

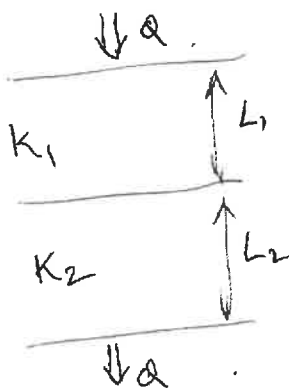
Q1) a) Darcy's law states that the seepage flow in granular materials is driven by the potential head difference.

Seepage flow velocity $v \propto \frac{dh}{ds}$; $v \propto i$

$v = Ki$ where k is the hydraulic conductivity of the granular medium.

Darcy's law is valid when the flow is laminar and it will break down for turbulent flows, that can occur in gravel or boulders. [10%]

b) Consider a 2-layered system.



Vertical flow Q will be same
 $Q = Q_1 = Q_2$ $L = L_1 + L_2$

$Q = K_{eq} \times i \times A$ (Take $A=1$)

$i = \frac{dh}{L} \Rightarrow dh = \frac{QL}{K_{eq}}$

$i = i_1 + i_2$

layer 1 $i_1 = \frac{dh_1}{L_1}$

layer 2 $i_2 = \frac{dh_2}{L_2}$

$Q_1 = K_1 \frac{dh_1}{L_1}$

$Q_2 = K_2 \frac{dh_2}{L_2}$

$dh_1 = \frac{Q_1 L_1}{K_1}$; $dh_2 = \frac{Q_2 L_2}{K_2}$

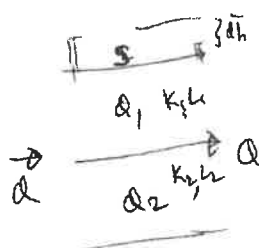
$\therefore dh = dh_1 + dh_2 = \frac{Q_1 L_1}{K_1} + \frac{Q_2 L_2}{K_2} = \frac{QL}{K_{eq}}$

$\Rightarrow Q \frac{L_1}{K_1} + Q \frac{L_2}{K_2} = Q \frac{(L_1 + L_2)}{K_{eq}} \Rightarrow \frac{K_2 L_1 + K_1 L_2}{K_1 K_2} = \frac{L_1 + L_2}{K_{eq}}$

$\therefore K_{eq} = \frac{(L_1 + L_2)(K_1 K_2)}{K_2 L_1 + K_1 L_2} = \frac{(L_1 + L_2)}{\frac{K_2 L_1 + K_1 L_2}{K_1 K_2}} = \frac{L_1 + L_2}{\frac{L_1}{K_1} + \frac{L_2}{K_2}} \rightarrow ①$

Consider horizontal flow.

$Q = Q_1 + Q_2$. dh driving the flow is same.



$K_{eq} \frac{dh}{L} = K_1 \frac{dh}{L_1} \times L_1 + K_2 \frac{dh}{L_2} \times L_2$

$\therefore K_{eq} = \frac{K_1 L_1 + K_2 L_2}{L_1 + L_2} \rightarrow ②$

[20%]

c) Using ① & ②;

$K_{eq} = \frac{3 + 5}{\frac{3}{2.6 \times 10^{-5}} + \frac{5}{3.84 \times 10^{-4}}}$

$= \frac{8}{\frac{3}{2.6 \times 10^{-5}} + \frac{5}{3.84 \times 10^{-4}}} = 6.23 \times 10^{-5} \text{ m/s}$

3m: $2.6 \times 10^{-5} \text{ m/s}$

5m: $3.84 \times 10^{-4} \text{ m/s}$

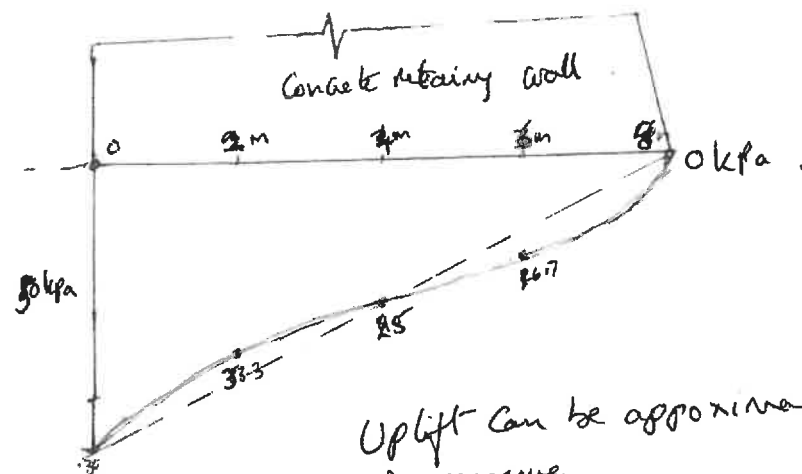
$$K_h = \frac{3 \times 2.6 \times 10^{-5} + 5 \times 384 \times 10^{-4}}{3 + 5}$$

$$= \underline{2498 \times 10^{-4} \text{ m/s}}$$

$$\therefore \text{Anisotropy ratio } \alpha = \sqrt{\frac{K_h}{K_v}} = \sqrt{\frac{2.498 \times 10^{-4}}{6.23 \times 10^{-5}}} = 2.0022 \approx \underline{2}$$

2 d) Flownet was constructed with $\alpha = 2$: shown on next page

2 e)



$$U = \int p dx = \frac{1}{2} \times 50 \times 8 \times \frac{200}{1400} = \underline{200 \text{ kN}}$$

$$\text{Weight of the retaining wall} = \gamma_c \times 10.5 \times \frac{(2.5 + 8)}{2} = 36.125 \times 24 = \underline{1638 \text{ kN}}$$

$$\therefore W' = W - U = 1638 - 200 = \underline{1438 \text{ kN}}$$

$$\text{Horizontal thrust} = H = \frac{1}{2} \times 5 \times 50 = \underline{125 \text{ kN}}$$

$$\therefore \text{FoS against sliding} = \frac{W' \tan \phi}{H} = \frac{1438 \times \tan 30^\circ}{125} = \underline{6.641}$$

\therefore Quite safe.

[25%]

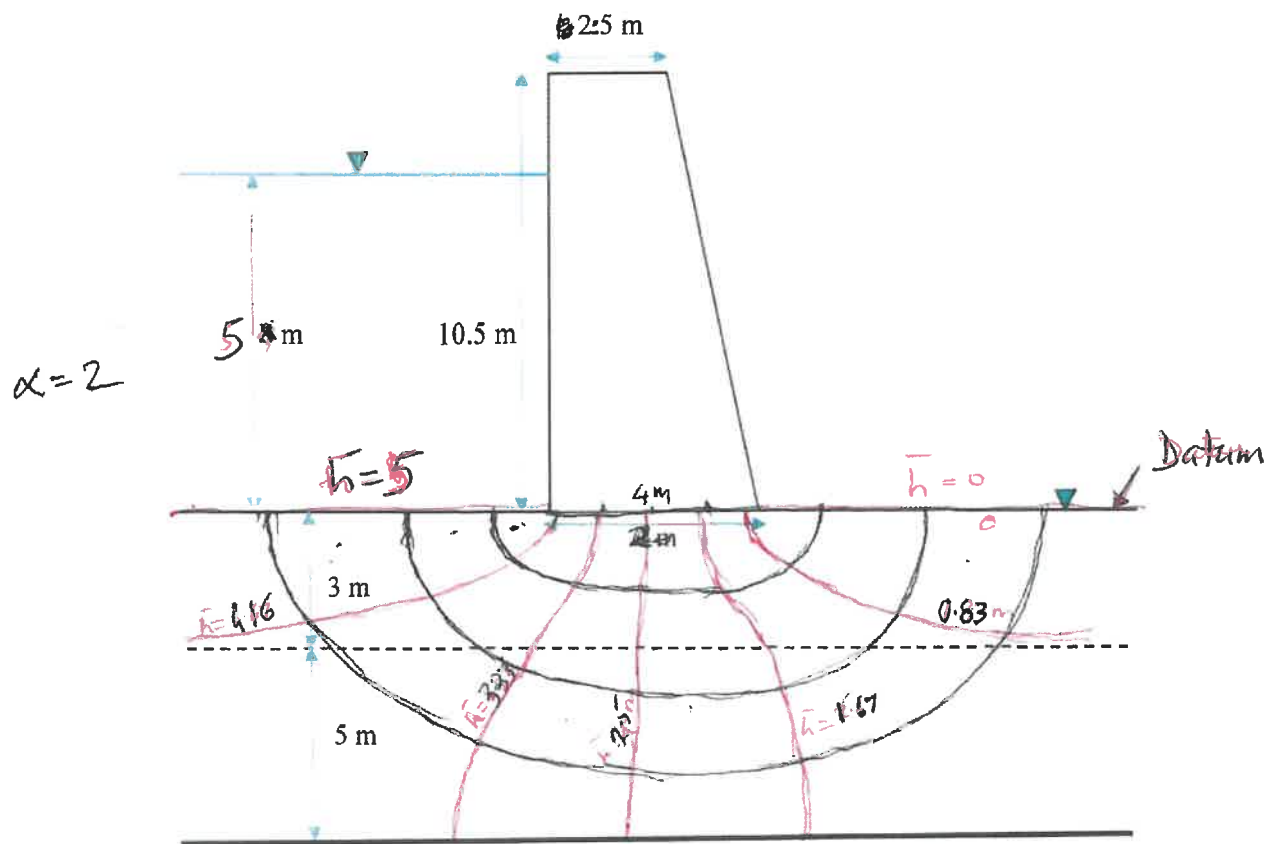


Fig. 2

$$N_f = 3.5$$

$$N_h = 6$$

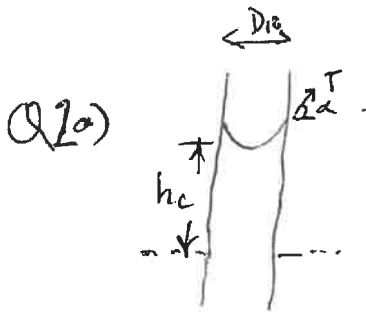
$$Q = \sqrt{K_h K_v} \Delta h \times \frac{N_f}{N_h}$$

$$= \sqrt{2.498 \times 10^{-4} \times 6.23 \times 10^{-5}} \times 5 \times \frac{3.5}{6}$$

$$= 5.638 \times 10^{-4} \text{ m}^3/\text{s} / \text{m width}$$

$$= \frac{50299.46}{31438.4} \text{ litres/day / m}$$

[25%]



Weight of fluid Surface Tension force

$$\frac{\pi}{4} D_{10}^2 \cdot h_c \gamma_w = 2 \pi D_{10} T \sin \alpha$$

$$\therefore h_c = \frac{4 T \sin \alpha}{D_{10} \gamma_w}$$

(15%)

D_{10} - average void size in granular media

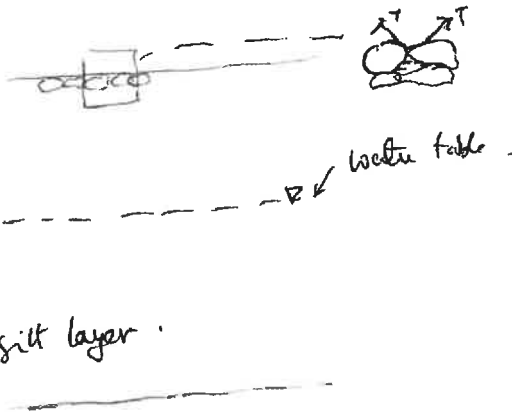
T - Surface Tension

α - wetting angle

γ_w - unit weight of water

h_c - height of capillary rise

2b) Consider a silt layer with water table below the soil surface. Soil above the water table will be under suction due to capillary rise, but stays saturated. When a small rainfall occurs, the pot marked surface can get filled with rainfall, which destroys the surface tension. So suddenly the water table is now at surface, and pore pressures above the previous water table will become +ve. This changes the effective stress here, from being large before rainfall (due to suction) to a smaller value. This drop in effective stresses can cause stability issues for foundations, slopes etc.



2c) Consider the silty slope at an angle of 20° . First calculate the capillary rise

h_c

$$h_c = \frac{4 T \sin \alpha}{D_{10} \gamma_w} = \frac{4 \times 0.0746 \sin 70^\circ}{0.012 \times 10^{-3} \times 9.81 \times 10^3} = 2.34 \text{ m}$$

Consider datum through point B.

Pressure heads

$$h_A = 2.5 \text{ m} \\ h_B = 2.0 \text{ m}$$

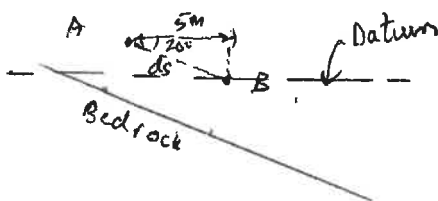
Elevation heads

$$y_B = 0 \quad y_A = 5 \tan 20^\circ = 1.82 \text{ m}$$

\therefore Potential heads

$$\bar{h}_A = 2.5 + 1.82 = 4.32 \text{ m}$$

$$\bar{h}_B = 2.0 + 0 = 2 \text{ m}$$



Hydraulic gradient $\bar{i} = \frac{dh}{ds}$

$$ds = \sqrt{5^2 + 1.8^2} = 5.321 \text{ m}$$

$$dh = 4.32 - 2 = 2.32 \text{ m}$$

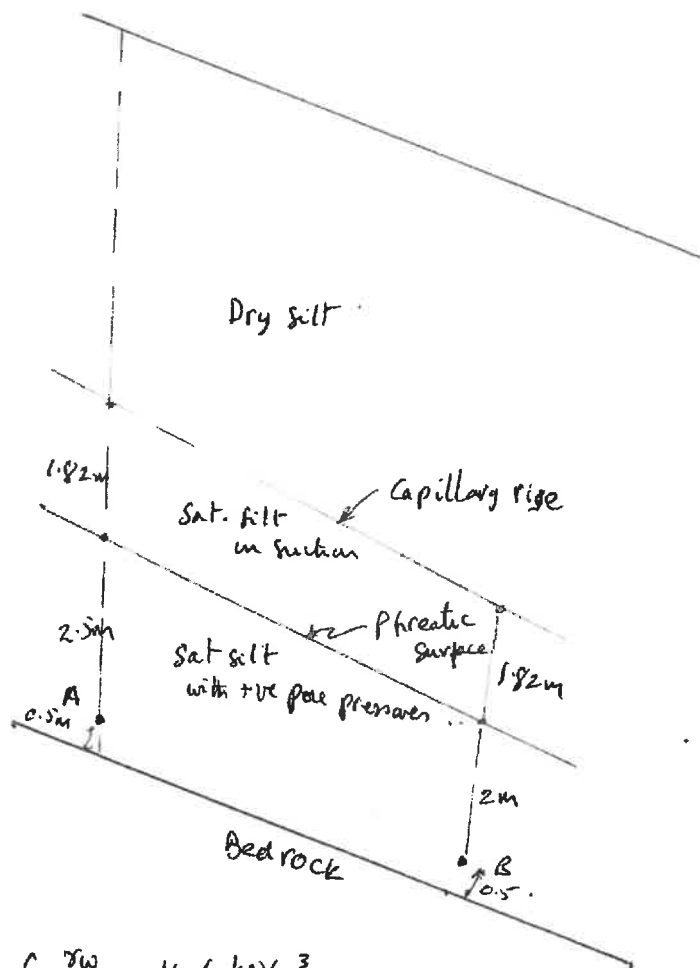
$$\therefore \bar{i} = \frac{2.32}{5.321} = 0.436$$

Seepage flow rate $Q = k \bar{i} A$. Consider c/s area $1 \text{ m}^2 = A$.

$$\therefore Q = 6.8 \times 10^{-6} \times 0.436 \times 1 = 2.9648 \times 10^{-6} \text{ m}^3/\text{s} / \text{m}^2$$

$$= \underline{256.16 \text{ litres/day}} \quad [25\%]$$

2d)

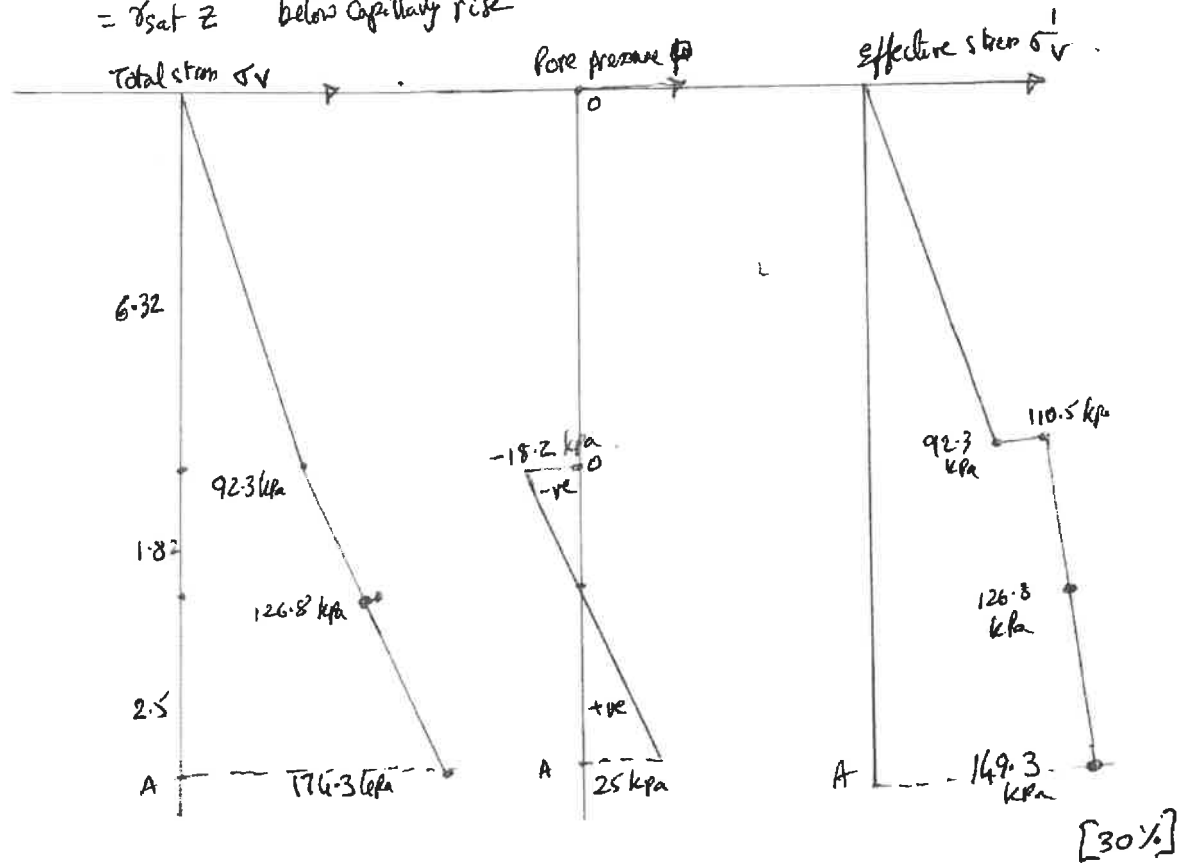


$$\gamma_d = \frac{G_s \gamma_w}{1+e} = 14.6 \text{ kN/m}^3$$

$$\therefore e = \frac{2.7 \times 9.81}{14.6} - 1 = 0.8142$$

$$\gamma_{sat} = \frac{(G_s + e) \gamma_w}{1+e} = \frac{2.7 + 0.8142}{1.8142} \times 9.81 = 19 \text{ kN/m}^3$$

So $\sigma_v = \gamma_d \cdot z$ in dry soil.
 $= \gamma_{sat} z$ below capillary rise



2e) Seepage flow governed by Darcy's law, driven by hydraulic gradient occurs in the void space between particles.

Heat flow governed by Fourier's law, driven by temperature gradient. Can occur in the fluid in the void space as well as through the solid particles via conduction.

Contaminant transport is governed by Fick's law, driven by the concentration gradients. Occurs mostly through the fluid in the void space between granular particles (if adsorption is ignored).

[15%]

Q3 (a) UK Environment Act 1995 definition: Contaminated Land is any land ...in such a condition, by reasons of substance in, on, or under the land, that harm, or pollution of controlled waters, is being, is likely to be, caused. In practice this means that not only actual pollution but also potential pollution would apply. Also that the reception is both humans and controlled waters. [10%]

(b) The definition of a contaminated land requires the present of a source, a pathway and a receptor. If any of those three parts are not present then the site is not classed as contaminated. [10%]

(c) One of: Petroleum leakage from underground petrol tanks, mining, agriculture, one of many industrial activities. In general, contaminants will migrate through the subsurface and contaminate the subsoil and groundwater. Contaminants are either heavy metals or organics or a mix of both, all pose risks to human health via ingestion, inhalation or skin contact. [10%]

(d) Solubility: Chemicals containing ionic bonds and molecules that have covalent bonds but have a dipole (e.g. ethanol) tend to be soluble with a maximum solubility limit in water. Above this, solution becomes saturated, and some of the chemical will be present as 'free phase', either solid or liquid. For example oil only dissolves in low amounts in water and so the majority is present as a separate liquid (i.e. NAPL). Substances which are more soluble are more likely to desorb from soils. Octanol/water partitioning coefficient, determines solubility and phase.

pH: pH <7 acidic and pH >7 alkaline aqueous solution and neutral at 7, chemicals in water can be affected by pH in different ways e.g. many metals are more soluble at lower (i.e. acidic) pH and so can be leached from soil and pose a greater risk. Higher pH would lead to some of these metals precipitating, meaning they are no longer a threat. Groundwater is often slightly acidic, due to factors such as local geology and the dissolution of acidic gases (e.g. carbon dioxide, which reacts with water to give a pH of ~5.5). The speciation of metals also varies with pH and depends on the anions present.

Redox potential (Eh): Eh relates to oxidation and reduction processes which occur together in chemical reactions. E.g. iron reacts with oxygen and hydrogen ions: iron is oxidised (Fe to Fe²⁺) and oxygen reduced (O₂ to O²⁻). Oxygen environment oxidising and lack of oxygen is usually reducing. Chemical properties vary depending on the Eh value as well as variation in pH. Eh-pH diagram shows the chemical states an element may take in water with different pH and redox conditions and allow the prediction of behaviour of a chemical under different environmental conditions. Eh of soil environments depends on chemistry of groundwater and soil. As with pH, Eh has positive and negative effects on soil contamination. For example, in oxidising conditions, Cr³⁺ is oxidised to 'Cr⁶⁺' which is considerably more toxic, and so one needs to encourage reducing conditions to prevent its formation. [30%]

(e) There are 3 main types of clay minerals: Kaolinite, Illite and montmorillonite. The latter has the smallest particle size largest specific area and the highest cation exchange capacity. This means it is the most reactive of the three types and is the type which will react most with any ground or groundwater contamination. Sorption is the most prominent contaminant interaction mechanism. The high cation exchange capacity means that heavy metals will be sorbed onto the surface of the clay particles, replacing cations such as Ca or Mg already present. Montmorillonite also has a much thicker diffuse double layer around the clay particle, hence forms a strong bond with ions. Montmorillonite can also form complexation with organics. Montmorillonite (and also Illite) have high buffering capacity which means that they can resist the change in pH conditions. Montmorillonite also has a much lower permeability and is hence commonly used as a landfill liner material preventing the leaching of contaminants. [20%]

(f) Sandy soils are usually much easier to remediate than clayey soils and generally become contaminated easier due to their higher permeability and the contamination will spread wider. Remediation will depend on where the groundwater is and whether it is also contaminated. Remediation will also depend on whether the contaminants are heavy metals, organics or a cocktail of both. Bioremediation is a cost-effective and common approach for organic contamination in permeable soils. Permeable reactive barriers are also common in groundwater contamination with relatively high groundwater flow. Clays are difficult to remediate in situ and are likely to be extracted for S/S treatment. There are many other examples, so any other examples and scenarios, with good justifications will be good answers. [20%]

4. $z = 2\text{m}$, $v_f = 0.5 \times 10^{-8} \text{ m/s}$, $D_d = 0.5 \times 10^{-9} \text{ m}^2/\text{s}$, $\tau = 0.45$, $\alpha = 0.35$.

(a) $D_d^* = 0.5 \times 10^{-9} \times 0.45 = 0.225 \times 10^{-9} \text{ m}^2/\text{s}$

$c/c_0 = 0.00$ means that β (erfc term, databook) = 3

Therefore:

$z/\sqrt{4 \times D_d^* \times t} = 2/\sqrt{4 \times 0.225 \times 10^{-9} \times t} = 3$

which leads to $t = 4.938 \times 10^8 \text{ secs} = 15.6 \text{ years}$

[20/1] 2

(b) $c/c_0 = 0.01$, means that $B = 1.825$

Therefore:

$z/\sqrt{4 \times D_d^* \times t} = 2/\sqrt{4 \times 0.225 \times 10^{-9} \times t} = 1.825$

which leads to $t = 1.33 \times 10^9 \text{ secs} = 42.3 \text{ years}$

(10/1) 2

(c) $D_i = D_d^* + v_f \alpha = 0.225 \times 10^{-9} + 0.5 \times 10^{-8} \times 0.35 = 1.975 \times 10^{-9} \text{ m}^2/\text{s}$

$c/c_0 = 0.00$, means that $\beta = 3$

Therefore:

$(2 - 0.5 \times 10^{-8} t)^2 = (3)^2 (4 \times 1.975 \times 10^{-9} t)$

$4 - 2 \times 10^{-8} t + 2.5 \times 10^{-17} t^2 = 7.11 \times 10^{-8} t$

$2.5 \times 10^{-17} t^2 - 9.11 \times 10^{-8} t + 4 = 0$

$t = [9.11 \times 10^{-8} \pm \sqrt{8.3 \times 10^{-15} - 4 \times 2.5 \times 10^{-17} \times 4}] / 2 \times 2.5 \times 10^{-17}$

$t = [9.11 \times 10^{-8} \pm \sqrt{7.9 \times 10^{-15}}] / 5 \times 10^{-17}$

$44361117 \text{ secs} = 1.4 \text{ years}$

(30/1) 2

(d) When diffusion is the dominant transport process (part (a)), then it will take nearly 16 years for the first sign of the contaminant to emerge from the wall. When the emergence of a small amount of contaminant (1%) is acceptable (part (b)), this will take a much longer time of around 43 years, because of the way the diffusion process takes place. If dispersion is the dominant transport process then the time is much reduced from (a). Hence dispersion causes much faster contaminant transport than diffusion. Also the performance of the in-ground barrier wall relies on it achieving an acceptable level of physical integrity and to remain intact to prevent dispersion through the wall.

[20/1] 2

(e) The effect of sorption is to reduce both the apparent dispersion coefficient and the apparent advective velocity of the contaminant by a retardation factor causing a delay in the breakthrough curve. Hence in part (a) the D^*d will be reduced by and the time will be increased and so will the design life. In part (b) the effect will be the same with increased design life by the same ratio. In part (c) the apparent advective velocity will also reduce as well as the effective dispersion coefficient, leading to a much higher increase in the design life than calculated.

(10/1) 2

(f) The resilience of such in-ground barrier can be enhanced by design through the use of barrier materials which have enhanced resistance to chemical damage e.g. clays which lower diffusion coefficient and higher sorptive capacities, there are such commercially available clays, but clearly they are expensive. The in-ground barrier materials can also be designed to perhaps self-healing when damaged. The wall can also be designed to be thicker with sacrificial thicknesses if there are sufficient concerns or unknowns.

(10/1) 2

ENGINEERING TRIPOS PART IIA 2025
MODULE 3D8: Geo-Environmental Engineering
Extracts from the Examiners' Report

Q1: Permeability and flownets

This question was on horizontal and vertical seepage flow through layered granular media. Most candidates answered this question very well with two candidates scoring the full marks. Generally the candidates could handle the anisotropy of the soil and construct a flownet correctly. The stability of the gravity retaining wall was also worked out well by most candidates with a few candidates making numerical errors.

Q2: Seepage through a slope

This question was on seepage flow through a sloping ground. Surprisingly many candidates found this question a bit difficult, particularly working out the potential heads at the locations given. Many forgot to define a datum and instead used the pressure heads given. Also many candidates could not sketch the total and effective stresses correctly. It was however pleasing to see that a few candidates could answer this question well.

Q3: Contaminated land – fate of contaminants and remediation

This was a descriptive six part question on different aspects of contaminated land and remediation including legal, risk, groundwater conditions and remediation. Answered by only one student. Typical of response to such descriptive questions, students usually provide very brief answers that lack elaboration and usually only provide part of the answer. Sometime they also provide a wrong answer or do not really answer the question although they write a lot sometimes.

Q4 Pollutant transport across an in-ground barrier system

A question of six parts on contaminant transport – 3 parts calculations-based and 3 parts descriptive. The question relates to an in-ground barrier system with calculations requested for its design life under diffusion and dispersion/advection flow for different design requirements provided. A popular question answered by most and generally answered well. Again the calculations parts answered better than the descriptive parts.