1

Physical Parameters

1.1. Unit weights and volumes

While performing CPTs, the unit weights of soils are generally not measured, leading to imprecision in derived parameters. Mayne [MAY 07] proposed a formula that relates the saturated unit weight to the CPT sleeve friction and specific gravity of grains (units: kN/m³ and kPa):

$$\gamma_{sat} = 2{,}6 \log f_s + 15\left({}^{\gamma_s}/_{\gamma_w}\right) - 26.5 \qquad [1.1]$$

He also suggested two simple alternative expressions:

$$\gamma_{sat} = 26 - \frac{14}{1+[0.5 log(f_s+1)]^2} \qquad [1.2]$$

and

$$\gamma_{sat} = 12 + 1.5 ln(f_s + 1) \qquad [1.3]$$

Robertson *et al*. [ROB 15] proposed the following formula to estimate the total unit weight using CPT results:

$$\gamma/\gamma_w = 0.27\left[log R_f\right] + 0.36[log(q_t/p_a)] + 1.236 \qquad [1.4]$$

with R_f expressed in %.

For NC to low overconsolidated clays, Mayne and Peuchen [MAY 12] proposed the following method for a quick estimate of the total unit weight from the cone resistance–depth ratio:

$$m_q = {}^{\Delta q_t}/_{\Delta z} \approx {}^{q_t}/_{z} \qquad [1.5]$$

As a rule-of-thumb estimate:

$$\gamma = \gamma_w + m_q/8 \qquad [1.6]$$

or with a little more refinement:

$$\gamma = 0.636 q_t^{0.072}\left(10 + m_q/8\right) \qquad [1.7]$$

In addition, for $30 < m_q < 70$:

$$\gamma = \gamma_w + 0.056\left(m_q\right)^{1.21} \; r^2 = 0.623 \qquad [1.8]$$

If a seismic piezocone is used, γ_{sat} can be estimated from the correlation between shear wave and depth, as given by Mayne [MAY 07]:

$$\gamma_{sat} = 8{,}32 \log V_s - 1{,}61 log\ z \; r^2 = 0{,}808 \qquad [1.9]$$

or the mass density [MAY 99]:

$$\rho_t = 1 + \frac{1}{0.614 + 58.7(\log z + 1.095)/V_s} \qquad [1.10]$$

The total unit weight can be estimated from the DMT as follows [MAY 02]:

$$\gamma = 1.12\gamma_w\left(\frac{E_D}{\sigma_{atm}}\right)^{0.1} . I_D^{-0.05} \qquad [1.11]$$

From Vidalie's [VID 77] research on French muds, peats and soft clays with $30 < w_L < 180$, $12 < \gamma < 20$ (kN/m³), and all the soils being close to the A-line on the Casagrande chart, it is possible to derive a closed-form relationship between the total unit weight (kN/m³) and moisture content (%):

$$\gamma = 42.42 w^{-0.239} \; R^2 = 0.9987 \qquad [1.12]$$

1.2. Soil behavior type index and soil classification index

The soil behavior type index Ic is related to the boundaries of each SBT_n zone, which is defined from CPT results as follows:

$$I_C = [(3.47 - logQ_t)^2 + (logF_r + 1.22)^2]^{0.5} \quad [1.13]$$

where

$$Q_t = (q_t - \sigma_{v0})/\sigma'_{v0} \quad [1.14]$$

and

$$F_r(\%) = (f_s/(q_t - \sigma_{v0})).100 \quad [1.15]$$

This index is widely used for correlations.

Based on CPTu results, Jefferies and Davies [JEF 93] introduced a cone soil classification index $*I_c$, which can be used for soil classification if $B_q < 1$:

$$*I_C = \left[\{3 - log[Q_t(1 - B_q)]\}^2 + \{1.5 + 1.3logF_r\}^2\right]^{0.5} \quad [1.16]$$

1.3. Consistency or Atterberg limits

Skempton [SKE 53] developed the Casagrande plasticity chart, including the influence of soil activity (A), which provides some information on the minerals constituting the clay (Figure 1.1). In this chart, the equations for the A- and U-lines are, respectively:

A-line: $I_p = 0.73(w_L - 20)$ [1.17]

U-line: $I_p = 0.9(w_L - 8)$ [1.18]

Later, Biarez and Favre [BIA 76] proposed an alternative to the A- and U-lines:

$$I_p = 0.73(w_L - 13) \quad [1.19]$$

Based on oedometric test results, it is possible to deduce the consistency index (CI) for remolded sands or clays from the consolidation stress σ_c [FAV 02]:

$$CI = 0.46(log\sigma_c - 0.54) \quad [1.20]$$

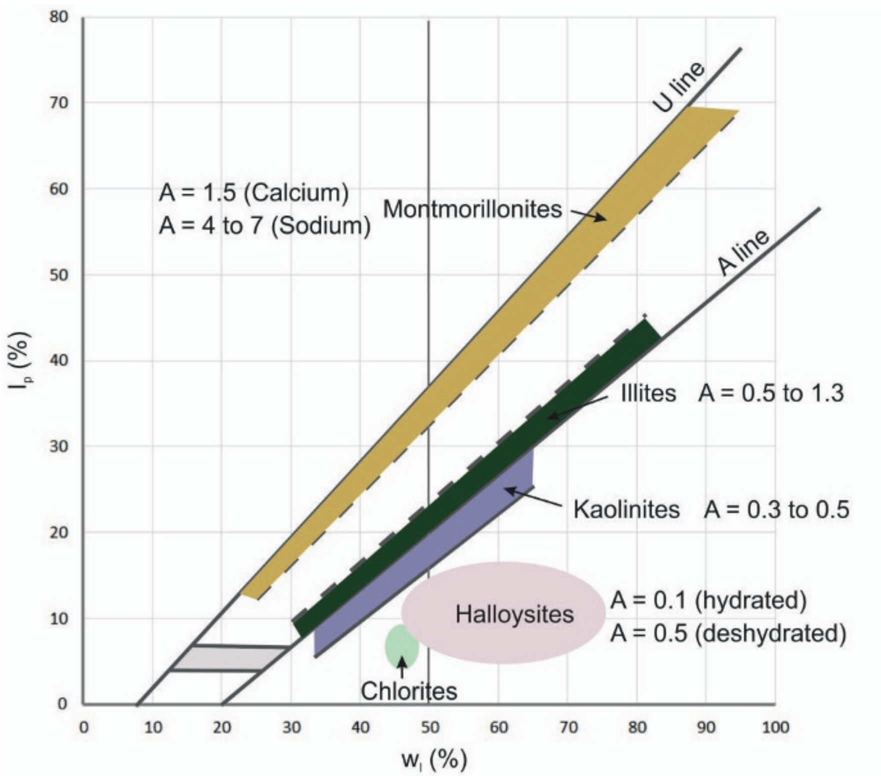

Figure 1.1. *Casagrande's plasticity chart (adapted from [SKE 53]). For a color version of the figure, please see www.iste.co.uk/verbrugge/soils.zip*

1.4. Consistency and liquidity indices

For normally consolidated clays with $20 < w_L < 200$, consistency and liquidity indices can be deduced from the total overburden pressure, as described by Biarez and Favre [BIA 76]:

$$I_L = 0.46(1 - log\sigma_{v0}) \quad [1.21]$$

$$CI = 0.46(log\sigma_{v0} + 1.2) \qquad [1.22]$$

where σ_{v0} is expressed in bars (1 bar ~ 100 kPa).

1.5. Rigidity index

This index is defined by the ratio of the shear modulus to the shear stress. For undrained and drained conditions, it is, respectively, given by:

$$I_r = \frac{G}{s_u} \; or \; I_r = \frac{G}{\sigma' tan\varphi'} \qquad [1.23]$$

Keaveny and Mitchell [KEA 86] derived the rigidity index from the plasticity index and the OCR of the form:

$$I_r \approx \frac{exp\left(\frac{137-I_p}{23}\right)}{1+ln\left[1+\frac{(OCR+1)^{3.2}}{26}\right]^{0.8}} \qquad [1.24]$$

From CPTu results, Mayne [MAY 01] proposed that:

$$I_r = exp\left[\left(\frac{1.5}{M} + 2.925\right)\left(\frac{q_t-\sigma_{v0}}{q_t-u_2}\right) - 2.925\right] \qquad [1.25]$$

where

$$M = \frac{6\,sin\varphi'}{3-sin\varphi'} \qquad [1.26]$$

Strictly speaking, the calculation of M thus needs CIU triaxial tests but can be approximated with the φ’ values presented in Chapter 4.

1.6. Relative density of sands

For clean sands with less than 15% fines and at medium compressibility, Jamiolkowski *et al*. [JAM 01] related the relative density to cone tip stress in the following way:

$$D_R(\%) = 100\left[0.268\ln\left(\frac{q_t/\sigma_{atm}}{\sqrt{\sigma'_{v0}/\sigma_{atm}}}\right) - 0.675\right] \qquad [1.27]$$

For high or low compressibility of the sand, we have to add or subtract up to 15% of the value resulting from this formula.

For preconsolidated sands, Mayne [MAY 09a] suggested multiplying the value 0.675 by $OCR^{0.2}$ in the above formula. An alternative expression for quartz-silica sands [MAY 14] is:

$$D_R\ (\%) = 100\sqrt{\frac{1}{305.OCR^{0.2}}\left(\frac{q_t/\sigma_{atm}}{\sqrt{\sigma'_{v0}/\sigma_{atm}}}\right)} \qquad [1.28]$$

In addition, for carbonate sands, the author suggested that:

$$D_R(\%) = 0.87\left(\frac{q_t/\sigma_{atm}}{\sqrt{\sigma'_{v0}/\sigma_{atm}}}\right) \qquad [1.29]$$

Some refinements regarding the influence of compressibility and the OCR were derived by Kulhawy and Mayne [KUL 90] from tests performed in a calibration chamber:

$$D_R^2 = \frac{\left({}^{q_c}/_{\sigma_{atm}}\right)}{K\left({}^{\sigma'_{v0}}/_{\sigma_{atm}}\right)^{0.5}} \qquad [1.30]$$

where D_R in decimal form and K is given in Table 1.1.

Soil	K
NC high compressibility	280
NC medium compressibility	292
NC low compressibility	332
Average	350
Low OCR (<3)	390
Med. OCR (3–8)	403
High OCR (>8)	443

Table 1.1. *K values after [KUL 90]*

From DMT results of alluvial soils (clays, silts and sands), [TOG 15] proposed that:

$$D_R = 43ln(K_D)\ if\ I_D \geq 1.!\ and\ 4 \leq K_D \leq 7 \quad [1.31]$$

$$D_R = 48ln(K_D) + 9\ if\ I_D \geq 1.!\ and\ K_D \leq 4 \quad [1.32]$$

An expression for the relative density of sandy soils was derived from SPT results by Natarajan and Tolia [NAT 72]:

$$D_R = \left(\frac{2.8}{0.01\sigma'_{v0}+0.7}\right) N + 30 \quad [1.33]$$

with D_R expressed in % and σ'_{v0} in kPa.

A simpler form was given by [KUL 90]:

$$D_R^2 = \frac{N_{60}}{60+25\ logD_{50}} \quad [1.34]$$

with D_r in decimal form and D_{50} in mm.

Another expression was given by the same authors:

$$D_R(\%) = 12.2\ + 0.75[222N + 2311 - 711OCR - 779(\sigma'_{v0}/\sigma_{atm}) - 50C_u^2]^{0.5} \quad [1.35]$$

with 1 < OCR < 3.

Although more parameters are required, the precision is not significant as $r^2 = 0.77$.

1.7. Wave velocity

Currently, the SCPT is uncommon. To estimate the shear wave velocity or to check the measured value, the correlations given below can be useful.

According to Baldi *et al.* [BAL 89], for uncemented sands (units: m/s and MPa):

$$V_s = 277q_t^{0.13}.(\sigma'_{v0})^{0.27} \quad [1.36]$$

Moreover, for clays [MAY 95] (units: m/s and kPa):

$$V_s = 1.75q_t^{0,627}\ r^2 = 0.736 \quad [1.37]$$

More generally, for all types of soils [HEG 95] (units: m/s and kPa):

$$V_s = [10.1 log q_t - 11.4]^{1.67}.\left[{f_s}/{q_t}.100\right]^{0.3} \quad [1.38]$$

For clays, silts and sands, Mayne [MAY 06] directly relates V_s to the sleeve friction which is expressed in kPa:

$$V_s = 118.8\ log f_s + 18,5 \quad [1.39]$$

For uncemented Holocene- and Pleistocene-age soils, Robertson and Cabal [ROB 15] suggested that (units: m/s and kPa):

$$V_s = [\alpha_{vs}\,(q_t - \sigma_v)/p_a]^{0.5} \quad [1.40]$$

where

$$\alpha_{vs} = 10^{(0.55 I_c + 1.68)} \quad [1.41]$$

For an alluvial site characterized by clay layers, which are sometimes weakly organic alternating with silt and sand [TOG 15], it is given by:

$$V_s = 277q_c^{0.13}(\sigma'_v)^a \quad [1.42]$$

where a= 0.22 if $\sigma'_v \leq 100$ kPa, otherwise a=0.17.

1.8. Cation exchange capacity

Although widely used in soil chemistry and soil science, the cation exchange capacity (CEC) is quite unknown in soil mechanics. The cation exchange capacity of a soil is the number of moles of adsorbed cation charge that can be desorbed from the unit mass of soil under given conditions. This depends on the kind and amount of clay minerals present in the soil.

CEC is related to the swelling potential and the aptitude for lime stabilization of clayey soils. Table 1.2 gives the CEC values for most usual clay minerals [GRI 68].

Yilmaz [YIL 04] proposed the following relationship to yield the CEC from w_L:

$$CEC\ (meq/100g) = e^{(2.63\ +0.02w_L)}\ r = 0.97 \quad [1.43]$$

In addition, Vidalie [VID 77] proposed that:

$$CEC\ (meq/100g) = \alpha.I_P \quad [1.44]$$

with $0.25 < \alpha < 1$ and the accepted mean value being $\alpha = 0.5$.

Clay mineral	CEC (meq/100 gr)
Kaolinite	3–15
Smectite	80–150
Illite	10–40
Chlorite	10–40
Vermiculite	100–150

Table 1.2. *Clay minerals versus CEC values*