values of net limit pressures, corresponding to heavy overconsolidated plastic clays.

Then, and it will be the same conclusion for all geotechnical studies, it appears interesting, to be able to compare results of laboratory tests and those of in situ tests in order to check that they fit together.

2 INTEREST OF SOIL PHYSICAL IDENTIFICATION

It will be important for every studies to have for each layer a significant range of values of some physical properties as ρ_d dry density of total soil, ρ_s dry density of soil particles, W_N water content percentage in weight of particles smaller than 400 µm, written % 400 µ, that smaller than 2 µm (% 2µ) liquidity limit, W_L, blue methylene value of 0–400 µ soil fraction, $VB_{0.400\mu}$, methylene blue value of total soil written VB_{OD}.

We must keep in mind that W_N is not equal to the real water content at depth sampling, but is equal to retention water content. Only ρ_d is able to assess water content in a saturated state through relation:

$$W_{SAT} = 1/\rho_d - 1/\rho_s \text{ with } \rho \text{ in T/m}^3.$$

When we look at the oedometric diagram on Figure 1, we can write, Braja (2011), Gress (2011), Gress (2012):

$$Cc = \rho s \frac{W_L - 0{,}075}{\log \frac{\sigma'_{7,5}}{\sigma'_L}} = \rho s \frac{W_{NC} - 0{,}075}{\log \frac{\sigma'_{7,5}}{\sigma'_{vo}}} = \rho s \frac{W_{NC} - Wcp}{\log \frac{\sigma'_P}{\sigma'_{vo}}} \quad (1)$$

for ρ_w, density of water, equal to 1 T/m^3 and where:

- W_L: liquidity limit, written for it's real value,
- σ'_L consolidation pressure corresponding to a void index e_L equal to ρ_s W_L; σ'_L is generally taken equal to 10 kPa,
- W_{NC} water content in a normaly consolidated and saturated state under σ'_{vo}, effective vertical pressure,
- $\sigma'_{7,5}$ consolidation pressure in a normaly consolidated state for a saturated water content of 0.075 (7.5%),
- w_{cp} saturated water content for a σ'_p consolidation pressure,
- Cc = compression index.

We can also write, Braja (2011), Gress (2011), Gress (2012), where Cr is recompression index:

$$Cr = \rho s \frac{W_{SC} - W_{CP}}{\log \frac{\sigma'_p}{\sigma'_{vo}}} \quad (2)$$

- W_{SC} water content in overconsolidated state,
- σ'_p preconsolidation pressure.

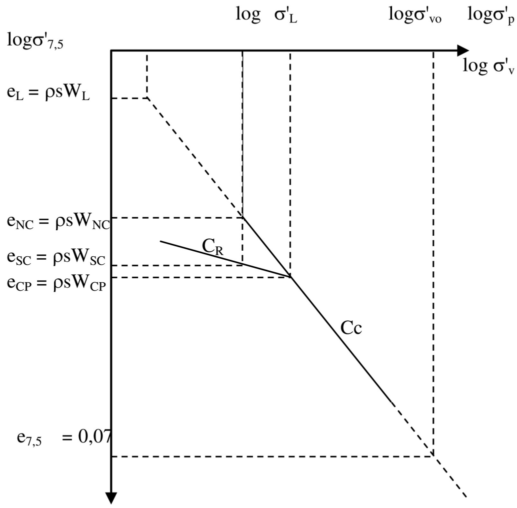

Figure 1. Oedometer test results.

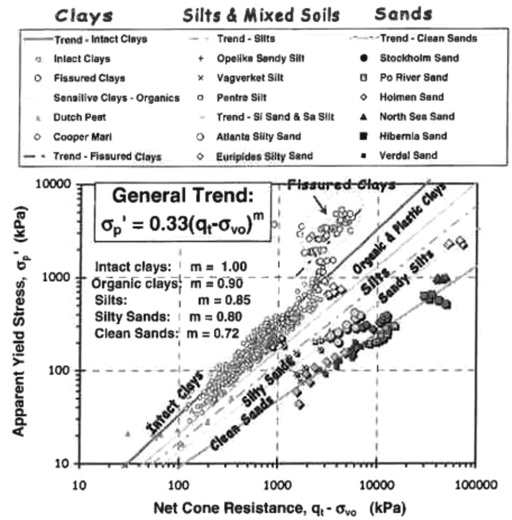

Figure 2. Generalized yield stress vs net cone resistance for clays, silts and sandy soils (Mayne).

When we look at the two first formulae (1) giving Cc, we can compare them to:

Terzaghi formula:

$$Cc \approx 0{,}9\ (W_L - 0{,}1) \qquad (3)$$

that we can write with little numerical values difference when $W_L < 100\%$:

$$Cc = 0{,}85\ (W_L - 0{,}075) \qquad (4)$$

and to Herrero formula:

$$Cc = W_N - 0{,}075 \qquad (5)$$

This comparison implies that in fact (5) should be written:

$$Cc \approx \rho s \frac{W_{NC} - 0{,}075}{4{,}2 - \log\sigma'vo} \qquad (6)$$

where σ'_{vo} is in kPa

Then using (4) and (6) and with $\rho_s = 27\,kN/m^3$, for non organic soils, we can write:

$$W_{NC} \approx 0{,}075 + 0{,}315\ (W_L - 0{,}075)\ (4{,}2 - \log\sigma'vo) \qquad (7)$$

Using relations (1) last one in comparaison with (2) and relation (7), we can also write:

$$W_{NC} \approx 0{,}075 + 0{,}315(W_L - 0{,}075)(4{,}2 - 0{,}2\log\sigma'vo - 0{,}8\log\sigma'p) \qquad (8)$$

σ'_{vo} and σ'_p being in kPa and taking Cr equal to 0.2 Cc.

Having measured ρ_d and knowing that:

$$W_{SC} = \frac{1}{\rho d} - \frac{1}{\rho s} \quad \text{with}\ \rho\ \text{in}\ T/m^3 \qquad (9)$$

it appears that σ'_p is linked with ρ_d, ρ_s, σ'_{vo} and W_L through:

$$\log\sigma'_p \approx 5{,}25 - 0{,}25\log\sigma'_{vo} - \frac{1/\rho d - 1/\rho s - 0{,}075}{0{,}252(W_L - 0{,}075)} \qquad (10)$$

This is the first way to check that σ'_p oedometer values in kPa are fitting with physical properties as ρ_d ρ_s in T/m^3 and W_L, knowing σ'_{vo} in kPa.

3 INTEREST OF CPTu TESTS

For soft soil, CPTu is a very interesting test giving values of cone resistance qc and induced pore pressure u allowing the knowledge of the variation of q_T, net cone resistance, with depth. Mayne (*Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*. IOS press. Millpress) has proposed a formula between q_T and σ'_p as:

$$\sigma'p \approx 0{,}33\ (q_T - \sigma v)^m \quad \text{in kPa} \qquad (11)$$

where σ_v total vertical pressure, m a parameter linked to soil plasticity as indicated on Figure 2.

Working on this formula, we, Gress (2012), have proposed an improvement as:

$$\sigma'p \approx \frac{(q_T - \sigma_v)^m}{\sigma'_{vo}{}^{0{,}25}} \qquad (12)$$

with $m \approx \frac{W_L + 0{,}14}{W_L + 0{,}23}$ for 0/400 µm soils (13)

and $m \approx \frac{VB_{OD} + 4{,}44}{VB_{OD} + 5{,}87}$ for coarse soils (14)

With formula (11) some difficulties are a raising when we want to make it fit with formulae (21) and (23), wich we have observed, for numerous geotechnical French studies of more than 3000 bridges. We have then to introduce effective vertical stress σ'_{vo} in the formula, $(\sigma'_{vo})^{0,25}$ with σ'_{vo} in kPa being numerically near from 0,33 in a range of frequent depth of investigation (15 meters). Formula (12), for 0/400 µm soils, has the advantage to be continuous. Formula (13) introduces a physical parameter VB_{OD}, used very often in France.

Blue methylene value test NF 94-068 (NF 1998), measures the weight of blue methylene that coats the internal and external surface of clayey particles. $VB_{0.400\mu}$ is the weight of blue methylene needed for 100 g of dry soil, devided by 100 g. We know moreover that blue methylene value for the total soil VB_{OD} is given by:

$$VB_{OD} = \%400\mu \times VB0.400\mu \quad (15)$$

For French soils, W_L and VB0.400µ are linked through formulae (16):

$$W_L \approx 0,14 + 0,063\ VB0.400\mu \quad (16)$$

From (12) we can write:

$$\sigma'p^{0,8}\ \sigma'vo^{0,2} \approx (q_T - \sigma_v)^{0,8m} \quad (17)$$

It is interesting to remember that in an oedometer diagram $\sigma'_{eq} = \sigma'^{0.8}_{p} \sigma'^{0.2}_{vo}$ is the pressure leading, in a normally consolidated path, to the same void index than that for an overconsolidated path through a load at σ'_p and finally an unload down to σ'_{vo}.

We understand through relation (12) the interest of CPTu tests. We have shown, Gress & Mouroux (2014), that the measurement of fs sleeve friction through CPT tests gives an idea of the value of the methylen blue value of the total soil VB_{OD}, VB_{OD} being linked to SBI, soil behaviour index, through:

$$VB_{OD} = \frac{1,83\,SBI - 1,44}{3,6 - SBI} \quad (18)$$

SBI is given by Robertson, Lune T. et al. (1992), through formula (19):

$$SBI^2 = (3,47 - \log Q_T)^2 + (\log Fr + 1,22)^2 \quad (19)$$

$$\text{with } Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad (20)$$

$$Fr = \frac{fs}{q_T - \sigma_{vo}} \quad (21)$$

Table 1 gives soil behaviour type for some ranges of Ic values.

Table 1. Boundaries of soil behaviour type (Robertson).

Soil behaviour type Index, I_c	Zone	Soil behaviour type
		(Figure 5.8)
$I_c < 1.31$	7	Gravelly sand
$1.31 < I_c < 2.05$	6	Sands – clean sand to silty sand
$2.05 < I_c < 2.60$	5	Sand mixtures – silty sand to sandy silt
$2.60 < I_c < 2.95$	4	Silt mixtures – clayey silt to silty clay
$2.95 < I_c < 3.60$	3	Clays
$I_c > 3.60$	2	Organic soils – peats

4 INTEREST OF PMT TESTS

We have done in France numerous CPT and PMT tests in the same sites. The advantage of PMT tests is that we can have continuous results, but each meter, for alternating layers of soft soils and stiff soils.

Though comparison of results of the two tests, we can write in kPa the formula:

$$pl^* \approx (q_T - \sigma_v)^{0,8} \quad (22)$$

pl* being net limit pressure.

Formulae (17) and (22) then implies that:

$$\sigma'ep = \sigma'p^{0,8}\ \sigma'vo^{0,2} = pl^{*\ m} \quad (23)$$

This interesting formulae shows that net limit pressure is very well linked to preconsolidation pressure. PMT tests are another interesting way to check σ'_p values.

5 INTEREST OF VANE TESTS

Numerous geotechnical engineers have worked, on the correlation that could exist between undrained cohesion Cu and net limit pressure pl*. On Figure 3 we have summarize all the works done on the subject in France. In fact, it appears that formula (24) fits very well, and continuously with all the formulae found in geotechnical literature.

$$Cu \approx (pl^*)^{0,7} \text{ in kPa} \quad (24)$$

Through (23) and (24), we can write:

$$Cu \approx (\sigma'p^{0,8}\ \sigma'vo^{0,2})^{0,7/m} \quad (25)$$

For m = 1, corresponding to very plastic clays, formulae (25) gives results very close to those given by Jamiokolwski formula:

$$Cu \approx \lambda_{Cu}\ \ \sigma'vo^{0,2}\ \ \sigma'p^{0,8} \quad (26)$$

One thing of major interest is that through formula (25), we have a relation between σ'_p and Cu through σ'_{vo}, for clayey soil to silty sand soils, using m parameter.

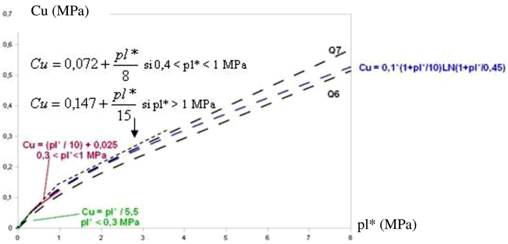

Figure 3. Comparison of Cu and pl*.

6 CONCLUSIONS

We have shown here a set of formulae allowing either to check if the values given by oedometer tests are fitting with physical properties and results of in situ tests, either giving some useful complementary results, when we have few results of oedometer tests, which is often the case.

Of course like every correlations, they are to be improved locally, keeping in mind that we have worked on non organic, non salty soils and saturated soils, having a consolidation history.

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