This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.
Relevant relations in order to better assess preconsolidation pressure values for the design of underground constructions in soft ground

J.C. Gress

Ecole Nationale des Travaux Publics de l’Etat, Vaulx en Velin, France

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 $\rho_d$ dry density of total soil, $\rho_s$ 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, $V_{B0,400}$, methylene blue value of total soil written $V_{BOD}$.

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 $\rho_d$ is able to assess water content in a saturated state through relation:

$$W_{SAT} = \frac{1}{\rho_d} - \frac{1}{\rho_s}$$

with $\rho$ in T/m$^3$.

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

$$C_c = \frac{\rho_s W_L - 0.075}{\log \frac{\sigma'_{v0}}{\sigma'_{vo}}} = \frac{\rho_s W_{NC} - 0.075}{\log \frac{\sigma'_{vo}}{\sigma'_{p}}} = \frac{\rho_s W_{NC} - W_{CP}}{\log \frac{\sigma'_{p}}{\sigma'_{vo}}}$$

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

- $W_L$: liquidity limit, written for it’s real value,
- $\sigma'_{vo}$ consolidation pressure corresponding to a void index $e_v$ equal to $\rho_s$, $W_L$; $\sigma'_{vo}$ is generally taken equal to 10 kPa,
- $W_{NC}$: water content in a normally consolidated and saturated state under $\sigma'_{vo}$, effective vertical pressure,
- $\sigma'_{7.5}$: consolidation pressure in a normally consolidated state for a saturated water content of 0.075 (7.5%),
- $w_{cp}$ saturated water content for a $\sigma'_{p}$ consolidation pressure,
- $C_c$ = compression index.

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

$$C_r = \frac{\rho_s W_{SC} - W_{CP}}{\log \frac{\sigma'_{p}}{\sigma'_{vo}}}$$

- $W_{SC}$: water content in overconsolidated state,
- $\sigma'_{p}$ preconsolidation pressure.
When we look at the two first formulae (1) giving $C_c$, we can compare them to:

Terzaghi formula:

$$C_c \approx 0.9 \left( W_L - 0.1 \right)$$

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

$$C_c = 0.85 \left( W_L - 0.075 \right)$$

and to Herrero formula:

$$C_c = W_N - 0.075$$

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

$$C_c \approx \rho_s \frac{W_{NC} - 0.075}{4,2 - \log \sigma_{vo}}$$

where $\sigma_{vo}$ is in kPa

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

$$W_{NC} \approx 0.075 + 0.315 \left( W_L - 0.075 \right) \left( 4.2 - \log \sigma_{vo} \right)$$

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

$$W_{NC} \approx 0.075 + 0.315 \left( W_L - 0.075 \right) \left( 4.2 - \log \sigma_{vo} - 0.8 \log \rho \right)$$

$\sigma_{vo}$ and $\sigma'$ being in kPa and taking $C_r$ equal to 0.2 $C_c$

Having measured $\rho_d$ and knowing that:

$$W_{SC} = \frac{1}{\rho_d} \left( 1 - \frac{1}{\rho_s} \right)$$

with $\rho$ in T/m$^3$

it appears that $\sigma'$ is linked with $\rho_d$, $\rho_s$, $\sigma_{vo}$ and $W_L$ through:

$$\log \sigma' = 5.25 - 0.25 \log \sigma_{vo} - \frac{1}{\rho_d} - \frac{1}{\rho_s} - 0.075 \frac{0.25 \left( W_L - 0.075 \right)}{0.25 \left( W_L - 0.075 \right)}$$

This is the first way to check that $\sigma'$ oedometer values in kPa are fitting with physical properties as $\rho_d$$\rho_s$ in T/m$^3$ and $W_L$, knowing $\sigma_{vo}$ in kPa.

3 INTEREST OF CPTu TESTS

For soft soil, CPTu is a very interesting test giving values of cone resistance $q_T$ 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 $\sigma_p$ as:

$$\sigma_p \approx 0.33 \left( q_T - \sigma_v \right)^m$$

where $\sigma_v$, 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:

$$\sigma' \approx \left( \frac{q_T - \sigma_v}{\sigma_{vo}} \right)^{0.25}$$

with $m = \frac{W_L + 0.14}{W_L + 0.23}$ for 0/400 µm soils

and $m = \frac{0.44}{VB_{OD} + 5.87}$ for coarse soils
With formula (11) some difficulties are a rising when we want to make it fit with formulae (21) and (23), which we have observed, for numerous geotechnical French studies of more than 3000 bridges. We have then to introduce effective vertical stress \(\sigma'_{vo}\) in the formula, \((\sigma'_{vo})^{0.25}\) with \(\sigma'_{vo}\) in kPa being numerically near from 0,33 in a range of frequent depth of investigation (15 meters). Formula (12), for 0/400 \(\mu\)m 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. \(VB_{400\mu}\) 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:

\[
VB_{od} = \%400\mu \times VB_{400\mu} 
\]

For French soils, \(W_L\) and \(VB_{400\mu}\) are linked through formulae (16):

\[
W_L \approx 0.14 + 0.063 \times VB_{400\mu} 
\]

From (12) we can write:

\[
\sigma'_{p}^{0.8} \times \sigma'_{vo}^{0.2} \approx (q_T - \sigma_v)^{0.8m} 
\]

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

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

\[
VB_{od} = \frac{1.83 \times SBI - 1.44}{3.6 - SBI} 
\]

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

\[
SBI = (3.47 - \log Q_t)^2 + (\log Fr + 1.22)^2 
\]

with \(Q_t = \frac{q_T - \sigma_{vo}}{\sigma'_{vo}}\)  

\[
Fr = \frac{f_s}{q_T - \sigma_v} 
\]

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

<table>
<thead>
<tr>
<th>Soil behaviour type</th>
<th>Index, Ic</th>
<th>Zone</th>
<th>Soil behaviour type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_c \leq 1.31)</td>
<td>7</td>
<td></td>
<td>Gravelly sand</td>
</tr>
<tr>
<td>(1.31 &lt; I_c &lt; 2.05)</td>
<td>6</td>
<td></td>
<td>Sands – clean sand to silty sand</td>
</tr>
<tr>
<td>(2.05 &lt; I_c &lt; 2.60)</td>
<td>5</td>
<td></td>
<td>Sand mixtures – silty sand to sandy silt</td>
</tr>
<tr>
<td>(2.60 &lt; I_c &lt; 2.95)</td>
<td>4</td>
<td></td>
<td>Silt mixtures – clayey silt to silty clay</td>
</tr>
<tr>
<td>(2.95 &lt; I_c &lt; 3.60)</td>
<td>3</td>
<td></td>
<td>Clays</td>
</tr>
<tr>
<td>(I_c &gt; 3.60)</td>
<td>2</td>
<td></td>
<td>Organic soils – peats</td>
</tr>
</tbody>
</table>

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:

\[
pl^* \approx (q_T - \sigma_v)^{0.8} 
\]

\(pl^*\) being net limit pressure.

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

\[
\sigma'_{ep} = \sigma'_{p}^{0.8} \times \sigma'_{vo}^{0.2} = pl^*^{m} 
\]

This interesting formulae shows that net limit pressure is very well linked to preconsolidation pressure. PMT tests are another interesting way to check \(\sigma'_p\) 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.

\[
Cu \approx (pl^*)^{0.7} \text{ in kPa} 
\]

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

\[
Cu \approx (\sigma'_{p}^{0.8} \times \sigma'_{vo}^{0.2})^{0.7m} 
\]

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

\[
Cu \approx \lambda_{cu} \times \sigma'_{vo}^{0.2} \times \sigma'_{p}^{0.8} 
\]

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

REFERENCES


