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Exercise 6 – 14/11/2023

Parameter determination based on data from in-situ tests

1. Standard Penetration Test (SPT)

Introduction to the SPT Test Procedure

The test uses a thick-walled sample tube. This is driven into the ground at the bottom of a borehole by blows from a slide hammer. More specifically, the test consists of the following steps:

1. Driving the standard split-barrel sampler a distance of 460 mm into the soil at the bottom of the boring.
2. Using a 63.5-kg driving mass (or hammer) falling "free" from a height of 760 mm.
3. Counting the number of blows to drive the sampler the last two 150 mm distances (total = 300 mm) to obtain the ***N*** number.

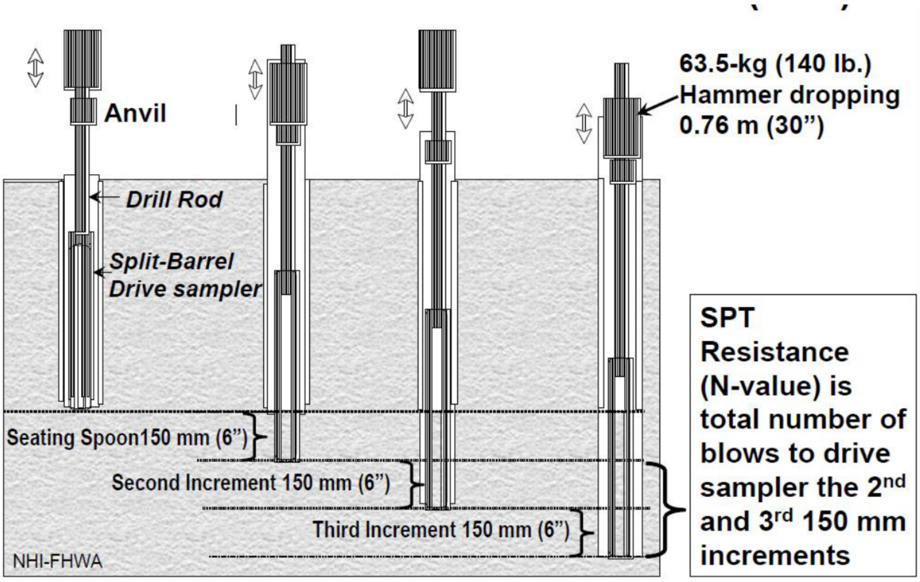
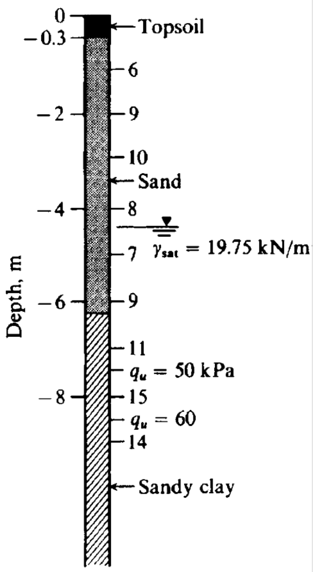


Figure 1 : SPT - Procedure

Based on the data returning from the test, one can estimate the shear strength angle φ' of the soil in the first few meters of the subsurface.

Problem Statement

The Figure below depicts, on the righthand side, the measured blow count, ***N***, with a SPT test in relation to the depth below ground surface. The groundwater table (GWT) is at - 4.4 m bgs (below the ground surface). We assume that the unit weight of the sand increases linearly from γ = 15 kN/m^3 to γ = 18.1 kN/m^3 above GWT, while below the GWT, the saturated unit weight is γ_{sat} = 19.75 kN/m^3.



Empirical values for ϕ, D_r, and unit weight of granular soils based on the SPT at about 6 m depth and normally consolidated [approximately, $\phi = 28° + 15° D_r$ ($\pm 2°$)]

Description		Very loose	Loose	Medium	Dense	Very dense
Relative density D_r		0	0.15	0.35	0.65	0.85
SPT N'_{70}:	fine	1–2	3–6	7–15	16–30	?
	medium	2–3	4–7	8–20	21–40	> 40
	coarse	3–6	5–9	10–25	26–45	> 45
ϕ:	fine	26–28	28–30	30–34	33–38	
	medium	27–28	30–32	32–36	36–42	< 50
	coarse	28–30	30–34	33–40	40–50	
γ_{wet}, kN/m^3		11–16*	14–18	17–20	17–22	20–23

* Excavated soil or material dumped from a truck has a unit weight of 11 to 14 kN/m^3 and must be quite dense to weigh much over 21 kN/m^3. No existing soil has a D_r = 0.00 nor a value of 1.00. Common ranges are from 0.3 to 0.7.

Figure and Table of Problem 1, from Bowles (1988).

Question

- Referring to Table above, make reasonable estimates of the relative density $\boldsymbol{D_r}$ and shear strength angle $\boldsymbol{\varphi'}$ ***(called in the table ϕ)*** for the sand both
  - above the GTW and
  - below the GTW.

Definitions of Interest

- By knowing the measured blow count, ***N***, the standard blow count $\boldsymbol{N'_{70}}$, (i.e. the adjusted blow count based on the energy ratio, $\boldsymbol{E_r}$, defined below), can be calculated as

$$N'_{70} = C_N \eta_1 \eta_2 \eta_3 \eta_4 N \tag{1}$$

where η_i are adjustment factors defined below (see Appendix) and **C_N** is a coefficient that considers the overburden vertical stress:

$$C_N = \left(\frac{95.76}{\sigma'_{v0}}\right)^{0.5} \tag{2}$$

with $\boldsymbol{\sigma'_{v0}}$ is the effective vertical overburden stress at the given depth $\sigma'_{v0} = \sigma_{v0} - p_w = \gamma z - \gamma_w z$

The coefficients η provide a correction of the blows counts based on the drill system and for the specific problem they are set as follows:

- $\eta_1 = \frac{Er}{70}$ (energy efficiency coefficient)
- $\eta_2 = 1$ (rod length correction)
- $\eta_3 = 1$ (sampler correction)
- $\eta_4 = 1$ (borehole diameter correction)

- Assume E_r = 60 (= actual hammer energy to the sampler/input energy in percentage) for the ***N*** values shown in the Figure. E_r then allows one to estimate the energy efficiency coefficient, $\boldsymbol{\eta_1}$. This allows ultimately for the estimation of N'_{70}.
- Using this value, for a given grain size of geomaterial, the relative density, D_r, can be estimated using the Table. Once the D_r is estimated, the shear strength angle can be evaluated according to the following empirical formula:

$$\varphi' = 28° + 15° Dr\ (\pm 2°) \qquad (3)$$

2. Cone Penetration Test (CPT)

Problem Statement

The CPT test consists of pushing the standard cone into the ground at a rate of 10 to 20 mm/s and recording the resistance. The Table of problem 2 (data are reported in the excel file ***"Ex5 – Data")*** shows the result of a Cone Penetration Test CPT. The GWT is located at depth 3 m. We assume an average γ = 16.5 kN/m^3 above the GWT and γ_{sat} = 19.81 kN/m^3 below the GWT.

Depth, m	q_c, MPa	q_s, kPa	Soil classification
0.51	1.86	22.02	Sandy silt
1.52	1.83	27.77	Silt and clayey silt
1.64	1.16	28.72	Very silty clay
2.04	1.15	32.55	Very silty clay
2.56	2.28	24.89	Silty sand
3.04	0.71	22.02	Silty clay
3.56	0.29	12.44	Clay
4.08	0.38	15.32	Clay
4.57	1.09	21.06	Very silty clay
5.09	1.22	31.60	Very silty clay
5.60	1.57	28.72	Silt and clayey silt
6.09	1.01	30.64	Very silty clay
6.61	6.90	28.72	Sand
7.13	5.41	39.26	Sand
7.62	10.50	26.81	Sand
8.13	4.16	27.77	Sand
8.65	2.45	43.09	Silt and clayey silt
9.14	8.54	26.11	Sand
9.66	24.19	76.60	Sand
10.18	32.10	110.12	Sand
10.66	23.34	71.82	Sand
11.18	5.86	62.24	Silty sand
11.70	4.17	57.45	Sandy silt
12.19	17.93	86.18	Sand
12.71	24.71	73.73	Sand
13.22	25.79	76.60	Sand
13.71	13.27	85.22	Sand
14.23	1.41	43.09	Very silty clay
14.75	2.73	196.30	Clay
15.24	1.75	108.20	Clay
15.75	1.02	78.52	Clay
16.27	0.82	36.38	Clay
16.76	1.88	72.77	Very silty clay
17.28	1.46	106.29	Clay
17.80	1.15	51.71	Clay

Table of Problem 2, from Bowles (1988).

Questions

- Plot the tip resistance (qT), the sleeve friction (fs), and friction ratio (fr=fs/qT%) with respect to depth.
- Considering the friction ratio, provide comments related to its variation with depth and type of soil.
- Compute the undrained shear strength $\mathbf{s_u}$ at depth 5.6 m (assuming N_k=15), and the shear strength angle **φ'** at depth 7.62 m.

Definitions of Interest

- From CPT test, the undrained shear strength s_u can be estimated according to the following empirical formula:

$$s_u = \frac{q_T - \sigma_{v0}}{N_k} \quad (4)$$

where $\boldsymbol{\sigma_{v0}}$ if the vertical total stress, and $\mathbf{N_k}$ is the cone factor that here is set equal to 15 (typical values ranges from 15 to 20).

- Moreover, shear strength angle φ' can be also evaluated according to the following empirical formula:

$$\varphi' = 29° + \sqrt{q_T} \quad (5)$$

where $\mathbf{q_T}$ should be in MPa.

3. The Pressuremeter Test (PMT)

Introduction to PMT Test Procedure

The pressuremeter is composed of a dilatable probe placed in a borehole, tubes for transmitting fluids (air and water), a pressure and volume controller, and a reserve of compressed gas (Figure below). The principle of the test consists of inflating a dilatable probe in a borehole and linking the pressure of the inflation to a measurement of the deformability of the soil, the pressuremeter Young modulus $\mathbf{E_{sp}}$ and a measurement of the pressure limit $\mathbf{p_{LM}}$.

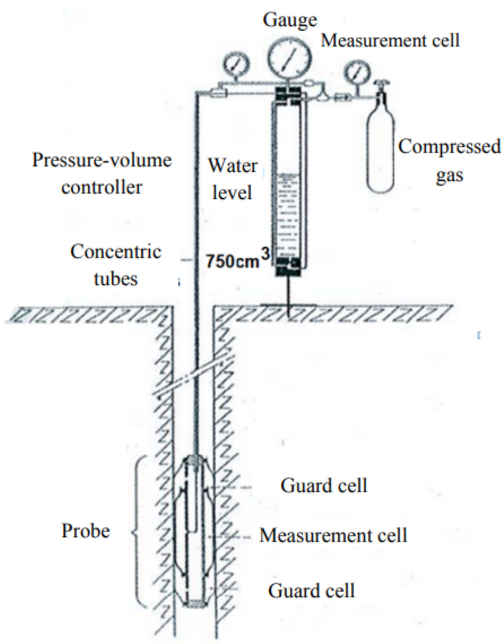


Figure 2 Diagram of the principle of the Pressuremeter (Monnet et al., 2015)

Problem statement

A pressuremeter test is conducted in soft clay. The resulting plot of cell pressure p versus total injected volume is given in the Figure below. The test point is 4 m bgs and the unit weight of the overlying strata is γ_{sat} = 19.81 kN/m^3 (the soil is also saturated above the GWT as a result of capillarity; the AEV of the soil is greater than 30 kPa and a hydrostatic pore water pressure distribution can be assumed over depth). The GWT is 3 m bgs. For S=100% take Poisson ratio v=0.5.

Question

➢ Calculate the lateral stress coefficient K_0.

- Calculate the shear modulus $\boldsymbol{G}$

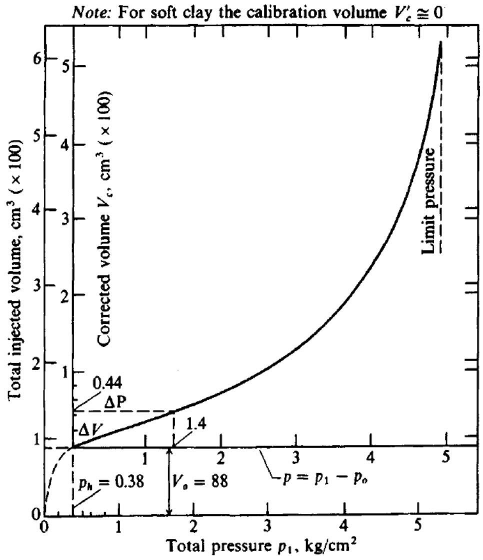


Figure 3 Data from a pressuremeter test in soft clay

Definitions of interest

In practice we obtain the slope $\frac{\Delta V}{\Delta p}$ from the linear part of the cell pressure versus volume plot, to obtain the shear modulus as follows:

$$G = \frac{E_{sp}}{2(1+v)} = V_o' \frac{\Delta p}{\Delta V} \tag{7}$$

where

- $\boldsymbol{E_{sp}}$ is the pressuremeter Young modulus
- v is the Poisson ratio
- V_o' is the volume of the measuring cell at average pressure $\Delta p,\ V_o' = V_0 + V_c$,
- where V_0 is the volume of the measuring cell at the start of the linear part of the cell pressure, while Vc is the average of the additional (to V_0) injected volume in the linear part of the cell pressure versus volume plot,
- $\Delta p,\ \Delta V$ are defined in the Figure above

The pressuremeter Young modulus $\boldsymbol{E_{sp}}$ is then calculated by using an estimated value of v with the use of the relation $E_{sp} = E_s = 2G(1+v)$.

The value p_h shown on the Figure above is taken as the expansion pressure of the cell membrane in solid contact with the soil and is approximately the in-situ lateral stress $\boldsymbol{\sigma_h}$. The lateral stress coefficient $\boldsymbol{K_0}$ is defined as follows:

$$K_o = \frac{\sigma_h'}{\sigma_{vo}'} \tag{8}$$

References

Bowles, J. E. (1988). Foundation Analysis and Design, 4th Edition, McGrew-Hill.

Monnet, J. (2015). In situ tests in Geotechnical Engineering. John Wiley & Sons.

Appendix

Hammer for η_1					Remarks
	Average energy ratio E_r				
	Donut		Safety		
Country	**R-P**	**Trip**	**R-P**	**Trip/Auto**	R-P = Rope-pulley or cathead $\eta_1 = \mathbf{E}_r/\mathbf{E}_{rb} = E_r/70$ For U.S. trip/auto $w/\mathbf{E}_r = 80$ $\eta_1 = 80/70 = 1.14$
United States/ North America	45	—	70–80	80–100	
Japan	67	78	—	—	
United Kingdom	—	—	50	60	
China	50	60	—	—	

Rod length correction η_2			Remarks
Length	> 10 m	η_2 = 1.00	N is too high for $L < 10$ m
	6–10	= 0.95	
	4–6	= 0.85	
	0–4	= 0.75	

Sampler correction η_3			Remarks
	Without liner	η_3 = 1.00	Base value
With liner:	Dense sand, clay	= 0.80	N is too high with liner
	Loose sand	= 0.90	

Borehole diameter correction η_4			Remarks
Hole diameter:†	60–120 mm	η_4 = 1.00	Base value; N is too small when there is an oversize hole
	150 mm	= 1.05	
	200 mm	= 1.15	

* Data synthesized from Riggs (1986), Skempton (1986), Schmertmann (1978*a*) and Seed et al. (1985).
† η_4 = 1.00 for all diameter hollow-stem augers where SPT is taken through the stem.