HOMEWORK – 1 Solution

Question 1 (25%)

At Adana Ceyhan Crude Oil Tank Farm, a steel tank with a diameter of 90 m will be carrying a uniform pressure of 200 kPa, at the ground surface. An example borehole log for this site is given below. Assume that all soils have a dry and saturated unit weights of 19 and 20 kN/m^3, respectively. Use 2V:1H stress distribution.

a) Is the borehole depth sufficient? Make some calculations and comment in a few sentences.

The given borehole depth is 25 m, and it is not sufficient. The following guidelines give some idea about the required depth of the borehole.

One of the rule of thumbs says that the depth of boreholes should be 1 to 2 times the least dimension of the loaded area. If we use the least dimension as 90 m, and 1.0 as a minimum value, **the depth of the borehole should be at least 90 m below the loaded area**.

Another guideline is **De Beer's Rule:** Borehole should extend at least to a depth where stress increase **$\Delta\sigma'_v = 10\%(\sigma'_{vo})$**

Using 2V:1H stress distribution:

$$\Delta\sigma'_v = \frac{Force}{New\ enlarged\ area} = \frac{(200\ kPa) \times (\frac{\pi \cdot D^2}{4})}{\frac{\pi \cdot (D_{new})^2}{4}} = \frac{(200) \times (\frac{\pi \cdot 90^2}{4})}{\frac{\pi \cdot (90+z)^2}{4}}$$

$$= \frac{1620000}{(90+z)^2}$$

The ground water table is at a depth of 9.5 m below ground surface. Assuming that the required borehole depth will be deeper than 9.5 m:

$$\sigma'_{vo} = 9.5 \times 19 + (z - 9.5) \times (20 - 10) = 85.5 + 10z$$

$$\Delta\sigma'_v = \frac{1620000}{(90+z)^2} = 0.1 \times (85.5 + 10z)$$

$$\boldsymbol{z \cong 61.8\ m}$$

The depth of the boreholes, according to De Beer's rule, should be about 62 meters deep from the level of the base of the tank at the ground surface. Therefore the given borehole depth of 25 m is not sufficient.

b) Calculate the immediate settlement using the Standard Penetration Test data and equation 4.18(c) in CE366 Lecture Notes (no need to consider shape factor, fs, and other factors).

Equation 4.18(c) in CE366 Lecture notes state that:

Immediate settlement:

$$S_i = q \cdot B^{0.7} \cdot \frac{\mathrm{I_c}}{3}$$

$$\text{where} \quad I_c = \frac{1.71}{(N_{60})^{1.4}}$$

Where $\overline{N_{60}}$ is the average value of the SPT N_{60} value over the depth of influence of foundation, (i.e. 2B below the foundation level). When the q is in kPa, and B in meters, the result will be in milimeters.

Standard penetration test results, from the borehole log, is given in the table below. Since borehole diameter, rod length etc is not given in the borehole log, the following assumptions are made.

- Since no other information is available, borehole diameter is assumed to be a standard size borehole with a diameter in the range of 65-115 mm, which requires no correction: C_B = 1.0.
- Since no other information is available, the sampler is assumed to be a standard sampler, which requires no correction: C_s=1.0.
- For the rod length, the rod length is assumed to be the same as the depth of the SPT.
- For energy ratio, ER, Table 2.1 indicates that the typical Standard Penetration Tests carried out in Turkey have an energy ratio of ER=0.45

Depth from ground surface (m)	**SPT N value**	**Rod length (m)**	**Rod Length factor, C_R**	**$N_{60} = N \times (ER/0.6) \times C_B \times C_S \times C_R$ $N_{60} = N \times (0.45/0.6) \times 1.0 \times 1.0 \times C_R$ $N_{60} = N \times 0.75 \times C_R$**
1.5	28	1.5	0.75	15.8
3.0	32	3.0	0.75	18
4.5	22	4.5	0.85	14
6.0	39	6.0	0.85	24.9
7.5	56	7.5	0.95	39.9
9.0	38	9.0	0.95	27.1
10.5	49	10.5	1.0	36.8
12.0	19	12.0	1.0	14.3
13.5	R	13.5	1.0	R
15.0	42	15.0	1.0	31.5
16.5	26	16.5	1.0	19.5
18.0	R	18.0	1.0	R
19.5	R	19.5	1.0	R
21.0	R	21.0	1.0	R
22.5	R	22.5	1.0	R
24.0	R	24.0	1.0	R

Average SPT N_{60} value over the depth of influence of 2B below the loaded area will be calculated. Note that the depth of influence is 180 m, and we have SPT N values available up to 25 m depths.

If we want to include R (refusal) values into the average value, one can assume at least R=50,

N_{60} = (15.8+18+14+24.9+39.9+27.1+36.8+14.3+31.5+19.5+6×50) / 16 = 33.9 = 34

$$S_i = q \cdot B^{0.7} \cdot \frac{I_c}{3}$$

When q is in kPa, and B in meters, the result will be in milimeters.

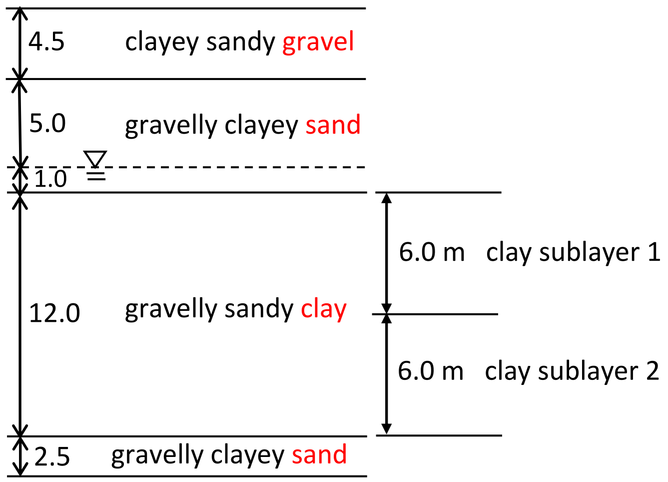
$$I_c = \frac{1.71}{(\overline{N_{60}})^{1.4}} = \frac{1.71}{(34)^{1.4}} = 0.0123$$

$$S_i = 200\ kPa \cdot (90\ m)^{0.7} \cdot \frac{0.0123}{3} = \mathbf{19.1\ mm}$$

Since Refusal N values are assumed as equal to 50, and it is probably higher than 50, this S_i value is probably an upper limit, and in reality the immediate settlement will be less than this.

c) Calculate the primary consolidation settlement of the clay layer. Since the clay layer is thick, subdivide the clay into two sublayers with equal thicknesses. Laboratory consolidation tests on undisturbed samples taken from this clay indicated that the OCR = 1.5, Cc = 0.3, Cr/Cc = 0.2, Cα/Cc=0.04, eo=0.5 and cv=16 m^2/year.

The soil profile obtained from the borehole is shown below.



Given:

OCR = 1.5

eo = 0.5

Cc= 0.3

Cr/Cc = 0.2

Cα/Cc=0.04

cv=12 m^2/year

Consolidation settlement calculations will be carried out for the mid-depth of each clay sublayer.

<u>For clay sublayer 1:</u>

At a depth of 13.5 m below ground surface:

$$\sigma'_{vo} = 9.5 \times 19 + 4 \times (20 - 10) = 220.5 \quad kPa$$

Vertical stress increase at the mid-depth of clay sublayer 1:

$$\Delta\sigma'_v = \frac{Force}{New\ enlarged\ area} = \frac{(200) \times (\frac{\pi \cdot 90^2}{4})}{\frac{\pi \cdot (90 + z)^2}{4}} = \frac{(200) \times (\frac{\pi \cdot 90^2}{4})}{\frac{\pi \cdot (90 + 13.5)^2}{4}} = 151.2 \ \ kPa$$

$$\sigma'_{vf} = \sigma'_{vo} + \Delta\sigma'_v = 220.5 + 151.2 = 371.7 \ \ kPa$$

The clay has a OCR = $\frac{\sigma'_p}{\sigma'_{vo}} = 1.5$ Therefore $\sigma'_p = 1.5 \times 220.5 = 330.8 \ kPa$

The final effective vertical stress is larger than preconsolidation pressure of clay, $\sigma'_{vf} > \sigma'_p$

$$S_c = \frac{C_r}{1+e_o} \cdot H \cdot log\frac{\sigma'_p}{\sigma'_{vo}} + \frac{C_c}{1+e_o} \cdot H \cdot log\frac{\sigma'_{vf}}{\sigma'_p}$$

$$S_c = \frac{(0.2 \times 0.3)}{1+0.5} \cdot 6 \cdot log\frac{330.8}{220.5} + \frac{0.3}{1+0.5} \cdot 6 \cdot log\frac{371.7}{330.8} = 0.0423 + 0.0608$$
$$= 0.103 \ m$$

For clay sublayer 2:

At a depth of 19.5 m below ground surface:

$$\sigma'_{vo} = 9.5 \times 19 + 10 \times (20 - 10) = 280.5 \ \ kPa$$

Vertical stress increase at the mid-depth of clay sublayer 2:

$$\Delta\sigma'_v = \frac{Force}{New\ enlarged\ area} = \frac{(200) \times (\frac{\pi \cdot 90^2}{4})}{\frac{\pi \cdot (90+z)^2}{4}} = \frac{(200) \times (\frac{\pi \cdot 90^2}{4})}{\frac{\pi \cdot (90+19.5)^2}{4}} = 135.1 \ kPa$$

$$\sigma'_{vf} = \sigma'_{vo} + \Delta\sigma'_v = 280.5 + 135.1 = 415.6 \ kPa$$

The clay has a OCR = $\frac{\sigma'_p}{\sigma'_{vo}} = 1.5$ Therefore $\sigma'_p = 1.5 \times 280.5 = 420.8 \ kPa$

The final effective vertical stress is smaller than preconsolidation pressure of clay, $\sigma'_{vf} < \sigma'_p$

$$S_c = \frac{C_r}{1+e_o} \cdot H \cdot log\frac{\sigma'_f}{\sigma'_{vo}}$$

$$S_c = \frac{(0.2 \times 0.3)}{1+0.5} \cdot 6 \cdot log\frac{415.6}{280.5} = 0.041 \ m$$

The consolidation settlement of the clay layer is:

$$S_c = 0.103 + 0.041 = \mathbf{0.144 \ m}$$

d) How long time will it take for the 95% of the primary consolidation settlement of the clay layer to occur.

Using the equation for time factor, and $T_v = 1.13$ for U=95% degree of consolidation:

$$T_v = \frac{c_v \cdot t}{d^2}$$

$$1.129 = \frac{12 \ (m^2/yr) \cdot t}{6^2}$$

t = 3.4 years

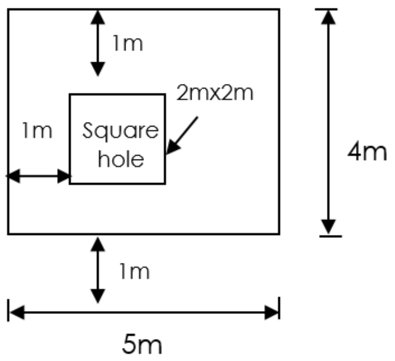
Note that the 12-m-thick clay layer has a permeable material at the top and at the bottom of it, therefore the maximum drainage distance of the clay, d = 6 m.

e) Calculate the amount of secondary consolidation settlement of the clay layer 10 years after construction of the tank.

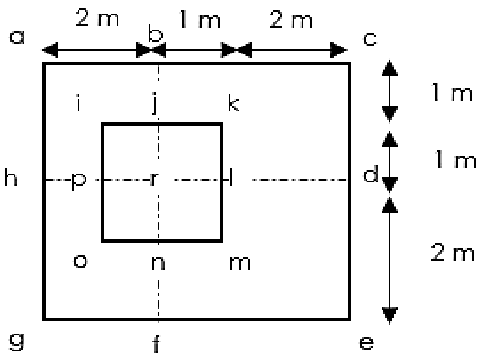
$$S_{sc} = \frac{C_\alpha}{1+e_o} \cdot H \cdot log\frac{t}{t_p} = \frac{(0.04 \times 0.3)}{1+0.5} \cdot 12 \cdot log\frac{10}{3.4} = 0.045\ m\ = \mathbf{4.5\ cm}$$

Question 2 (10%)

The figure below shows a plan view of a rectangular footing with a 2m x 2m square hole (through its entire thickness). The hole is located at 1 m from the left edge and is equally positioned between the top and lower edges of the footing. If the uniform contact pressure under the footing is 200 kPa, compute the vertical stress at a point 2m below the center of the square hole.



Solution:



For area (abrh)

z = 2 m

$$\left.\begin{matrix} mz = 2 \\ nz = 2 \end{matrix}\right\} \left.\begin{matrix} m = 2/2 = 1 \\ n = 2/2 = 1 \end{matrix}\right\} I_{r1} = 0.176$$

For area (bcdr)

$$\left.\begin{matrix} mz = 3 \\ nz = 2 \end{matrix}\right\} \left.\begin{matrix} m = 3/2 = 1.5 \\ n = 2/2 = 1 \end{matrix}\right\} I_{r2} = 0.195$$

For area (rdef)

$$\left.\begin{matrix} mz = 3 \\ nz = 2 \end{matrix}\right\} \left.\begin{matrix} m = 3/2 = 1.5 \\ n = 2/2 = 1 \end{matrix}\right\} I_{r3} = 0.195$$

For area (hrfg)

$$\left.\begin{matrix} mz = 2 \\ nz = 2 \end{matrix}\right\} \left.\begin{matrix} m = 2/2 = 1 \\ n = 2/2 = 1 \end{matrix}\right\} I_{r4} = 0.176$$

For area (ijrp)

$$\left.\begin{matrix} mz = 1 \\ nz = 1 \end{matrix}\right\} \left.\begin{matrix} m = 1/2 = 0.5 \\ n = 1/2 = 0.5 \end{matrix}\right\} I_{r5} = 0.085$$

For area (jklr)

$$\left.\begin{matrix} mz = 1 \\ nz = 1 \end{matrix}\right\} \left.\begin{matrix} m = 1/2 = 0.5 \\ n = 1/2 = 0.5 \end{matrix}\right\} I_{r6} = 0.085$$

For area (rlmn)

$$\left.\begin{matrix} mz = 1 \\ nz = 1 \end{matrix}\right\} \left.\begin{matrix} m = 1/2 = 0.5 \\ n = 1/2 = 0.5 \end{matrix}\right\} I_{r7} = 0.085$$

For area (onrp)

$$\left.\begin{matrix} mz = 1 \\ nz = 1 \end{matrix}\right\} \left.\begin{matrix} m = 1/2 = 0.5 \\ n = 1/2 = 0.5 \end{matrix}\right\} I_{r8} = 0.085$$

$$\Delta\sigma_z = \sigma \cdot I_r = 200\,[\,I_{r_1} + I_{r_2} + I_{r_3} + I_{r_4} - I_{r_5} - I_{r_6} - I_{r_7} - I_{r_8}\,]$$

$$\Delta\sigma_z = \sigma \cdot I_r = 200\,[\,2 * 0.195 + 2 * 0.176 - 4 * 0.085\,] = 200 * 0.402 = 80.4\ kPa$$

Question 3 (15%)

The following CPT data is obtained at the site**.** Plot the given data with respect to depth and identify different soil layers. Estimate the undrained shear strength of the soil at the depth of 4.0 m assuming the cone factor as N_k=18.

The soil is normally consolidated with a unit weight of $\gamma = 19kN/m^3$ to GWT at depth 3 m and $\gamma_{sat} = 20kN/m^3$ for below GWT

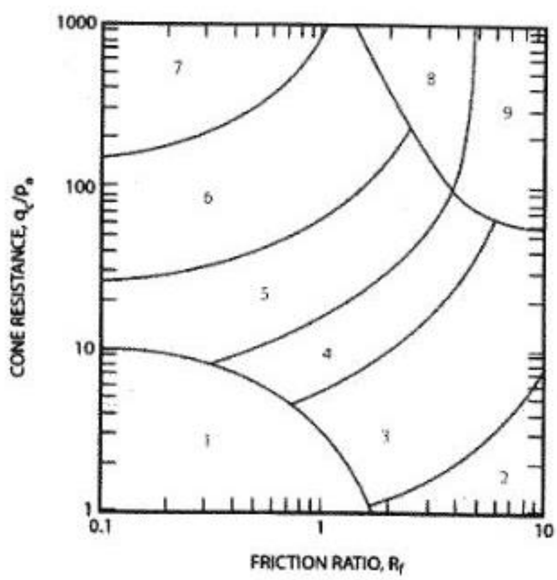
Depth (m)	**q_c (MPa)**	**q_s (kPa)**
1	0.5	20
2	0.7	31
3	1.1	55
4	1.4	42
5	0.8	35
6	0.6	27
7	0.6	27
8	0.8	24
9	0.9	45
10	1.1	22
11	1.5	15
12	2	24
13	2.2	20
14	2.6	26
15	2.7	32
16	2.1	27
17	1.8	29
18	1.6	16
19	2.6	21
20	3	30

Solution:

Depth (m)	q_c (MPa)	q_c (kPa)	q_s (kPa)	F_R (%)* [1]	Soil Classification* [2]
1	0.5	500	20	4.00	Clay-silty clay to clay
2	0.7	700	31	4.43	Clay-silty clay to clay
3	1.1	1100	55	5.00	Clay-silty clay to clay
4	1.4	1400	42	3.00	Clay-silty clay to clay
5	0.8	800	35	4.38	Clay-silty clay to clay
6	0.6	600	27	4.50	Clay-silty clay to clay
7	0.6	600	27	4.50	Clay-silty clay to clay
8	0.8	800	24	3.00	Clay-silty clay to clay
9	0.9	900	45	5.00	Clay-silty clay to clay
10	1.1	1100	22	2.00	Silt mixtures-clayey silt to silty
11	1.5	1500	15	1.00	Sand Mixtures – silty sand to
12	2	2000	24	1.20	Sand Mixtures – silty sand to
13	2.2	2200	20	0.91	Sand Mixtures – silty sand to
14	2.6	2600	26	1.00	Sand Mixtures – silty sand to
15	2.7	2700	32	1.19	Sand Mixtures – silty sand to
16	2.1	2100	27	1.29	Sand Mixtures – silty sand to
17	1.8	1800	29	1.61	Silt mixtures – clayey silt to silty
18	1.6	1600	16	1.00	Sand Mixtures – silty sand to
19	2.6	2600	21	0.81	Sand Mixtures – silty sand to
20	3	3000	30	1.00	Sand Mixtures – silty sand to

* 1: Note that; $F_R\ (\%) = \frac{q_s}{q_c} x100$

* 2: Soil classification is obtained by using Figure 2.19 in lecture notes.

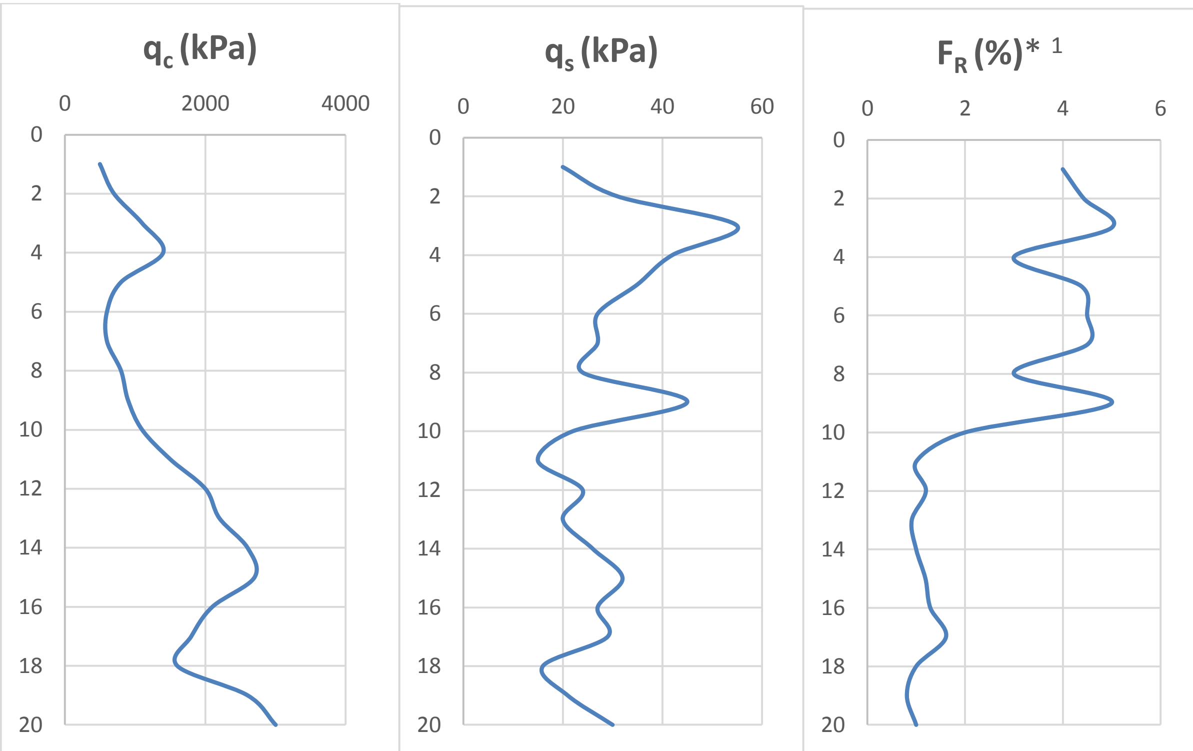


Zone	Soil Behavior Type
1	Sensitive, fine grained
2	Organic soils - clay
3	Clay – silty clay to clay
4	Silt mixtures – clayey silt to silty clay
5	Sand mixtures – silty sand to sandy silt
6	Sands – clean sand to silty sand
7	Gravelly sand to dense sand
8	Very stiff sand to clayey sand*
9	Very stiff fine grained*

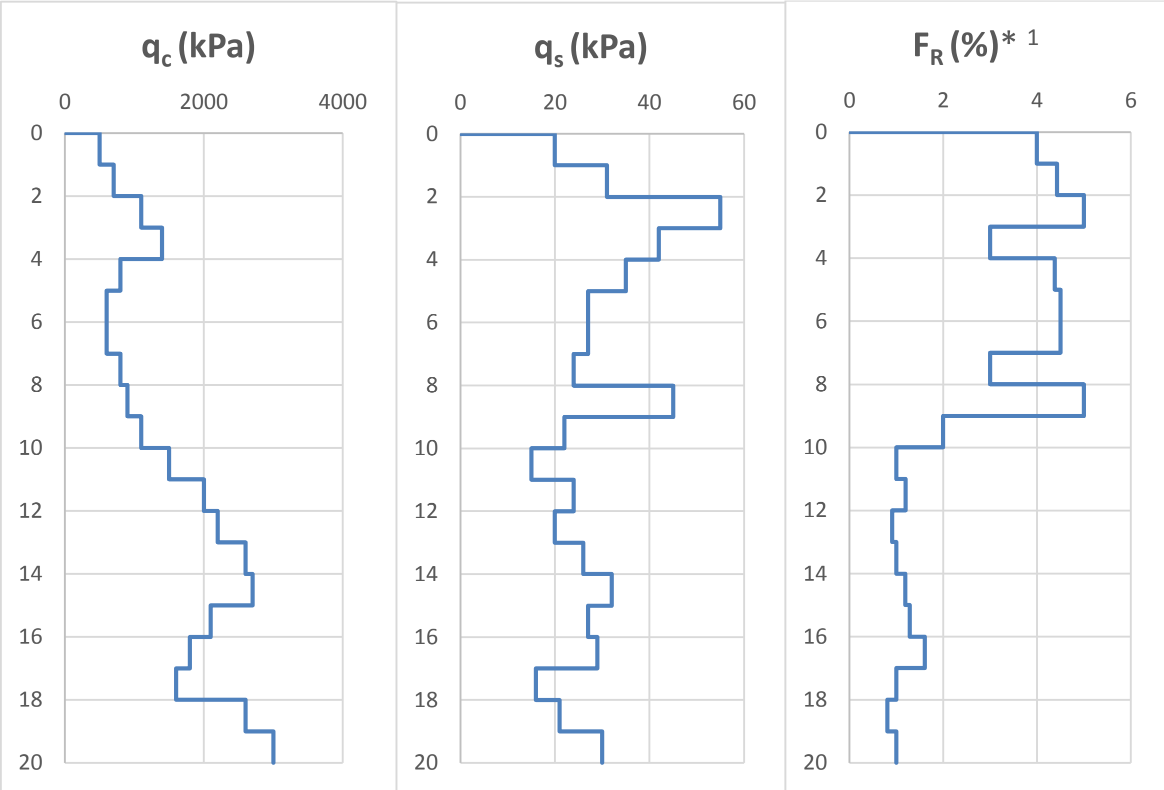
* *Heavily overconsolidated or cemented*

P_a = *atmospheric pressure* = 100 kPa = 1 tsf

Plot of the Cone Penetration Test data (CPT) is shown in below figure. In reality CPT data is continous data with depth, since in this problem we are given data in every 1 m depth, these data can be plotted in the following two ways:



Plot of the Idealized Cone Penetration Test data (CPT) is shown in below figure.



Undrained shear strength at depth 4.0 m is estimated by using formula below assuming the cone factor $N_k = 18$.

$$c_u = \frac{q_c - p_0}{N_k}$$

where; p_0 is total overburden pressure at the level of cone tip

Since $\gamma_d = 19\ kN/m^3$

$\gamma_{sat} = 20\ kN/m^3$

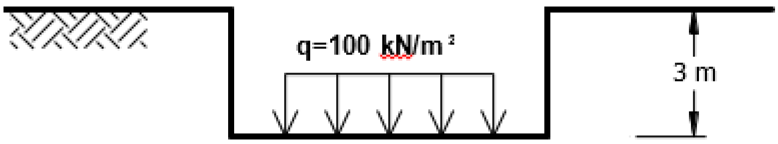
Then,

$p_0 = 3 * 19 + 20 * 1 = 77\ kPa$

$$c_u = \frac{1400 - 77}{18} = 73.5\ kPa\ (@z = 4.0\ m)$$

Question 4 (5%)

Estimate the net foundation pressure after the application of a gross foundation pressure of 100 kPa at a foundation depth of 3 meters. Unit weight of the soil can be taken as 19 kN/m^3.



$$q_{net} = q_{gross} - \sigma'_{v,0} = 100 - 19x3 = 43\ kPa$$

Question 5 (10%)

At 5 m depth, a silty sand layer was encountered and a Standard Penetration Test (SPT) was performed. For the first, second and third 15 cm increments, the blowcounts were reported as 4,7,8 blows, respectively. Safety hammer of an energy ratio of 55 % was used during the test. The borehole diameter was reported as 110 mm and the SPT sampler used was a standard sampler with constant inside diameter (no room for liner). The length of the rod from the bottom of the safety hammer to the sampler at 5 m depth was measured as 6.2 m. Estimate the overburden and procedure corrected SPT blowcounts ($N_{1,60}$) for 30 cm penetration of the sampler (water table depth is at 3 m and the unit weights of soil above and below water tables can be assumed as 18 and 19 kN/m^3, respectively)

$$N_{60} = Nx\frac{ER}{0.6}xC_BxC_SxC_R$$

$$N_{1,60} = NxC_N$$

$$N_{60} = Nx\frac{ER}{0.6}xC_BxC_SxC_R$$

$$N = 7 + 8 = 15\ blows/30\ cm$$

$$N = 15\ no\ silty\ sand\ corrcetion$$

$$Hammer\ Energy\ Ratio = 55\ \%$$

$$C_B = 1.00\ \ from\ Table\ 2.2$$

$$C_S = 1.00\ \ from\ Table\ 2.2\ (standard\ sampler)$$

$$C_R = 0.95\ \ from\ Table\ 2.2$$

$$N_{60} = 15x\frac{0.55}{0.6}x1.00x1.00x0.95 = 13\; blows/30\; cm$$

$$\sigma_v' = 3x18 + 2x(19 - 10) = 72\; kPa$$

$$C_N = 9.78\sqrt{\frac{1}{\sigma_v'(\frac{kN}{m^2})}} = 9.78\sqrt{\frac{1}{72}} = 1.15$$

$$N_{1,60} = N_{60}xC_N = 13x1.15 = 15\; blows/30\; cm$$

Table 2.1 SPT Hammer Efficiencies (Adopted from Clayton, 1990)

Country	Hammer Type	Hammer Release Mechanism	Hammer Efficiency, ER
Argentina	Donut	Cathead	0.45
Brazil	Pin Weight	Hand Dropped	0.72
China	Automatic	Trip	0.60
	Donut	Hand Dropped	0.55
	Donut	Cathead	0.50
Colombia	Donut	Cathead	0.50
Japan	Donut	Tombi trigger	0.78 - 0.85
	Donut	Cathead 2 turns + special release	0.65 - 0.67
UK	Automatic	Trip	0.73
USA	Safety	2 turns on cathead	0.55 - 0.60
	Donut	2 turns on cathead	0.45
Venezuella	Donut	Cathead	0.43
Turkey*	Donut	Cathead 2 turns	0.45

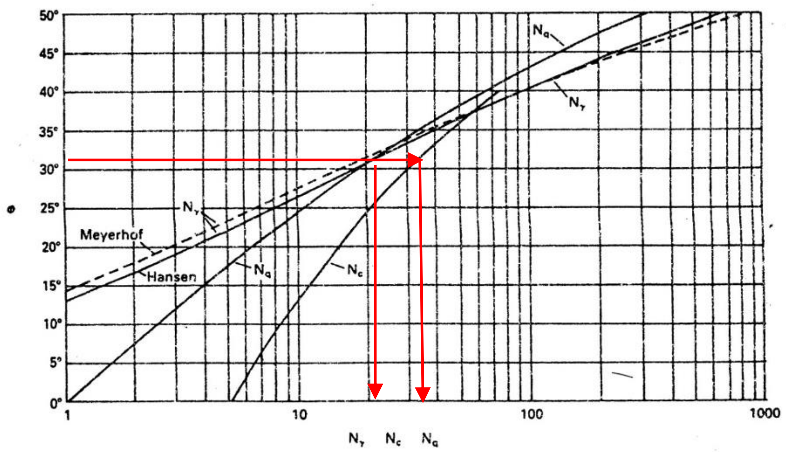
* Sivrikaya, O. and Toğrol, E. (2006)

Table 2.2 SPT Correction Factors (Robertson and Wride, NCEER 1997 Workshop)

Factor	Equipment Variables	Correction
Borehole diameter factor, C_B	65 - 115 mm	1.00
	150 mm	1.05
	200 mm	1.15
Sampling method factor, C_S	Standard sampler	1.00
	Sampler without liner	1.20
Rod length factor, C_R	3 m to 4 m	0.75
	4 m to 6 m	0.85
	6 m to 10 m	0.95
	10 m to 30 m	1.00
	> 30 m	<1.00

Question 6 (10%)

A square footing is 3 m by 3 m in plan. The sandy soil supporting the foundation has a friction angle of $\phi = 32^0$ and c= 0 kPa. The unit weight of soil, γ, is 18.5 kN/m^3. Determine the safe net load on the foundation with a factor of safety 3. Assume that the foundation depth is 2 meters, ground water table is well below the foundation depth, and that a general shear failure occurs in the soil.



$q_{f,gross} = (0.4).\gamma.B.N_\gamma + (1.2).c.N_c + \gamma.D.N_q$

For $\phi = 32^0 \rightarrow N_\gamma = 21$ and $N_q = 21$

$q_{f,gross} = (0.4) \times 18.5 \times 3 \times 21 + 0 + 18.5 \times 2 \times 21 = 1243.2$ kPa

$q_{f,net} = q_{f,gross} - \gamma.D = 1243.2 - 18.5 \times 2 = 1206.2$ kPa

$L_{f,net} = 1206.2 \times 3 \times 3 = 10855.8$ kN

Safe net load = $(L_{f,net})_{safe} = 10855.8/3 = 3618.6$ kN

Settlement may govern the response

Question 7 (25%)

A bearing wall carries a total load 220kN/m. It is to be supported on a 0.4 m deep continuous footing. The underlying soil is a medium dense sand with c'= 0, φ′= 37°, γ=19.2 kN/m^3. The groundwater table is at a great depth.

Compute the minimum footing width required to maintain a factor of safety of at least 2 against a bearing capacity failure. (Express your answer to the nearest 0.1 m.)

Solution

Use Terzaghi's method, Bearing capacity factors,

Using their equations:

$$N_q = (e^{\pi \cdot tan\varphi}) \cdot tan^2\left(45 + \frac{\varphi}{2}\right) = (e^{\pi \cdot tan37}) \cdot tan^2\left(45 + \frac{37}{2}\right) = 42.9$$

$$N_c = \left(N_q - 1\right) \cdot cot\varphi = (42.9 - 1)cot37 = 55.6$$

$$N_\gamma = 1.8 \cdot \left(N_q - 1\right) \cdot tan\varphi \quad (Hansen) \ = 1.8 \cdot (42.9 - 1) \cdot tan37 = 56.8$$

Or reading from Fig. 4.3.

N_c=54

N_q=41

N_γ=54 (Hansen)

overburden stress, σ=19.2 x 0.4 = 7.68 kPa

unit bearing capacity

$$q_f = (1/2)*(19.2)B(54)+(0)54+7.68(41) = 315+518B$$

$$q_{nf} = q_f - \gamma D = 315 + 518B - 19.2(0.4) = 307.32 + 518B$$

Allowable bearing capacity is

$q_n = q_{nf}$ / F = (307.32+518B) / 2 =153.66+259B

Compute required footing width, B

$$q \leq q_{n,all}$$

$$(P+Wfooting) \leq 153.66+259B$$

$$(220+24*(B)*0.4)/B = 153.66+259B$$

$$B \approx 0.68\ m$$

Therefore use B = 0.70 m