CE444: Geotechnical Design

Homework Assignment #4

February 15th, 2026

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Problem 1.

A 6-story reinforced concrete frame structure is to be supported on a 1.2 m thick mat foundation. The building is rectangular with a width of 30 m and a length of 50 m. The total dead plus live load on the mat foundation is 125 MN (excluding weight of mat foundation). The building will have a basement and the top surface of the mat foundation will be 5.6 m below the existing ground surface. Concrete total unit weight is γc = 24 kN/m3. Calculate the total settlements immediately after construction and 30 years after construction.

Subsurface Investigation: Subsurface condition is shown in the following boring log performed at the center of the building plan. Ground water table was encountered at depth of 4.8 m. Competent bedrock was encountered at depth of 14.8 m. The energy ratio for the SPT tests was 50%, the hole diameter was 150 mm and the "standard sampler" was used. For applying rod length corrections, assume that the rod length is equal to the depth. Assume total unit weight (above and below GWT) of γ = 17 kN/m3 for the entire soil profile. Extract N values from the mid-depth of each SPT. Apply corrections to Nmeasured if needed proposed by Burland and Burbidge (1985). Convert N values to N60.

Hint: On application of silt and gravel correction factors to SPT N values when using the Burland and Burbidge (1985) method (Page 14 in Handout #2)

The boring log describes the 1st soil layer under the foundation (depth 6.8 m to 8.8 m) and the 3rd soil layer (depth 11.8 m to 14.8 m) as SAND with adjectives like "slightly" silty and gravelly. You can use your engineering judgment to decide if you should apply the silt correction factor. There is no one correct answer. The 2nd soil layer (depth 8.8 m to 11.8 m) is clearly described as SILT and it is below the water table, so you should apply the SILT correction factor (you will notice that since N_measured<15, you will end up using N=N_measured).

Correct answers:

- Total qb at the base of foundation =112.1 kPa
- Avg N60 over the depth of influence = 7.9
- Sand starts OC and ends NC

- Total settlement after 30 years, w = 6.9 cm

Borehole Progress: Flush ret. %	W.D. [m]	Date	Depth [m]	Graphic Symbol	Strata Description	Datum	Test No.	Test Records: N	Seating Drive	Blwct 1	Blwct 2	Sample/ Test No.	Rock Core Quality: TCR [%]	SCR [%]	RQD [%]
		03/02	0.0		0.00 m to 1.00 m - Light brown, slightly silty, gravelly, fine to coarse, silcieous carbonate SAND, with occasional shell fragments. Gravels of calcarenite are fine to coarse.	6.0						B1 (0.00–1.00)			
			1.0		1.00 m to 3.80 m - Loose to medium dense, offwhite to light brown, slightly gravelly, slightly shelly, fine to coarse, siliceous carbonate/carbonate SAND, with fragments of calcarenite.	5.0	SPT2 (1.00–1.45)	38	10	14	24				
			2.0			4.0	SPT3 (2.00–2.45)	9	4	4	5				
			3.0			3.0	SPT4 (3.00–3.45)	12	6	6	6				
			4.0		3.80 m to 4.70 m - Extremely weak to very weak, offwhite, medium to thickly bedded, calcareous SANDSTONE, partially to distinctly weathered. from 3.80 m to 4.70 m - Non intact core.	2.0						RC1 (3.80–4.80)	100	0	0
60			5.0		4.70 m to 6.80 m - Stiff to very stiff, offwhite, slightly sandy, calcareous SILT.	1.0						RC2 (4.80–5.80)	50	0	0
60			6.0			0.0	SPT5 (5.80–6.25)	20	10	11	9				
			7.0		6.80 m to 8.80 m - Loose to medium dense, grey to light reddish grey, slightly silty to silty, gravelly, SAND. Gravels are fine to coarse, sub-rounded to sub-angular.	-1.0	SPT6 (6.80–7.25)	9	3	3	6				
			8.0			-2.0	SPT7 (7.80–8.25)	15	6	7	8				
			9.0		8.80 m to 11.80 m - Stiff, light to dark brown, slightly sandy, slightly gravelly, clayey SILT. Gravels are fine to coarse, angular to sub-angular.	-3.0	SPT8 (8.80–9.25)	10	5	4	6				
			10.0				SPT9								

BORING LOG BH-5279-15

Flush ret. %	W.D. [m]	Date	Depth [m]	Strata Description	Datum	Test No.	N	Seating Drive	Blwct 1	Blwct 2	Sample/Test No.	TCR [%]	SCR [%]	RQD [%]
			10.0	8.80 m to 11.80 m - Stiff, light to dark brown, slightly sandy, slightly gravelly, clayey SILT. Gravels are fine to coarse, angular to sub-angular.	-4.0	9.80 SPT9 10.25	9	6	5	4				
			11.0		-5.0	10.80 SPT10 11.25	9	4	4	5				
	5.91	04/02	12.0	11.80 m to 14.80 m - Very loose to loose, light to dark brown, silty, slightly gravelly, SAND. Gravels are fine to coarse, angular to sub-rounded.	-6.0	11.80 SPT11 12.25	8	3	6	2				
			13.0		-7.0	12.80 SPT12 13.25	5	3	2	3				
			14.0		-8.0	13.80 SPT13 14.25	9	3	5	4				
60			15.0	14.80 m to 22.20 m - Extremely weak to very weak, dark brown to dark reddish brown, very thickly bedded, GYPSUM, with occasional limestone, partially to distinctly weathered. Very close to medium spaced, horizontal to sub-horizontal fractures.	-9.0						14.80 RC3 15.10	100	100	100
60			16.0	from 16.20 m to 16.40 m - Non intact core.	-10.0						15.10 RC4 16.20	100	86	82
50			17.0		-11.0						16.20 RC5 17.70	80	50	47
0			18.0	from 17.70 m to 17.95 m - Non intact core.	-12.0						17.70 RC6 18.50	100	69	45
0			19.0	from 18.80 m to 19.10 m - Non intact core.	-13.0						18.50 RC7 20.00	90	70	67
			20.0	from 19.75 m to 20.00 m - Non intact core.										

BORING LOG BH-5279-15 (CONTINUED)

GIVEN:

A 6-story RC frame structure is to be supported on a mat foundation 1.2 m thick. The structure is width 30 m and length 50 m. The DL+LL on the foundation is 125 MN. The building will have a basement and the top surface of the foundation is depth 5.6 m from ground surface.

Boring hole logs are given from 0 to 20 m of depth. The groundwater table was encountered at depth 4.8 m. Bedrock was hit at depth 14.8 m. The energy ratio for the SPTs was 50% with a borehole diameter of 150 mm. A 'standard sampler' was used. Additionally, assume the following:

- γ_c = 24 kN/m^3
- Rod length is equal to depth
- γ = 17 kN/m^3 regardless of saturation

FIND:

PART A

Determine N_{60} values from mid-depth of each SPT applying corrections via Burland & Burbidge (1985) and energy correction methods.

PART B

Determine the total settlements immediately after construction and 30 years after construction.

SOLUTION:

PART A

Given that the top of the foundation is at 5.6 m and that the foundation is 1.2 m thick, it is assumed that soil above depth 6.8 m will be excavated. That means our first sublayer is in a sand that is considered 'slightly silty to silty, gravelly'. The groundwater has already been encountered. In the sublayer from depths 6.8 m to 8.8 m (also known as Sublayer 1) and the sublayer from depths 11.8 m to 14.8 m (also known as Sublayer 3), the Burland & Burbidge (1985) correction will not be used. In the sublayer from depths 8.8 m to 11.8 m (also known as Sublayer 2) the Burland & Burbidge (1985) will be used. The Burland & Burbidge (1985) correction is as follows.

$$N = \begin{cases} N_{measured} & \text{for } N_{measured} \leq 15 \\ 15 + \frac{N_{measured}-15}{2} & \text{for } N_{measured} > 15 \end{cases}$$

The mid-depth SPTs for each sublayer is SPT7 for Sublayer 1, SPT9 for Sublayer 2, and SPT12 for Sublayer 3. No other sublayers after Sublayer 3 have SPT data, so Sublayer 3 is our final considered sublayer.

Multiple factors are required to get N_{60}. To get the energy correction factor, C_h, the following relationship is used.

$$C_h = \frac{\text{Energy Ratio}}{60\%} = \frac{0.5}{0.6} = \frac{5}{6}$$

Assuming the rod length is equal to depth, the following relationship is used to get the rod length correction factor, C_r.

$$C_r = \begin{cases} 0.75 & \text{for rod length} < 4\ m \\ 0.85 & \text{for } 4\ m \leq \text{rod length} < 6\ m \\ 0.95 & \text{for } 6\ m \leq \text{rod length} < 10\ m \\ 1 & \text{else} \end{cases}$$

Since a standard sampler was used, the sampler correction factor, C_s is equal to 1. The borehole diameter correction factor, C_d is known to be 1.05 for borehole diameters equal to 150 mm.

These correction factors and the gathered N values can be used to obtain N_{60} using the following relationship.

$$N_{60} = C_h C_r C_s C_d N$$

N_{60} values, the factors, and SPTs used are then tabulated in **Table R1.**

PART B

To start this problem, it is important to define parameters of the foundation. This is done in **Table S1**.

B [m]	L [m]	Thickness [m]	γ [kNm^{-3}]
30	50	1.2	24

Table S1. Foundation parameters.

The top of the foundation is located at depth 5.6 meters. This means that a total of 5.6 m plus 1.2 meters of soil will be removed, putting the bottom of the foundation at depth 6.8 m. The stiff layer is gypsum is encountered at depth 14.8 m, making the value of H equal to 14.8 m minus 6.8 m, equaling 8.0 meters.

The value of q_b is found by summing the stress from the point load and the stress from the self weight of the foundation. This results in the below calculation.

$$q_b = \frac{Q}{BL} + \gamma \times \text{Thickness} = \frac{125MN(1000\frac{kN}{MN})}{30\ m \times 50\ m} + 24\ kNm^{-3} \times 1.2\ m = 112.13kPa$$

In order to define soil parameters, it is important to calculate the depth of influence. Keeping units in meters allows for the reference length, L_R, to be equal to 1 meter. The depth of influence, z_{f0}, is calculated in the following relationship.

$$z_{f0} = L_R\left(\frac{B}{L_R}\right)^{0.79} = 1\ m\left(\frac{30\ m}{1\ m}\right)^{0.79} = 14.69\ m$$

Now that the depth of influence is calculated, the averaged value of N_{60} across the depth of influence (i.e. the value of $\overline{N_{60}}$) can be obtained. By repeating the analysis found for **Part A** for all SPTs in the depth of influence, the value of $\overline{N_{60}}$ can be obtained.

SPT	z [m]	N_{60}
6	6.800000	7.481250
7	7.800000	12.468750
8	8.800000	8.312500
9	9.800000	7.481250
10	10.800000	7.875000
11	11.800000	7.000000
12	12.800000	4.375000
13	13.800000	7.875000
=AVG()	14.69	7.9

Table S2. Obtaining $\overline{N_{60}}$

Now that $\overline{N_{60}}$ is found, we can use the given information to begin calculating the value of the the many factors involved.

$$I_c = \frac{1.71}{\overline{N_{60}}^{1.4}} = \frac{1.71}{7.9^{1.4}} = 0.09539$$

Compressibility Index Eqn.

$$f_s = \left(\frac{1.25\frac{L}{B}}{\frac{L}{B} + 0.25}\right)^2 = \left(\frac{1.25\frac{50\ m}{30\ m}}{\frac{50\ m}{30\ m} + 0.25}\right)^2 = 1.18147$$

Shape Factor Eqn.

$$f_L = \begin{cases} \frac{H}{z_{f0}}\left(2-\frac{H}{z_{f0}}\right) & \text{if } H \leq z_{f0} \\ 1 & \text{else} \end{cases} \Rightarrow \frac{8\ m}{14.69\ m}\left(2-\frac{8\ m}{14.69\ m}\right) = 0.79271$$

Layer Thickness Factor Eqn.

$$f_t = 1 + R_{3yrs} + R_t \log\left(\frac{t\ [\text{yrs}]}{3\text{yrs}}\right)$$ *Time Factor Eqn.*

Note:

$$R_{3yrs}, R_t = \begin{cases} 0.3,\ 0.2 & \text{under static loading} \\ 0.7,\ 0.8 & \text{under fluctating/dynamic loading} \end{cases}$$

For both cases, I_c, f_s, and f_L are equal. The loading is static. Therefore, in the case of immediate settlement, f_t is equal to 1. On the other hand, in the case where 30 years of settlement are considered, f_t is equal to 1.5.

Before settlement may be calculated, it is important to determine what case the settlement falls under.

$$\text{Case} = \begin{cases} q_b < \sigma'_{vp}|_{z_f=0} & \text{OCOC} \\ q_b > \sigma'_{vp}|_{z_f=0} & \text{OCNC} \\ \text{else assume} & \text{NC} \end{cases}$$

The preconsolidation stress at the bottom of the footing, $\sigma'_{vp}|_{z_f=0}$ (which may also be called as σ'_{pf}), is equal to the vertical effective stress of the excavated soil. That soil is assumed to have been the only load on the site, meaning it's effective stress is the only weight the soil at that depth has felt. The value of σ'_{pf} is found with the following relationship.

$$\sigma'_{pf} = \gamma_s z_{excav} - \gamma_w(z_{excav} - z_w) = 17kNm^{-3}(6.8\ m) - 9.81kNm^{-3}(6.8\ m - 4.8\ m) = 95.98kPa$$

Based on the values obtained from calculation, this foundation is an OCNC case. OCNC settlement cases follow the below relationship for settlement. Values for settlement under time 0 (i.e. immediate settlement) and 30 years are then calculated.

$$w = L_R\left[0.10 f_s f_L f_t I_c \left(\frac{B}{L_R}\right)^{0.7}\right]\frac{q_b - \frac{2}{3}\sigma'_{pf}}{P_a}$$

RESULTS:

PART A

SPT	Depth [m]	N_{meas}	N	C_h	C_s	C_d	C_r	N_{60}
7	7.8	15	15	5/6	1.00	1.05	0.95	12.46875
9	9.8	9	9	5/6	1.00	1.05	0.95	7.48125
12	12.8	5	5	5/6	1.00	1.05	1.00	4.37500

Table R1. Tabulated results for mid-depth N_{60} and the factors for obtaining N_{60}.

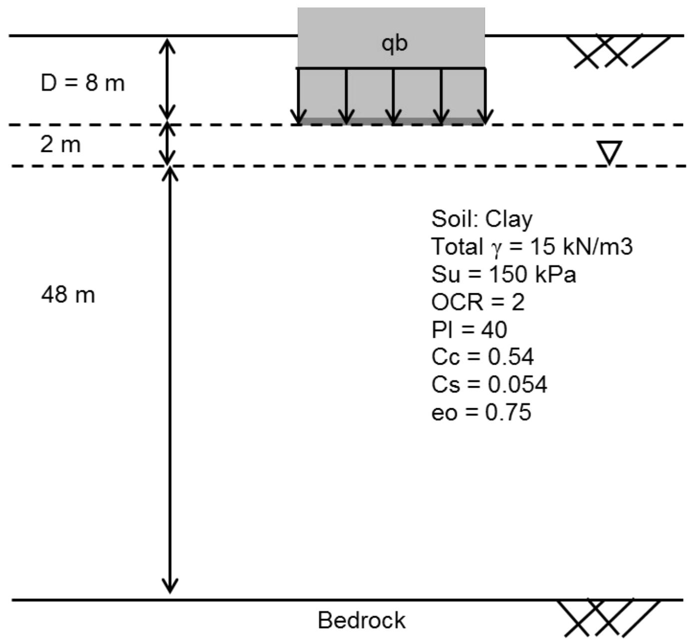
PART B

The immediate settlement is equal to 0.047 m (i.e. 4.7 cm). The settlement in 30 years is equal to 0.079 m (i.e. 7.9 cm).

Problem 2.

A uniform bearing pressure of 250 kPa is applied at the bottom of an 8 m deep basement excavation that is 30 m wide and 100 m long. Estimate (a) net immediate settlements using Janbu et al. (1956), (b) net consolidation settlement, (c) sum of immediate and consolidation settlements due to net load.

- Use correlations by Duncan and Buchignani (EPRI 1990 Figure 5-6) to estimate elastic soil modulus (Es).
- For calculating the consolidation settlement, break the clay layer into a number of sublayers (to be consistent let's all use 4 sublayers). Calculate the induced stress ($\Delta\sigma_v$) in the middle of each sublayer using the approximate 2:1 method. Apply the correction factor for 3D consolidation assuming Skempton A value of 0.4 at failure.



Hints:

- When calculating the consolidation settlement in clay, make sure to only consider the saturated portion of the clay layer, i.e. ranging from 10 m to 58 m depth.
- Note that Zf is the depth from the base of the foundation.
- When calculating alfa to apply 3D adjustment for consolidation settlement, you may simply use the value corresponding to the strip footing in Table 9-4 in Salgado (i.e. alpha=0.3). You may choose a slightly different value if you use interpolation.

Correct answers:

- K = 400 but other values could be correct (in calculating Eu)
- q_b^{net} = 130 kPa
- The first row of the table for consolidation settlement calculation is copied below:

Sublayer	Top Depth (m)	Mid Depth (m)	Bottom Depth (m)	Sublayer thickness, H0 (m)	σvo (kPa)	PWP (kPa)	σ'vo (kPa)	OCR	σ'vp (kPa)	Zf (m) = Depth from base of footing	Δσv (kPa) = (qb^{net}*B*L)/[(B+Zf)*(L+Zf)]	σ'vf (kPa) = σ'vo+Δσv	Case #	ε	ΔH (m) =H0*ε
1	10	16	22	12	240	58.9	181.1	2	362.3	8	95.0	276.2	Case 2	0.00565	0.068

GIVEN:

A soil profile of all clay is given. A 30 m by 100 m foundation with a uniform bearing pressure of 250 kPa is applied at the bottom of a basement at depth 8 m. The saturated clay layer is to be broken into four sublayers with Skempton's A equal to 0.4. Use the 2:1 method.

FIND:

PART A

Determine the net immediate settlement.

PART B

Determine the net consolidation settlement.

PART C

Determine the net total settlement.

SOLUTION:

PART A

The net bearing pressure to be considered, q_b^{net}, is found to be equal to the following.

$$q_b^{net} = \Delta\sigma_v - \sigma'_{excav} = 250kPa - 15kNm^{-3}(8m) = 130kPa$$

Using Janbu et al. (1956), the I_0 and I_1 factors may be graphically interpreted.

$$\frac{D}{B} = \frac{8\ m}{30\ m} \approx 0.3 \Rightarrow I_0(0.3) = 0.95 \qquad \textit{I_0 via Janbu et al. (1956)}$$

$$\frac{L}{B},\ \frac{H}{B} = \frac{100\ m}{30\ m},\ \frac{50}{30} \approx 3.3,\ 1.7 \Rightarrow I_1(3.3, 1.7) = 0.575 \qquad \textit{I_1 via Janbu et al. (1956)}$$

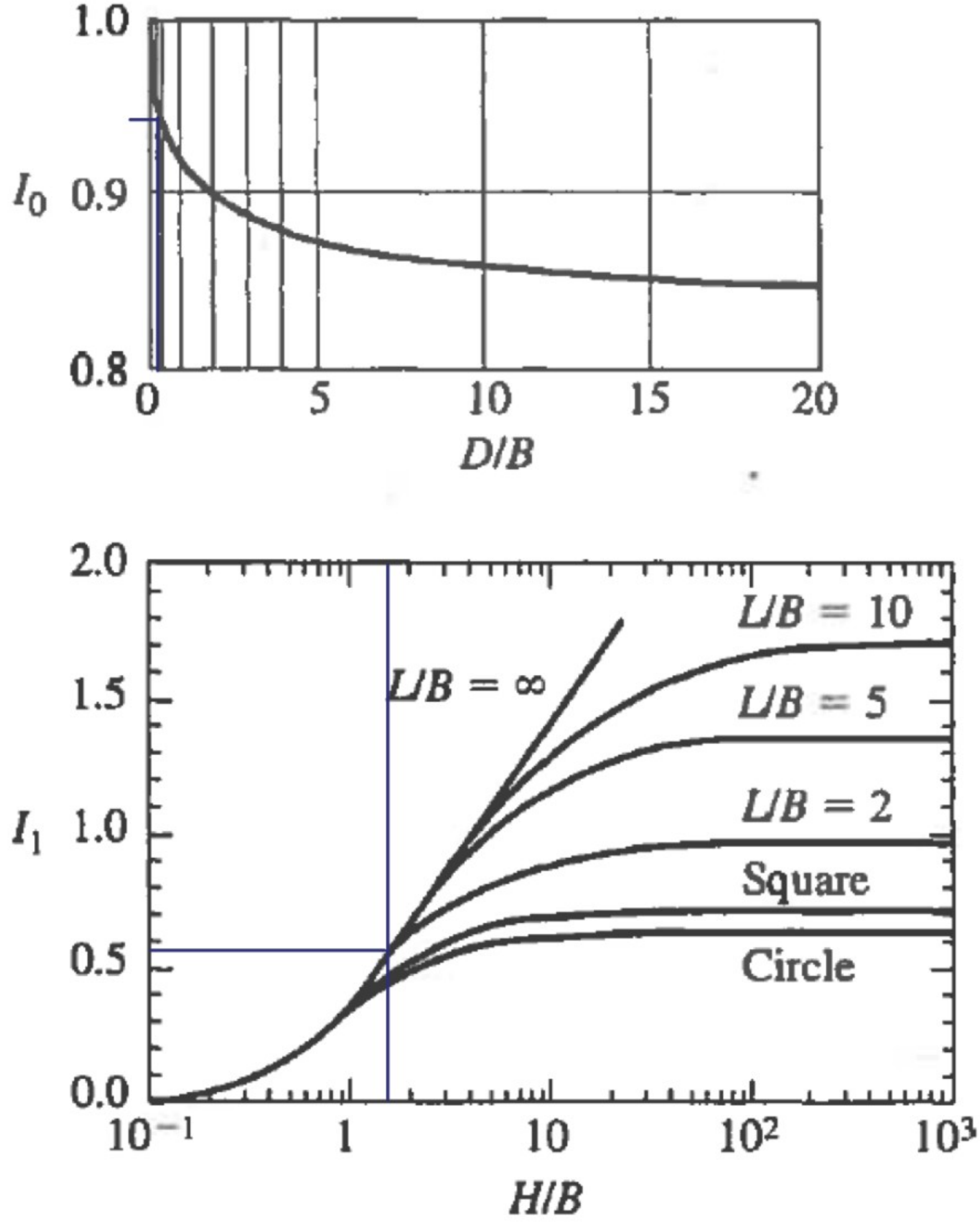


Figure S1. Janbu et al. (1956) with annotation.

It is known that the OCR of the clay is equal to 2 and that the PI is 40. The value of the elastic modulus of soil, E_u, can be obtained using Duncan and Buchignani (1990). This results in a value of K equal to 400.

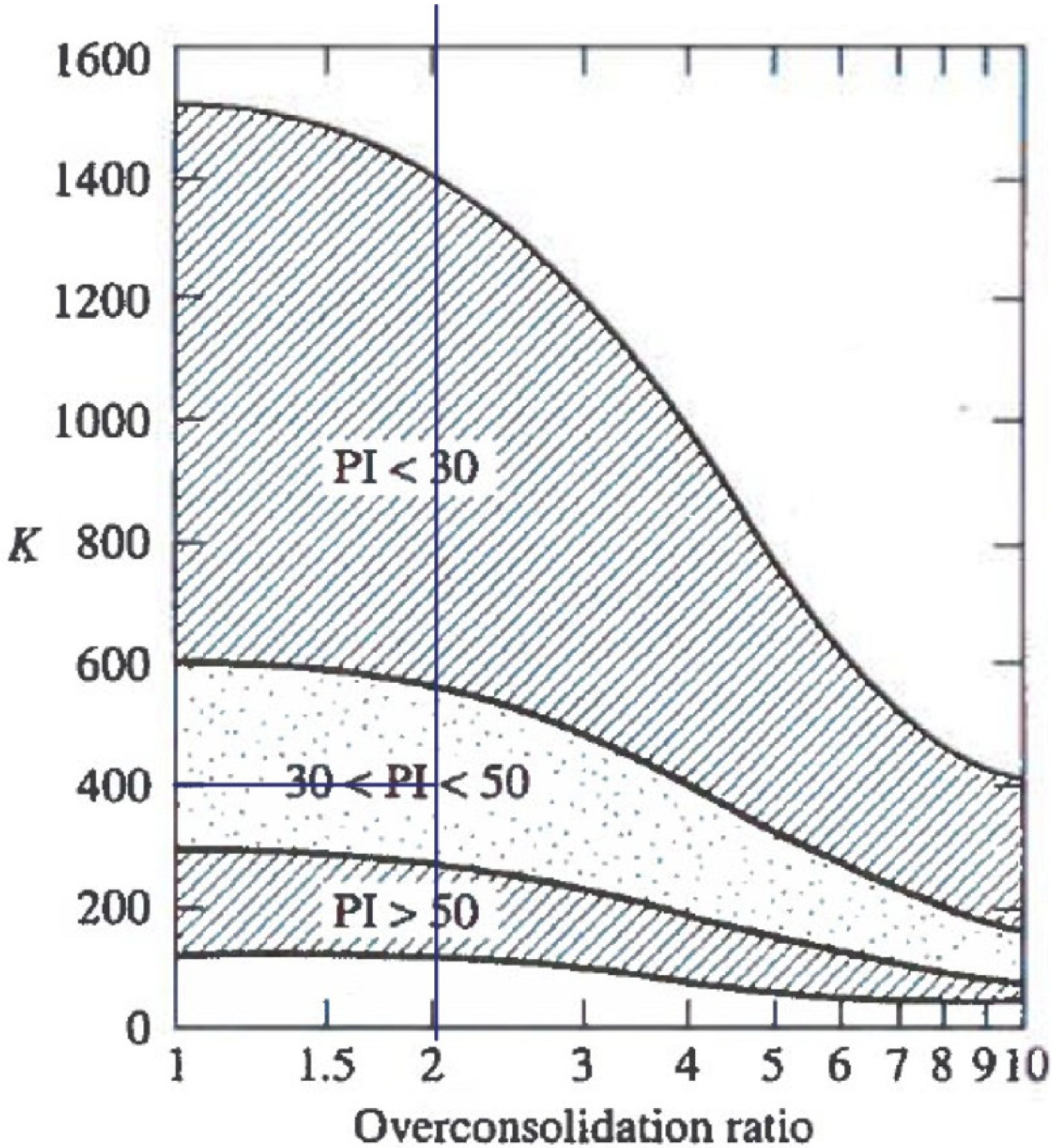


Figure S2. Duncan and Buchignani (1990) with annotation.

The value of E_u can then be obtained with the following relationship from Duncan and and Buchignani (1990).

$$E_u = KS_u = 400(150\ kPa) = 60000\ kPa$$

The net immediate settlement can then be calculated using the following relationship from Janbu et al. (1956).

$$w_i = I_0 I_1 \frac{q_b^{net} B}{E_u} = 0.95 \times 0.575 \left(\frac{130\ kPa(30\ m)}{60000\ kPa} \right)$$

PART B

Since only fully saturated clay can consolidate, the clay layer from depth 10 m to 58 m is to be broken up into four, 12 m sublayers. The midpoints of these sublayers are thus equal to the following.

$$\vec{z} = \{16, 28, 40, 52\}^T\ m$$

The initial vertical effective stress at these mid-depth points (also known as mid-points) is equal to the following.

$$\overrightarrow{\sigma'_{v0}} = \gamma_s \vec{z} - \gamma_w (\vec{z} - z_w)$$

$$\overrightarrow{\sigma'_{v0}} = (15kNm^{-3}\{16, 28, 40, 52\}^T\ m) - 9.81kNm^{-3}(\{16, 28, 40, 52\}^T\ m - 10m)$$

$$\overrightarrow{\sigma'_{v0}} = \{181.1, 243.4, 305.7, 368.0\}^T\ kPa$$

The preconsolidation stresses at mid-points can be obtained using the following relationship.

$$\overrightarrow{\sigma'_{vp}} = OCR \times \overrightarrow{\sigma'_{v0}} = 2 \times \{181.1, 243.4, 305.7, 368.0\}^T\ kPa = \{362.3, 486.8, 611.4, 736.0\}\ kPa$$

The additional vertical effective stress can be obtained per mid-points via the 2:1 method, as follows and then compiled into a vector.

$$\Delta\sigma'_v(z) = \frac{q_b^{net} BL}{(B + (z - D))(L + (z - D))}$$

z [m]	$\Delta\sigma'_v$[kPa]
16	95.0
28	65.0
40	47.7
52	36.6

$$\Rightarrow \overrightarrow{\Delta\sigma'_v} = \{95.0, 65.0, 47.7, 36.6\}^T\ kPa$$

The final vertical effective stress can then be found by summing the additional vertical effective stress with the initial vertical effective stress.

$$\overrightarrow{\sigma'_{vf}} = \overrightarrow{\sigma'_{v0}} + \overrightarrow{\Delta\sigma'_{v}} = \{181.1, 243.4, 305.7, 368.0\}^T\ kPa + \{95.0, 65.0, 47.7, 36.6\}^T\ kPa$$

$$\overrightarrow{\sigma'_{vf}} = \{276.2, 308.4, 353.4, 404.6\}^T\ kPa$$

Before settlement may be calculated, it is important to determine what case the settlement falls under.

$$\text{Case} = \begin{cases} OCR = 1 \text{ or } \sigma'_{v0} = \sigma'_{vp} & \text{NC} \\ \sigma'_{v0} < \sigma'_{vf} < \sigma'_{vp} & \text{OCOC} \\ \sigma'_{v0} < \sigma'_{vp} < \sigma'_{vf} & \text{OCNC} \end{cases}$$

For all mid-points, it is determined that the OCOC settlement case is true. This means that 1D consolidation settlement can be calculated per mid-point in the following relationship. H_0 is defined as the sublayer depths, which is equal to 12 m. e_0 and C_r are given in the soil profile.

$$w_{c,1D} = \frac{H_0}{1+e_0}\left[C_r \log(\frac{\sigma'_{vf}}{\sigma'_{v0}})\right]$$

z [m]	σ'_{v0} [kPa]	σ'_{vf} [kPa]	$w_{c,1D}$ [m]
16	181.1	276.2	0.0678
28	243.4	308.4	0.0381
40	305.7	353.4	0.0233
52	368.0	404.6	0.0152

$$\Rightarrow \overrightarrow{w_{c,1D}} = \{0.0678, 0.0381, 0.0233, 0.0152\}^T\ m$$

Skempton's μ is then used to convert the 1D consolidation to 3D consolidation. Skempton's μ is found via the following results. Skempton's α was found via linear interpolation.

$$\mu = A + \alpha(1 - A) = 0.4 - 0.29667(1 - 0.4) = 0.578002$$

Then, via the following relationship, the vector of 3D consolidation settlement is found.

$$\overrightarrow{w_{c,3D}} = \mu\overrightarrow{w_{c,1D}} = 0.578002\{0.0678, 0.0381, 0.0233, 0.0152\}^T\ m = \{0.0392, 0.0220, 0.0135, 0.0088\}^T\ m$$

The sum of the elements within $\overrightarrow{w_{c,3D}}$ is equal to the net consolidation settlement.

PART C

The sum of the net immediate settlement and net consolidation settlement is equal to the net settlement under the calculated net load.

RESULTS:

PART A

The net immediate settlement is equal to 0.0355 m, or 3.55 cm.

PART B

The net consolidation settlement is equal to 0.0835 m, or 8.35 cm.

PART C

The sum of settlement under the net bearing pressure is equal to 0.1190 m, or 11.90 cm.