Exam Code (Individual)……………………..

EXAM: BOM325 & BOM370 HYDROGEOLOGY AND GEOTECHNICS

Date: January 15, 2022
Time: 14:00-18:00
Location: Samhällsbyggnadsteknik

☎ phone 031-7721853 (Ayman Abed)

REFERENCE LITERATURE ETC.

Help allowed:	Chalmers approved calculator, compass, protractor, ruler, and a dictionary if desired. **No literature or notes. In addition to the exam paper, a semi-logarithmic graph paper is provided.**
PREL. GRADING LIST	Published on course home page Friday 4 February 2022 the latest, without bonus points (to enable anonymous marking). **Remember your exam code to be able to read the list.**
GRADING OF TASKS	At each problem the maximum points are indicated within parenthesis e.g. (10).
GRADING LIMITS	Exam contains 5 questions with 25 points each.

<u>Only answer 4 questions out of 5.</u>

You can answer in Swedish or English.

Total sum 100 points. Bonus points from coursework count in January exam only, and will be added before submitting grades to Ladok.

<50 points	Fail
50-59 points	Grade 3
60-74 points	Grade 4
>75 points	Grade 5

Note!

Any figures or calculations used for the solutions **shall** be shown in the solutions.

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Q1 – Aquifer properties and stationary flow (25 points)

Part 1 (20p):

The following table contains the positions (x,y) of three wells in the same aquifer, along with their location elevations (z) and the distances between well head and water level (s):

Well	x [m]	y [m]	z [m]	s [m]
1	0	0	125	10
2	100	200	112	14
3	400	0	105	15

(a) You are asked to:

- Evaluate the **hydraulic height** in each well. (3p)

  $h = z - s$

  Well 1: $h_1 = 125 - 10 = 115$ m

  Well 2: $h_2 = 112 - 14 = 98$ m

  Well 3: $h_3 = 105 - 15 = 90$ m

- Evaluate the **hydraulic gradients** between **well 1** and the **other wells**. (2p)

  $i = \Delta h/\Delta L$

  Hydraulic gradient between well 1 and well 2:

  $$i_{12} = \frac{(h_1 - h_2)}{L_{12}} \text{ where } L_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} = \sqrt{(100-0)^2 + (200-0)^2} = 223.607\ m$$

  then

  $$i_{12} = \frac{115 - 98}{223.607} = 0.076.$$

  Hydraulic gradient between well 1 and well 3:

  $$i_{13} = \frac{(h_1 - h_3)}{L_{13}} \text{ where } L_{13} = x_3 - x_1 = 400 - 0 = 400\ m$$

  then

  $$i_{13} = \frac{115 - 90}{400} = 0.063.$$

(b) A **tracer** is released in **well 1** and is observed in **well 2** after **4.17 days** and in **well 3** after **6.33 days**.

- Evaluate the **interstitial**, the **Darcy's velocity** and the **direction**. It is known that under the effect of gravity, **400 ml** of water drain from **one liter** of soil from the tested area. (8p)
- Calculate **the hydraulic conductivity** and the **intrinsic permeability** knowing that the dynamic viscosity of water is 0.001 kg/(m·s) and its density is 1000 kg/m^3 while the gravity acceleration is 9.81 m/s^2. (4p)

  Interstitial velocity between well 1 and well 2:

  $$v_{12} = \frac{L_{12}}{t_{12}} = \frac{223.607}{4.17} = 53.623\ m/day = 6.206 \times 10^{-4}\ m/s$$

Interstitial velocity between well 1 and well 3:

$$v_{13} = \frac{L_{13}}{t_{13}} = \frac{400}{6.33} = 63.191\ m/day = 7.314\ \times 10^{-4}\ m/s$$

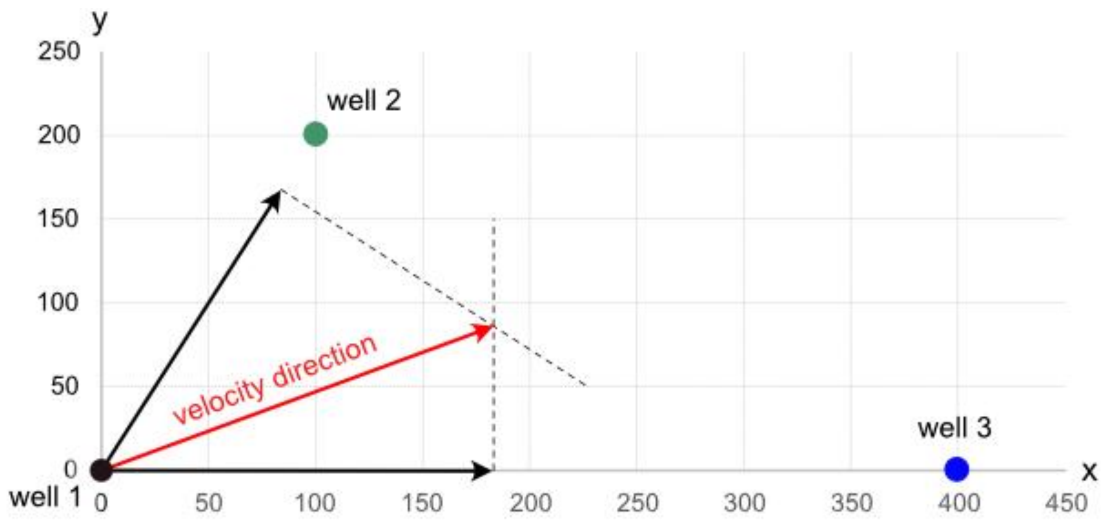
Darcy's velocity *q* = porosity *n* x interstitial velocity *v*

$$n = \frac{400}{1000} = 0.4$$

$$q_{12} = n\ \times v_{12} = 0.4\ \times 6.206\ \times 10^{-4} = 2.482 \times 10^{-4}\ m/s$$

$$q_{13} = n\ \times v_{13} = 0.4\ \times 7.314\ \times 10^{-4} = 2.926 \times 10^{-4}\ m/s$$

The direction:



Hydraulic conductivity and intrinsic permeability:
based on Darcy's law, the hydraulic conductivities are:

$$K_{12} = \frac{q_{12}}{i_{12}} = 2.482 \times \frac{10^{-4}}{0.076} = 3.27 \times 10^{-3}\ m/s$$

$$K_{13} = \frac{q_{13}}{i_{13}} = 2.926 \times \frac{10^{-4}}{0.063} = 4.64 \times 10^{-3}\ m/s$$

the intrinsic permeabilities:

$$k_{12} = \frac{K_{12}\ \mu}{\rho_w\ g} = \frac{3.27 \times 10^{-3} \times 0.001}{1000 \times 9.81} = 3.33 \times 10^{-10}\ m^2$$

$$k_{13} = \frac{K_{13}\ \mu}{\rho_w\ g} = \frac{4.64 \times 10^{-3} \times 0.001}{1000 \times 9.81} = 4.73 \times 10^{-10}\ m^2$$

(b) Calculate the aquifer **transmissivity** and **classify** its potentiality, given that the thickness of the aquifer is **10 m**. (3p)

Transmissivity *T* = hydraulic conductivity *K* x aquifer thickness *b*

$$T_{12} = K_{12} \times b = 3.27 \times 10^{-3}\ \times 10 =\ 3.27 \times 10^{-2}\ m^2/s = 2825.28\ m^2/day$$

$$T_{13} = K_{13} \times b = 4.64 \times 10^{-3} \times 10 = 4.64 \times 10^{-2}\, m^2/s = 4008.96\ m^2/day$$

The average transmissivity is $(2825.28 + 4008.96)/2 = 3417.12\, m^2/day$. Based on the provided table, the aquifer potentiality is classified as high.

Part 2 (5p):
A **confined** aquifer needs to be investigated concerning its properties. For this purpose, two wells (named as A and B) with a diameter of **0.2 m** and a distance between them of **150 m** are constructed far from the aquifer boundaries. Water is pumped at **well A** at a rate of **50 liters per min** and the drawdown is monitored in both wells. After some time, the water level in both wells becomes constant. The drawdown at **well A** is **10 m**, while at **well B** it is **5 m**. Evaluate **the transmissivity**, **the hydraulic conductivity** and **classify the aquifer** given that the thickness of the aquifer is **30 m**.

For steady (stationary) state, the transmissivity can be estimated based on Thiem's solution for a confined aquifer as:

$T = \frac{Q}{2\pi} \frac{\mathrm{Ln}\left(\frac{r_2}{r_1}\right)}{s(r_1) - s(r_2)} = \frac{72}{2\pi} \times \frac{\mathrm{Ln}\left(\frac{150}{0.1}\right)}{10-5} = 16.761\ m^2/day$. Based on the provided table, the aquifer potentiality is classified as weak.

The hydraulic conductivity of the aquifer is:

$$K = \frac{T}{b} = \frac{16.761}{30} = 0.559 \frac{m}{day} = 6.47 \times 10^{-6}\ m/s$$

Q2 Transient (non-stationary) flow (25 points)

Time-drawdown data for a **confined** aquifer are shown in the table below. These data come from an observation well which locates at **250 meters** from the main pumping well. The **pumping rate** is **1200 m^3/day**, and the **aquifer thickness** is **25 m**.

t [min]	s [cm]		t [min]	s [cm]		t [min]	s [cm]
3	9.0		47	155		160	253
5	21.0		50	161.5		200	259
8	40.0		60	174		260	280.5
12	64.0		70	186		320	296
20	97.5		80	192		380	311
24	109.7		90	204		500	332
30	125		100	213.5			
38	143		130	229			

You are asked to evaluate the **transmissivity**, the **hydraulic conductivity**, and the **storage coefficient** with **Cooper-Jacob method**. Please use the provided semi-logarithmic graph paper for your solution.

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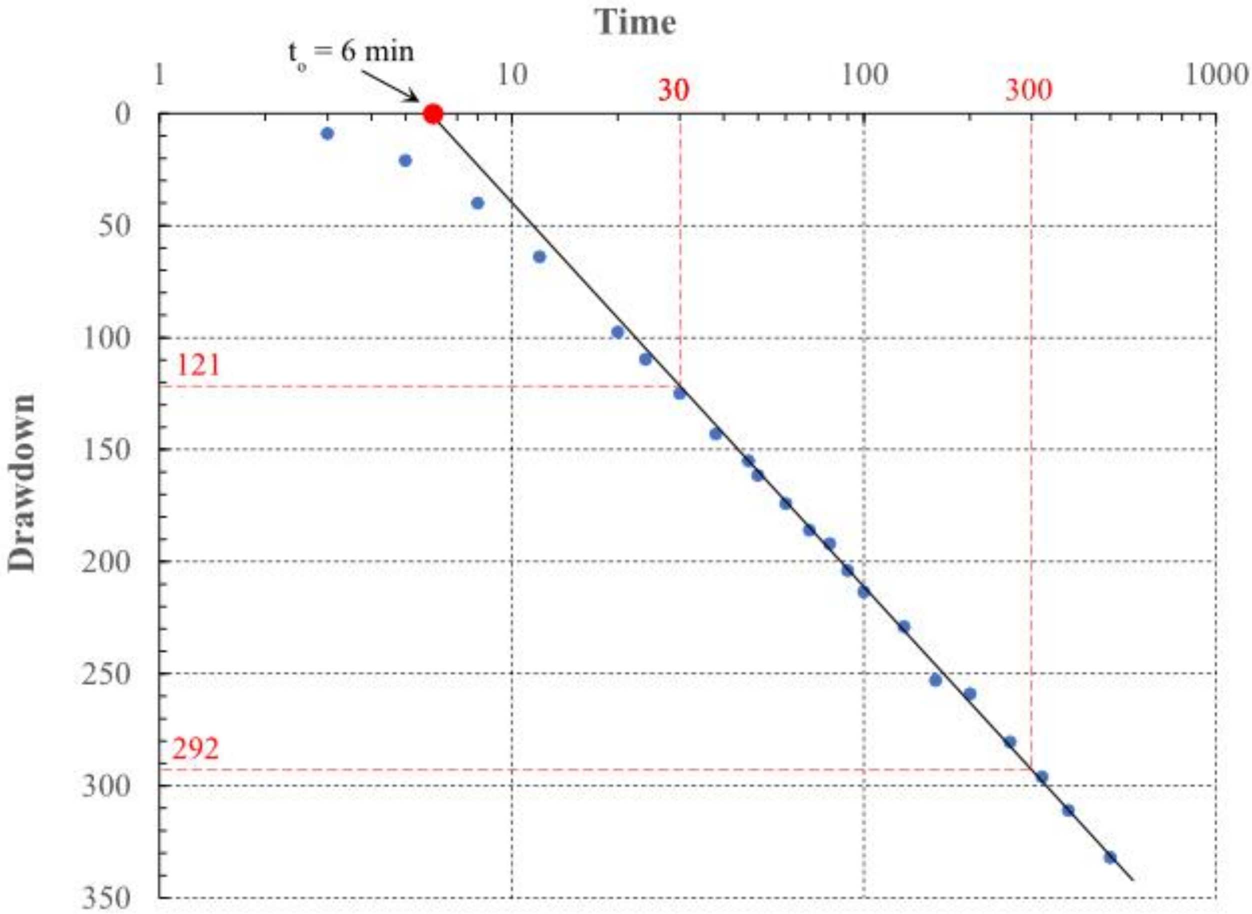


From the graph, t_o = 6 min = 0.004 day and Δs = 292 – 121 = 171 cm = 1.71 m.

Based on Cooper-Jacob solution:

$$T = \frac{0.183\ Q}{\Delta s} = \frac{0.183 \times 1200}{1.71} = 128.421\ m^2/day$$

Then the hydraulic conductivity is

$$K = \frac{T}{b} = \frac{128.421}{25} = 5.137\ m/day$$

The storage coefficient:

$$S = \frac{2.25 \times T \times t_o}{r^2} = \frac{2.25 \times 128.421 \times 0.004}{250^2} = 1.849 \times 10^{-5}$$

Check on the accuracy of the method for t = 20 min = 0.014 day:

$$u = \frac{r^2 \cdot S}{4 \cdot T \cdot t} = \frac{250^2 \times 1.849 \times 10^{-5}}{4 \times 128.421 \times 0.014} = 0.161 > 0.01$$

The method has a considerable error and Cooper-Jacob solution is not good enough is this case.

Q3 In situ stresses and basic characteristics (25 points)

Fig. Q3.1 shows a soil profile consisting of one sand layer of a total thickness of 12 m underlain by impermeable rock. The **groundwater table** is at a depth of **2 m**, the natural unit weight of the sand **γ = 18 kN/m^3** whereas the saturated unit weight **γ_{sat} = 22 kN/m^3** and the unit weight of water **γ_w = 10 kN/m^3**. The sand has an effective internal friction angle **φ' = 35^o**.

You are asked to

- Draw the **total vertical stress** profile, the **pore water pressure** profile and the **effective vertical stress** profile. (9p)
- Draw the **effective horizontal stress** profile. (4p)
- Construct the **Mohr circle** using the vertical and horizontal effectives stress at **point A** located at a depth of **7 m** (see Fig. Q3.1). Judge on the stability of the soil at that point by showing whether the soil fails or not? (7p)
- What will be the **effective vertical and horizontal stresses** at the soil surface if we decide to consider a **hydrostatic distribution of the capillary pressure** above the ground water table? (5p)

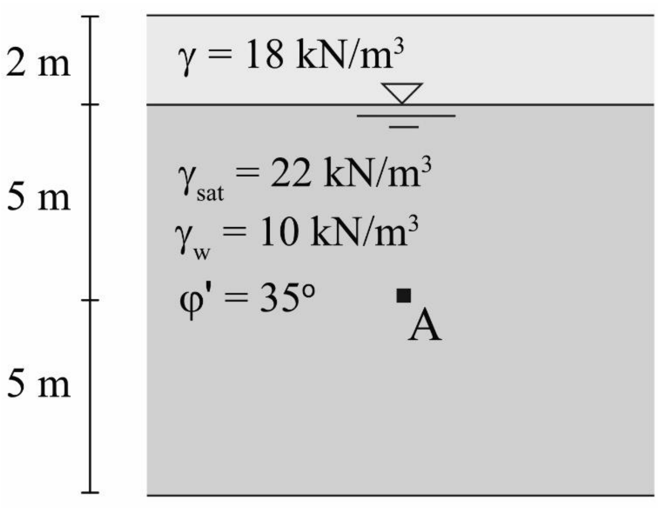


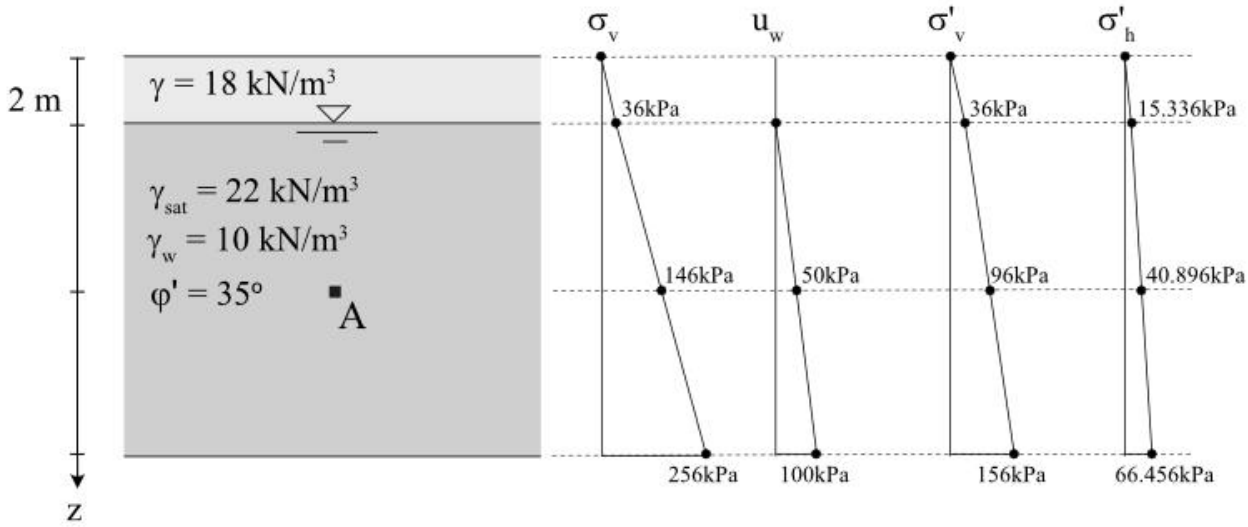
Fig. Q3.1.

- Total vertical stress at a depth z is calculated as $\sigma_v = \gamma \cdot z$ where γ is the unit weight of the soil. The unit weight changes depending on the soil saturation. Similarly, the pore water pressure at any depth z below water table is calculated as $u_w = \gamma_w \cdot z$ where $\gamma_w = 10$ kN/m^3 the unit weight of water. The effective vertical stress $\acute{\sigma}_v = \sigma_v - u_w$.

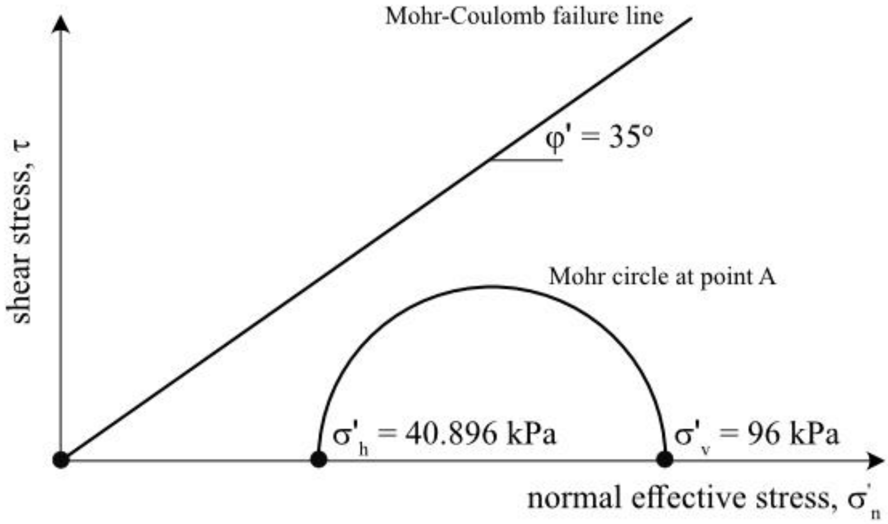
- The horizontal effective stress $\acute{\sigma}_h = K_o \cdot \acute{\sigma}_v$ where K_o is the coefficient of earth pressure at rest which can be calculated based on Jaky's formula:

$$K_o = 1 - \sin(\acute{\varphi}) = 1 - \sin(35) = 0.426.$$

Using these relationships, the following profiles yield:



- At Point A, $\acute{\sigma}_v = 96$kPa and $\acute{\sigma}_h = 40.896$kPa corresponding, in this case, to $\acute{\sigma}_1$ and $\acute{\sigma}_3$, respectively and we have $\acute{\varphi}$ = 35°. This means that we can plot in the plane $\tau - \acute{\sigma}_n$ both Mohr circle and Mohr-Coulomb failure line at Point A as follows:



The Mohr circle is well below the failure line meaning that the soil is stable at point A.

- If one considers a hydrostatic distribution of capillary pressure above the groundwater table then the negative pore water pressure at the soil surface will be $u_w = -\gamma_w \cdot z = -10 \times 2$ = -20 kPa. The total stress at the soil surface $\sigma_v = 0$ kPa. Consequently, the effective vertical stress at the soil surface considering the capillary pressure is $\acute{\sigma}_v = \sigma_v - u_w = 0 - (-20) = 20$ kPa. Finally, the corresponding effective horizontal stress $\acute{\sigma}_h = K_o \cdot \acute{\sigma}_v$ = 0.426× 20 = 8.52 kPa.

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Q4 Consolidation and creep (25 points)

Part 1: (10p)
Use the data of a 1D incremental loading compression test in Fig. Q4.1 for a **soft clay** at a depth of **4 m** to derive:

- The **compression index** C_c (corresponding to normally consolidated state) (3p)
- The **swelling index** C_s (corresponding to unloading/reloading to normally consolidated state) (3p)
- The **preconsolidation pressure** $\acute{\sigma}_c$ (4p)

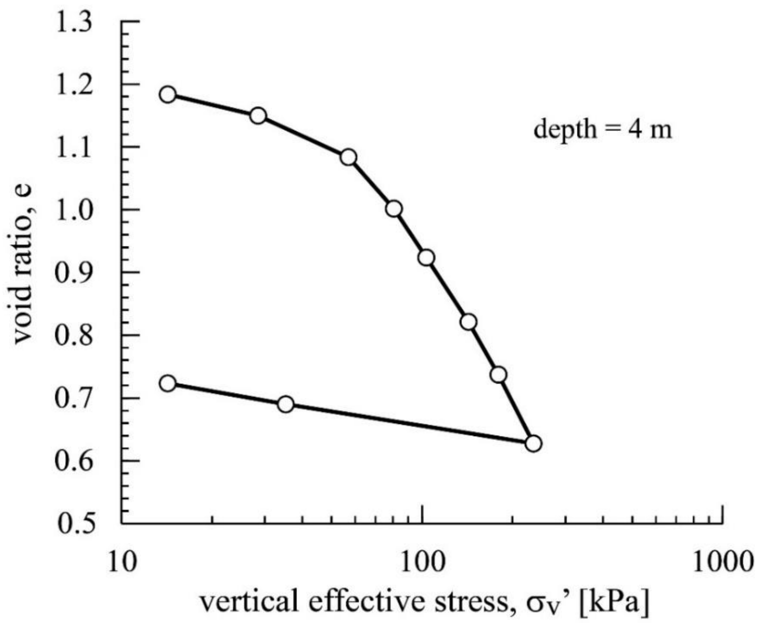
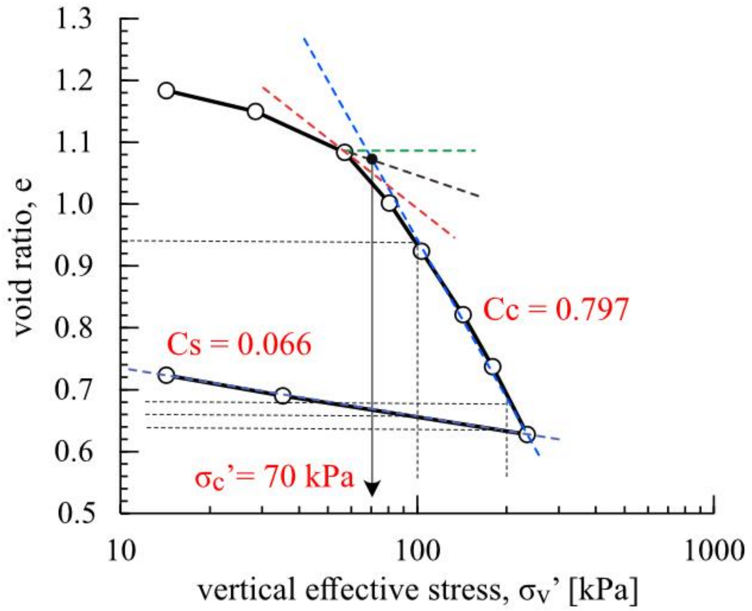


Fig. Q4.1.



- From the test one finds the following values:
  On the compression line:
  for $\acute{\sigma}_v$= 100 kPa e = 0.92
  for $\acute{\sigma}_v$= 200 kPa e = 0.68

  then $C_c = \frac{\Delta e}{\Delta \log(\acute{\sigma}_v)} = \frac{0.92-0.68}{\log(200)-\log(100)} = 0.797$

- On the unloading (swelling) part:
  for $\acute{\sigma}_v$= 100 kPa e = 0.66
  for $\acute{\sigma}_v$= 200 kPa e = 0.64

  then $C_s = \frac{\Delta e}{\Delta \log(\acute{\sigma}_v)} = \frac{0.66-0.64}{\log(200)-\log(100)} = 0.066$

- According to Casagrande's graphical method, as it shown in the graph above, the preconsolidation pressure $\acute{\sigma}_c$ = 70 kPa.

Part 2: (15p)
Given the soil profile and properties in Fig. Q4.2 and knowing that the **soft clay** in **Part 1** represents the **layer 2,** you are asked to calculate **the final total settlement** under the effect of an **infinitely long** and **uniform stress increment Δσ = 30 kPa** to be applied at the soil surface. Note that the groundwater table is at a depth of **2m**.

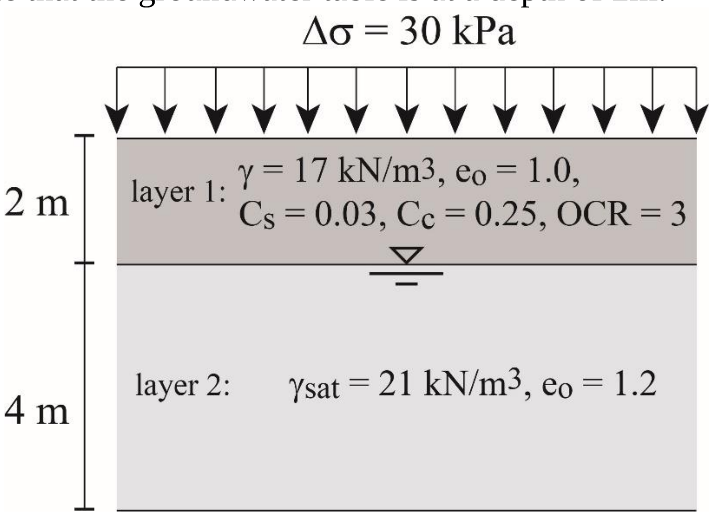


Fig. Q4.2.

The final total settlement is the sum of the settlements of layer 1 and layer 2.

Settlement of layer 1:
To estimate the settlement, one needs the initial and final vertical effective stresses at the middle of the layer.

- To calculate the initial effective stress at z = 1 m (middle of layer 1), we have:
  Total stress $\sigma_v = \gamma \cdot z = 17 \times 1 = 17$ kPa.
  Pore water pressure $u_w = 0$ kPa.

Then the effective stress $\acute{\sigma}_v = \sigma_v - u_w = 17 - 0 = 17$ kPa.

- The final stress = initial stress + effective stress increment = 17 + 30 = 47 kPa.
- To judge on the behaviour of the soil one needs the value of the preconsolidation pressure $\acute{\sigma}_c$ of this layer. That can be estimated based on the provided OCR value and the initial stress value:

  $OCR = \frac{\acute{\sigma}_c}{\acute{\sigma}_v} \xrightarrow{yields} \acute{\sigma}_c = OCR \times \acute{\sigma}_v = 3 \times 17 = 51$ kPa.

  As the final stress value is less than the preconsolidation pressure 47 kPa < 51 kPa then layer 1 is still overconsolidated (OC) response will be elastic, and the settlement is calculated based on C_s value only:

  $\Delta e = C_s \cdot \log\left(\frac{\acute{\sigma}_{vo}+\Delta\acute{\sigma}}{\acute{\sigma}_{vo}}\right) = 0.03 \times \log\left(\frac{47}{17}\right) = 0.013$

  Final settlement of layer 1, $\Delta s_1 = \frac{\Delta e}{1+e_o} \cdot H_1 = \frac{0.013}{1+1} \times 2 = 0.013$ m = 1.3 cm.

Settlement of layer 2:

Again, to estimate the settlement, one needs the initial and final vertical effective stresses but this time at the middle of layer 2.

- To calculate the initial effective stress at z = 4 m (middle of layer 2), we have:

  Total stress $\sigma_v = \gamma \cdot z = 17 \times 2 + 21 \times 2 = 76$ kPa.

  Pore water pressure $u_w = 2 \times 10 = 20$ kPa.

  Then the effective stress $\acute{\sigma}_v = \sigma_v - u_w = 76 - 20 = 56$ kPa.
- The final stress = initial stress + effective stress increment = 56 + 30 = 86 kPa.
- From part one, $\acute{\sigma}_c = 70$ kPa for this layer. As the final stress value is greater than the preconsolidation pressure 86 kPa > 70 kPa then layer 2 is going from overconsolidation OC toward normal consolidation NC state, thus the settlement is calculated based on the following formula:

  $\Delta e = C_s \cdot \log\left(\frac{\acute{\sigma}_c}{\acute{\sigma}_{vo}}\right) + C_c \cdot \log\left(\frac{\acute{\sigma}_{vo}+\Delta\acute{\sigma}}{\acute{\sigma}_c}\right) = 0.066 \times \log\left(\frac{70}{56}\right) + 0.797 \times \log\left(\frac{86}{70}\right) = 0.078.$

  Final settlement of layer 2, $\Delta s_2 = \frac{\Delta e}{1+e_o} \cdot H_2 = \frac{0.078}{1+1.2} \times 4 = 0.141$ m = 14.1 cm.

In the above calculation H_1 and H_2 refer to the thickness of layer 1 and layer 2, respectively.

The final settlement:

The final $\Delta s = \Delta s_1 + \Delta s_2 = 1.3 + 14.1 = 15.4$ cm.

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Q5 Flow nets (25 points)

Fig. Q5.1 shows the flow net under a concrete dam. The height of water behind the dam is **10 m** while in front of the dam it is **2 m**. The hydraulic conductivity of the foundation soil **K = 1x10^{-6} m/s** and the unit weight of water **γ_w = 10 kN/m^3**. Using the given flow net, you are asked to:

- Evaluate the **water discharge** below the dam. (5p)
- Estimate the **pore water pressure** at Points A, B, C, D and E. (10p)
- Estimate the **uplift force**. (5p)
- Knowing that the saturated unit weight of the soil is **21 kN/m^3** and the length of the flow net square at the exit is ***l* = 2 m** (see Fig. Q5.1), assess the **danger of piping**. (5p)

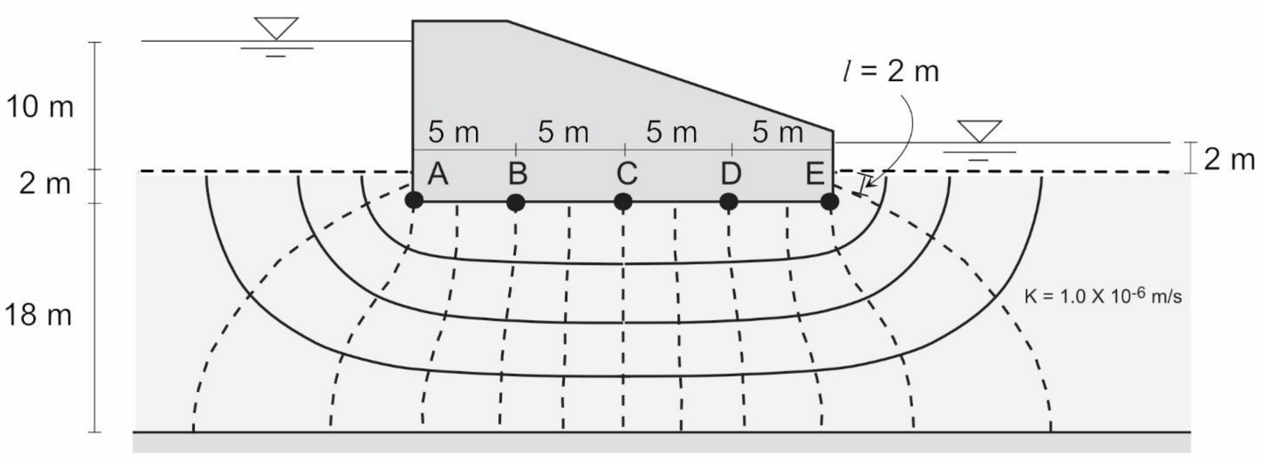

Fig. Q5.1.

- $Q = K \cdot m \cdot \Delta h = K \cdot m \cdot \frac{\Delta H}{n}$ where m = 4 is the number of flow channels and n = 12 is the number of equipotential (head) drops. The total head drop $\Delta H = H_1 - H_2$ = 30 - 22 = 8 m, where H_1 and H_2 are the total water head behind and in front of the dam, respectively. The equipotential drop per one square of the flow net $\Delta h = \frac{\Delta H}{n} = \frac{8}{12} = 0.667\ m$. The total head at any point $H = z + \frac{u_w}{\gamma_w}$ where z is the elevation of the point and u_w is the pore water pressure at that point. In this solution the reference zero level is taken at the bottom of the soil layer, but it is up to you to choose where to locate it as long as you refer to it always in your calculations. Consequently:
$$Q = K \cdot m \cdot \frac{\Delta H}{n} = 1 \times 10^{-6} \times 4 \times \frac{8}{12} = 2.667 \times 10^{-6}\ m^3/s\ = 0.23\ m^3/s$$

- To estimate the pressure, at one hand we have, at any point, $H = z + \frac{u_w}{\gamma_w} \xrightarrow{yields} u_w = \gamma_w\ (H - z\ )$ and on the other hand, at any point $H = H_1 - n_b \times \Delta h$ where n_b is the number equipotential drops in the flow net before reaching the considered point. Using these formulas, one will be able to estimate the pore water pressure at Points A, B, C, D and E as shown in the following table:

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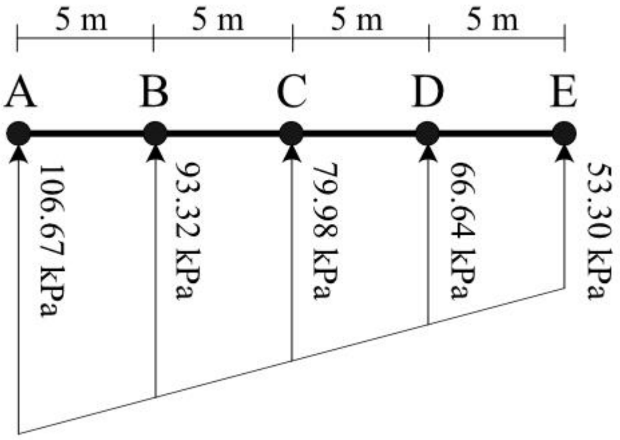
Point	n_b	H [m]	z [m]	u_w [kPa]
A	2	28.667	18	106.67
B	4	27.332	18	93.32
C	6	25.998	18	79.98
D	8	24.664	18	66.64
E	10	23.330	18	53.30

For example, at point C one has $H_1 = 30$ m, $n_b = 6$ and $\Delta h = 0.667\ m$ which yields $H = H_1 - n_b \times \Delta h = 30 - 6\ \times 0.667 = 25.998\ m.$
The elevation of Point C is $z\ =\ 18\ m$ then the pore water pressure at C is:
$u_w = \gamma_w\ (H - z\ ) = 10 \times (25.998 - 18) = 79.98$ kPa.

- By representing the previous values with a suitable scale, the following pore water pressure distribution results:



The uplift force is the integration (the area) of the above pore water pressure diagram. As we have fixed distances of 5 m then the uplift force can be calculated as:

$$F = \left[5 \times \left(\frac{106.67+93.32}{2}\right) + 5 \times \left(\frac{93.32+79.98}{2}\right) + 5 \times \left(\frac{79.98+66.64}{2}\right) + 5 \times \left(\frac{66.64+53.30}{2}\right)\right] = \frac{5}{2} \times [106.67 + 2 \times (93.332 + 79.98 + 66.64) + 53.30] = 1599.625 \text{ kN.}$$

Alternatively, in this special case due to the linear distribution of pressure one can calculate the uplift force directly as:

$$F = 20 \times \left(\frac{106.67+53.30}{2}\right) = 1599.7 \text{ kN}$$

- The critical hydraulic gradient $i_{critical} = \frac{\gamma_{sat}-\gamma_w}{\gamma_w} = \frac{21-10}{10} = 1.1$

  The hydraulic gradient at the exit $i_{exit} = \frac{\Delta h}{l} = \frac{0.667}{2} = 0.334$

  The safety factor against piping $FS = \frac{i_{critical}}{i_{exit}} = \frac{1.1}{0.334} = 3.293 < 5\ \rightarrow$ The structure is not safe against piping.

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Useful equations for hydrogeology

Water budget: $P - E = R_S + R_G \pm DM$

Darcy's law: $Q = KA\frac{dh}{dl}$ or $q = K\frac{dh}{dl}$

Fluid particle (interstitial) velocity: $v = q/n$

Interensic permeability: $k = \frac{K \cdot \mu}{\rho_w \cdot g}$

Hazen's equation: $K = c \cdot D_{10}^2$

Transmissivity: $T = b \cdot K$

Aquifer Potentiality

Transmissivity (m^2/day)	Potentiality Description
T < 5	Negligible
5 < T < 50	Weak
50 < T < 500	Moderate
T > 500	High

Effective stresses

Terzaghi: $\sigma' = \sigma - u$

Biot: $\sigma' = \sigma - \alpha \cdot u$

Hydraulic head: $h = z + \frac{p}{\rho_w g} = z + \frac{p}{\gamma_w}$

Hydraulic gradient: $i = dh/dl$

Storage coefficient: $S = S_y + \rho g b\,(n\beta_w + \beta_s)$

Thiem equation

Confined aquifer: $Q = 2\pi T\frac{s(r_1) - s(r_2)}{Ln(r_2/r_1)}$ or $s = \frac{Q}{(2\pi T)}Ln(R_0/r)$

Unconfined aquifer: $s^2(r_1) - s^2(r_2) = \frac{Q}{\pi K}Ln(r_2/r_1)$ or $s - \frac{s^2}{2h_0} = \frac{Q}{2\pi T_0}Ln(R_0/r)$

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Theis solution

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Cooper-Jacob solution

$$W(u) = -0,5772 - \ln(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Drawdown versus time, s – t

$$T = 0.183 Q/\Delta s$$
$$S = 2.25\, T\, t_o/r^2$$

Drawdown versus distance, s – r

$$T = 0.366 Q/\Delta s$$
$$S = 2,25 Tt/r_e^2$$

Flow net

Total discharge: $Q = m \cdot K \cdot \frac{\Delta H}{n}$

Critical hydraulic gradient: $i_{critical} = \frac{\gamma_{sat} - \gamma_w}{\gamma_w}$

Useful equations for geotechnics:

Mean effective stress: $p' = 1/3(\sigma_1' + \sigma_2' + \sigma_3')$

Deviator stress: $q = \sigma_1' - \sigma_3'$

Earth pressure at rest:

$$\sigma'_h = K_0\, \sigma'_v$$

$$K_0 \approx 1 - \sin \varphi'$$

$$K_0 \approx (1 - \sin \varphi')\sqrt{OCR}$$

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Overconsolidation:

Overconsolidation ratio: $OCR=\sigma_c'/\sigma_v'$

Pre-overburden pressure: $POP= \sigma_c'-\sigma_v'$

Compression index C_c (defined at normally consolidated region) and swelling index C_s (defined at overconsolidated region):

C_c *or* $C_s = \Delta e/\Delta \log\sigma' = (e_0-e_1)/\log_{10}(\sigma_1'/\sigma_0')$

Creep index C_α

$C_\alpha = \Delta e/\Delta \log t = (e_0-e_1)/\log_{10}(t_1/t_0)$

Shear strength of soils (based of effective stresses):

$\tau = c' + \sigma' \tan\phi'$

Mohr Coulomb failure criterion:

$(\sigma'_1 - \sigma'_3) = (\sigma'_1 + \sigma'_3) \sin\phi' + 2c' \cos\phi'$

Depth of a tension crack:

$$d = \frac{2c_u}{\gamma}$$

Undrained shear strength from triaxial test:

$$c_u = \frac{q_f}{2}$$

Settlement:

$$\text{Settlement} = \frac{\Delta e}{1+e_o} \cdot H$$

$\Delta e = C_s \cdot \log\left(\frac{\acute{\sigma}_{vo}+\Delta\acute{\sigma}}{\acute{\sigma}_{vo}}\right)$ for OC soil.

$\Delta e = C_c \cdot \log\left(\frac{\acute{\sigma}_{vo}+\Delta\acute{\sigma}}{\acute{\sigma}_{vo}}\right)$ for NC soil.

$\Delta e = C_s \cdot \log\left(\frac{\acute{\sigma}_c}{\acute{\sigma}_{vo}}\right) + C_c \cdot \log\left(\frac{\acute{\sigma}_{vo}+\Delta\acute{\sigma}}{\acute{\sigma}_c}\right)$ for OC soil becomes NC after loading.

Individual exam code…………………………..

Useful graphs for guidance: