Q1

a) Void ratio $e = \dfrac{v_v}{v_s}$ Porosity $n = \dfrac{v_v}{V}$

Total Volume $V = v_v + v_s$.

$\therefore n = \dfrac{v_v}{V} = \dfrac{v_v}{v_v + v_s}$

Dividing numerator & denominator by v_v

$n = \dfrac{v_v / v_v}{1 + v_s / v_v} = \dfrac{1}{1 + \frac{1}{e}}$

$$\boxed{n = \dfrac{e}{1+e}}$$ [10%]

b) i) Flownet shown on next page.   [20%]

ii) $Q = K \, \Delta \bar{h} \, \dfrac{N_f}{N_n}$

$\quad = 3.8 \times 10^{-9} \times 9 \times \dfrac{3}{8} = 1.2825 \times 10^{-8} \; m^2/s/m$.

Length of the earth dam = 500 m .

$\quad \therefore Q = 500 \times 1.2825 \times 10^{-8} = 6.4125 \times 10^{-6} \; m^3/s$

iii)
                              or 554.04 litres/day . (quite small)
Pore Pressures :
  At A : $\bar{h}_A \cong 5m$ $y_A = 0$ $h_A = 5$ $P_a = h_a \gamma_w \cong 50 \, kPa$.

  At B : $\bar{h}_B \cong 6m$ $y_B = 4m$ $h_B = 6 - 4 = 2\,m$ $P_B = 20 \, kPa$.

  At C = $\bar{h}_B \cong 6m$ $y_c = 8m$ $h_c = 6 - 8 = -2m$ $P_c = -20 \, kPa$ (suction)
                                                    as there is no air entry
                                                    [20%]

Q1(b)(i)

Datum

$h = 0$

$N_f = 3$

$N_e = 8$

No air entry

10 m

grout

$h = 1.25 m$

$h = 2.2 m$

$h = 3.375 m$

$h = 4.5 m$

$h = 5.625 m$

$h = 6.75 m$

$h = 7.875 m$

40 m

C

B

A

4 m

$h = 9 m$

Silty clay

Shale

9 m

8 m

4 m

-2-

(i)

$K_h = 2 K_v$

No air entry

$\overline{h} = 0$

Datum

Drain

5 m

90 m

G_L

2m

h=1.5m, h=3m, h=4.5m, h=6m, h=7.5m, h=9m

C
B
A

Shale

Silty clay

4 m
8 m
9 m

Q1 c) ii)

$$q = K_{eq} \, \Delta\bar{h} \, \frac{N_f}{N_d}$$

$$K_{eq} = \sqrt{K_h K_v} = \sqrt{4 K_v^2} = 2 K_v$$
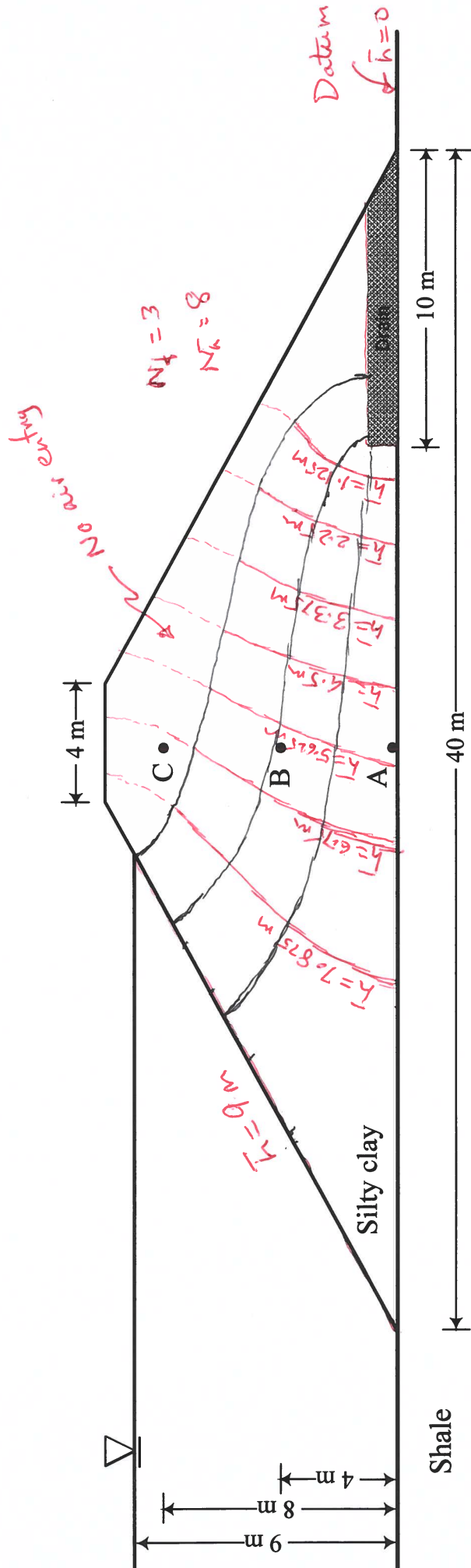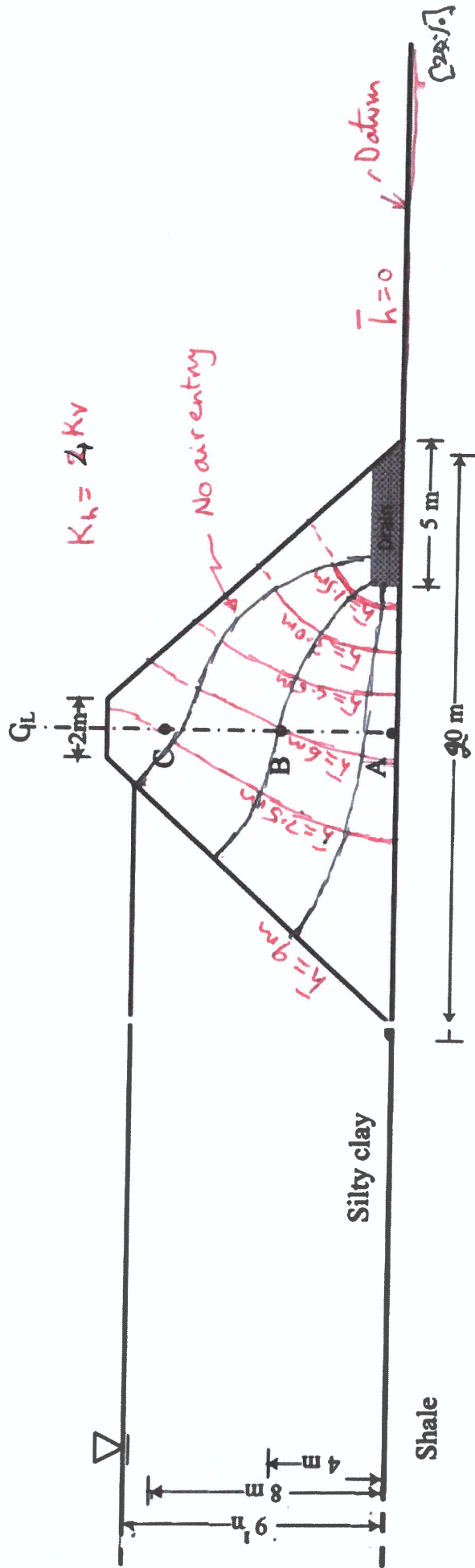
$$= 2 \times 3.8 \times 10^{-9} \times 9 \times \frac{3}{6} = 3.42 \times 10^{-8} \text{ m}^2/\text{s}$$

For a 500 m long dam $\quad Q = 9 \times 500 = 1.71 \times 10^{-5}$ m^3/s.

$$= 1477.44 \text{ litres/day}$$

Q 2) a) Thermal Conductivity λ is a material property that is related to the flow of heat in the granular media. It depends on conduction of heat in both the solid particles and the fluid that fills the voids. λ has units of W/m/K.

Volumetric heat capacity is the amount of heat energy that can be stored or extracted from the ground. It has the units of $J/m^3/K$.

Thermal diffusivity 'λ' is the ease with which heat flows in the granular media. It has the units of m^2/s and is akin to the ~~hydraulic~~ co-efficient of consolidation.

[10%]

b a) Falling head permeameter as shown:
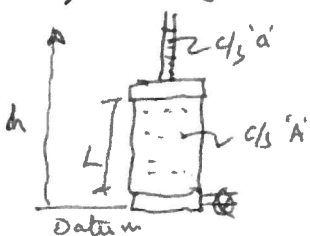
Flow through Soil Sample $Q = KiA = K\frac{h}{L} \times A \rightarrow ①$

Same flow causes a drop of dh in a time of dt in the narrow tube

$$Q = \frac{dh\, a}{dt} \rightarrow ②$$

Equating ① & ②

$$K\frac{h}{L} A = \frac{dh\, a}{dt} \implies \frac{d\bar{h}}{h} = \frac{KA}{aL} dt$$

Integrating $\int_{\bar{h}_1}^{\bar{h}_2} \frac{d\bar{h}}{h} = \frac{KA}{aL}\int_{t_1}^{t_2} dt$ where potential heads h_1, h_2 correspond to times t_1 & t_2

$$\frac{aL}{A} \ln\frac{\bar{h}_2}{\bar{h}_1} \times \frac{1}{t_2 - t_1} = K$$

$$\therefore \quad K = \left[\frac{aL}{A}\right]\left[\frac{1}{(t_2 - t_1)}\ln\frac{\bar{h}_2}{\bar{h}_1}\right]$$

↑ Depend on test setup   ↑ Recorded during test.

[10%]

− 4 −

2(c)

Head h (mm)

20   400

$y = -1812\ln(x) + 8819.6$
$R^2 = 1$

outliers

Time t (min)
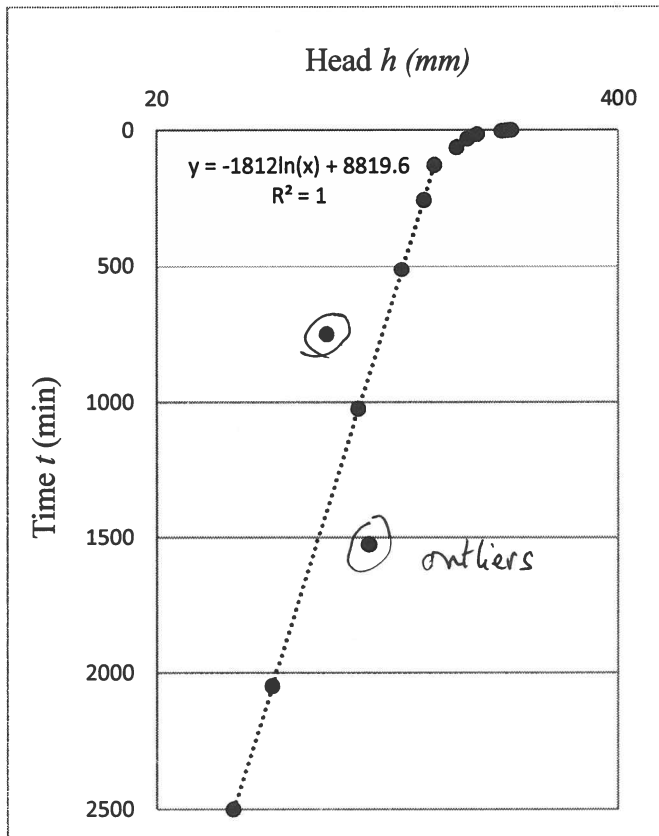
	1812	mm/min
	1.812	m/min
	0.0302	m/s
A/a	2500	
K=	1.20800×10^{-6}	m/s

[30%]

2(d)

$$K = k\frac{\gamma}{\mu} \implies K_{oil} = k\frac{\gamma_{oil}}{\mu_{oil}} \rightarrow ①$$

$$K_w = k\frac{\gamma_w}{\mu_w} \rightarrow ②$$

Dividing ① & ②

$$\frac{K_{oil}}{K_w} = \frac{\gamma_{oil}}{\gamma_w} \times \frac{\mu_w}{\mu_{oil}} = \frac{8.1}{9.81} \times \frac{1}{18}$$

$$K_{oil} = 1.208 \times 10^{-6} \times \frac{8.1}{176.58} = 5.54 \times 10^{-8} \text{ m/s}$$

Assumptions: Hydraulic oil and water occupy the same pore space in the soil.

[40%]

3 (a) Compare and contrast: (i) mineralogy, (ii) forces and bonds, (iii) Isomorphous substitution, (iv) microstructure, (v) surface chemistry, (vi) size, (vii) SSA and (viii) CEC. Link to (i) engineering properties: LL/PL, compressibility and swelling, permeability, shear strength, stiffness, cementitious properties, and relate to ground improvement, liquefaction, embankments, freeze/thaw and swelling damage etc etc and (ii) contaminant binding, sorption and desorption, surface modification for enhanced performance, sealing/expansive additives, contaminant transport and relate to landfill liner and cover design, cut-off walls, S/S, CO2 sequestration, geological disposal and storage etc
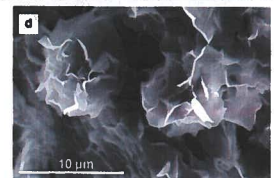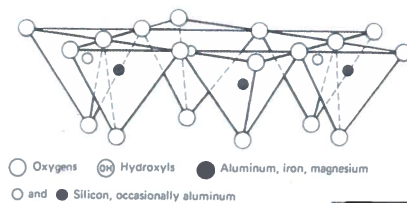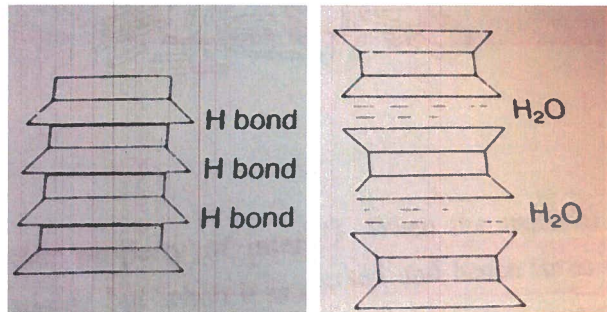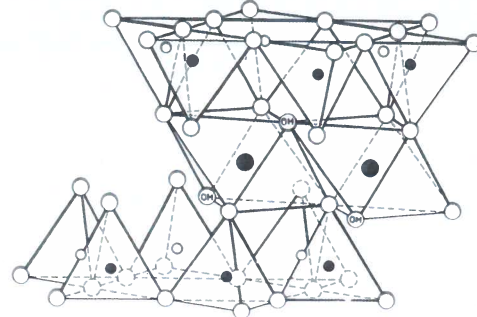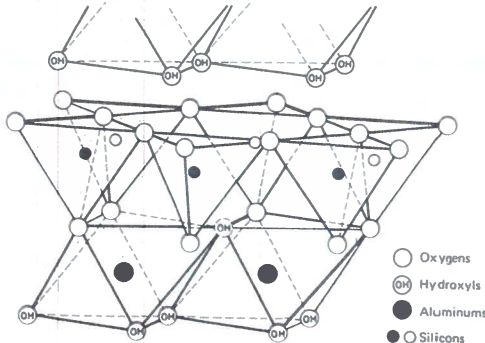
Clay	Diameter (mm)	Thickness (mm)	SSA (m^2/g)	CEC (meq/100g)
Kaolin	0.1-2	0.01-0.1	15-20	5-15
Montmorillonite	0.1-0.5	0.001-0.005	500-800	100-150

(b) (i) $$q = \frac{c_0 V - c_e V}{m}$$

pH 4		pH 8	
q	Ce	q	Ce
(mg/kg)	(mg/l)	(mg/kg)	(mg/l)
165	6.7	310	3.8
310	13.8	590	8.2
600	28	1020	19.6
1200	56	1660	46.8
1500	70.0	2490	100.2
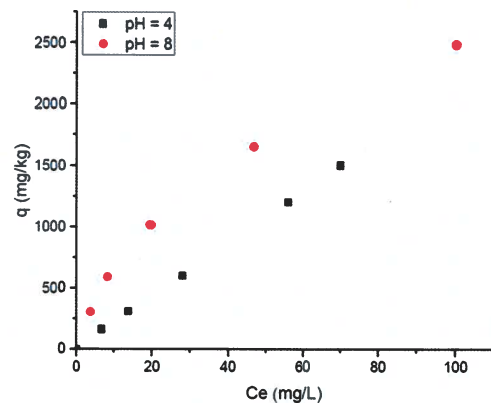
At pH=4, the adsorption isotherm is approximately linear. K_d = q/c_e which is indicated by the slope of the adsorption curve. So K_d = 21 L/kg.

At pH=8, the adsorption isotherm is non-linear. We can use the initial part of the graph to approximate to linear and calculate a Kd value for low concentrations. So looking at the initial 3 points a value of Kd can be calculated to be something in the range of 52- 82 L/kg. Freundlich isotherm is one way to model the whole data. The linear form in this case is log q = log K + n log Ce. The fitted line is shown below and the n is the slope while K = $10^{intercept}$, then n = 0.63, K = 133.7 L/kg.

(ii) The clay surface charge affected by pH is the variable charge (not the fixed charge). The effect is caused by the inorganic surface hydroxyl groups. They are amphoteric so they develop a positive charge at low pH values and a negative charge at high pH. Hence the adsorption cations is expected to increase with increasing pH from 4 to 8 as observed in the calculated above. The comparison is then between linear sorption and high affinity sorption and the students need to explain CEC and the effect of the nature of the surface change and sorption sites on the surface of a clay and their relationship to the sorption behavior.

Equation	y = a + b*x
Plot	log q
Weight	No Weighting
Intercept	2.12509
Slope	0.62502
Residual Sum of Squares	0.00415
Pearson's r	0.99506
R-Square(COD)	0.99104
Adj. R-Square	0.98825
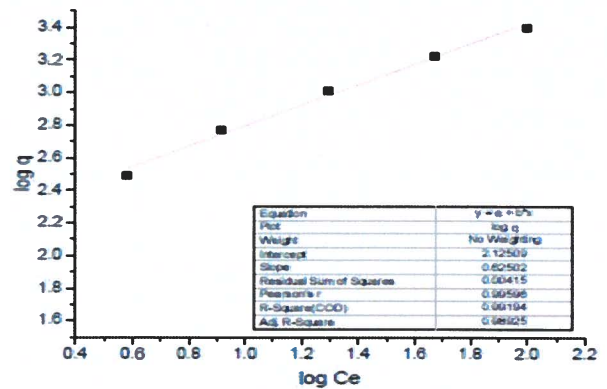
(c) Examples: there are many – these are just a few:

(i) When clays deposited in a freshwater environment are exposed to seawater, which has higher ion concentrations, their structure will change from dispersed to flocculated as a result of the diffuse double layer becoming thinner.

(ii) A phosphate heap placed on soil would cause the underlying soil to disperse, following rain which would cause the negatively charged waste to seep into the underlying ground turning into a dispersed soil, increasing it compressibility and resulting in settlement.

(iii) Acid rain reduces concentration of soils in reservoirs because the diffuse double later becomes thicker leading to a dispersive structures, hence weaker, and particles become more eroded. The same happens with washing detergents as they are dispersion agents.

(iv) Adding lime to a high water content would lead to a flocculated clay structure and this is used in practice in improvement such weak soils.

(v) Adding a dispersant to a soil sample containing clays to disperse for particle size distribution and using the sedimentation test to separate the different clay particles sizes.

(d) Typical example of a hydrocarbon spill in short term and long term: Commonly encountered petroleum products from underground storage tanks: gasoline, diesel, kerosene, heating & lubricating oils. Complex, composed of ~100 different chemical constituents. Each constituent will be extracted at different rate using SVE. Because of their complexity they are usually classified by their boiling point range. As boiling point is measure of volatility, applicability of SVE to petroleum products can be estimated from their boiling point range. Different densities: LNAPL 0.72-0.95 g/cm^3 and DNAPL 1.01-1.65g/cm^3 and different boiling points ranging from < 100°C to >400°C.
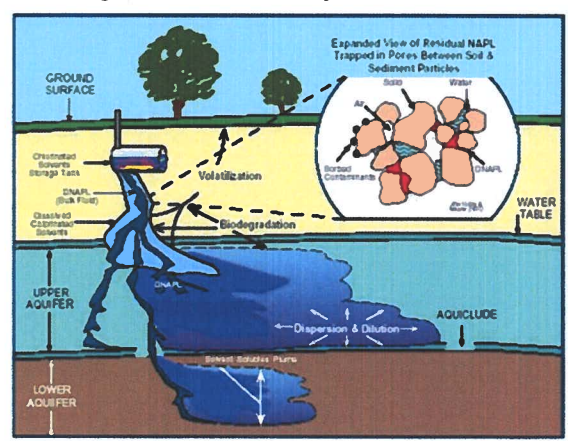
In sandy soils there will be far more contaminant transport and dispersion/spreading. In clays soils the advective transport will be much slower and if lenses of heterogeneities exist, this will accelerate spreading, and there will be far more sorption and retardation. Layered soils or heterogeneous soils will lead to further complex spreading and different behaviour betweent he different layers. Presence of perched water will cause further spreading and heterogeneity of the plume spreading. Presence of shallow ground water will lead to further spreading by dissolution of some phases and floating and sinking of others and the formation of plumes.
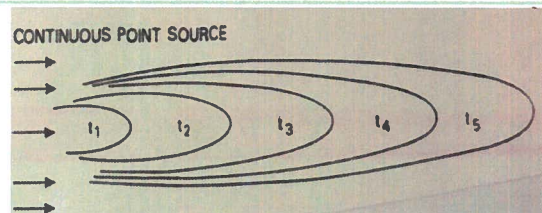
Very complex contamination and plume conditions. But as this is likely to be mainly organic contamination with no heavy metal or inorganic contaminants a combination of the following remediation strategies can be used: SVE, air venting, bioremediation and MNA as well as others. Make your case and justify your choice of remedial solutions.

Q4 Q4 cribs

C_0 = 24.5 mg/L K_v = 1.5 x 10^{-9} m/s
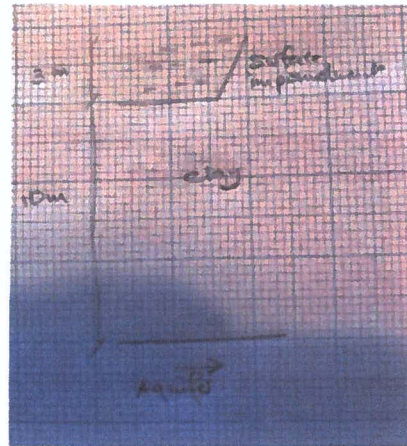
e = 0.7 D_d^* is 5.4 x 10^{-9} $m^2 s^{-1}$

α_l = 0.3 m   bulk density= 2650 kg/m3

Contaminant in aquifer considered to be reach 0.0245 mg L^{-1}

↑

Soil properties and contaminant concentration (initial),

c/s of the model problem.

(a)

(a)   n = e/(1+e) = 0.7/1.7 = 0.41   i = H/L = 13/10 = 1.3

v = K x I = 1.5 x 10^{-9} x 1.3 = 1.95 x 10^{-9} m/s

vf = v/n = 1.95 x 10^{-9} /0.41 = 4.759 x 10^{-9} m/s.

DI = D_d^* + α_l vf = 5.4 x 10^{-9} + 0.3 x 4.759 x 10^{-9} = 6.827 x 10^{-9} m^2/s.

$$\frac{c}{c_o} = \frac{1}{2} \text{ erfc} \left[\frac{z - v_f t}{\sqrt{4 D_l t}} \right]$$

c/co = 0.001, erfc = 0.002, hence β = 2.6

2.6 = (10 - 4.759x 10^{-9} x t)/ √(4 x 6.827 x 10^{-9} x t)

3.846 – 1.830 x 10^{-9} x t = 1.652 x 10^{-4} x √t

Solving quadratic equation for t, gives t = 0.3682 x 10^{9} secs = 11.67 years.

This value is lower than that obtained for diffusion alone in part (a). This shows that dispersion spread the contamination wider than diffusion, due to the nature of dispersion mechanisms and processes.   [15%]

(a)(b)

50% concentration point is at vf x t = 4.759 x 10^{-9} x 0.3682 x 10$_9$ = 1.752m.

Similar to part (b) we need to find the c/co at the depths of 2.5m, 5m and 7.5m.

At 5pm c/co = ½ erfc [5 – 1.752]/√[4 x 6.827 x 10^{-9} x 0.3682 x 10^9]

This gives c/co = 0.1016, hence c = 2.488 mg/L.

Similarly at 7.5m depth, c/co = 0.005 and c = 0.128 mg/L.

At 2.5m depth, c/co = 0.3711, c = 9.09 mg/L.

The dispersion curves follows the expected S shaped profile with the 50% concentration at depth of 1.752m. Link this point with the 24.5mg/L concentration at depth zero, roughly and plot the calculation c values at 2.5m, 5m and 7.5m, similar to the diffusion profile.   [20%]
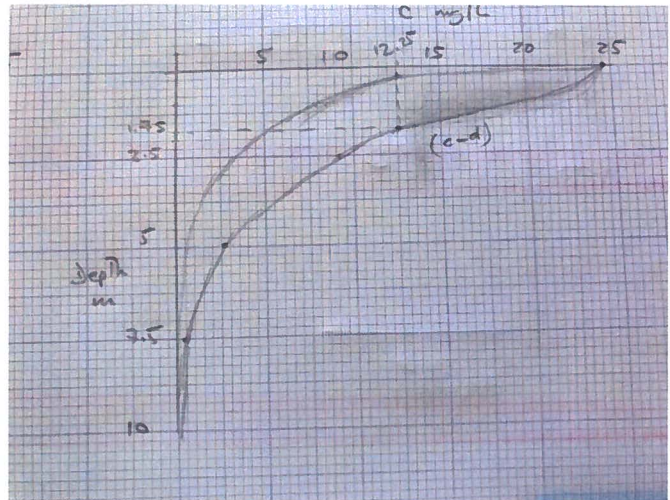
(c) For advective flow, the time that it will take the contaminant to reach the aquifer will simply be depth/vf = 10/ 4.759 x 10^{-9} = 2.1 x 10^9 secs = 66 years.

Given the slow velocity of the flow in clays, the time is expected to be long. Compared with the results in (c) this shows how dispersion accelerates the transport of contaminants. It also shows that diffusion is a faster process in low permeability soils than advection.   [5%]

(d)   Kd = 5 L/kg, Using bulk density of 2.65 kg/m^3 and e of 0.7, calculate the dry density (ρd) using bulk density/(1+e), hence dry density of the clay = 1560 kg/m^3.

The retardation factor can then be calculated using   Rd = 1 + (ρd Kd/n) = 20.02.

The effect is to reduce both the dispersion coefficient and the velocity by the retardation factor, hence DI/Rd = 6.827 x 10^{-9}/20.02 = 3.41 x 10^{-10} and Vf becomes vf/Rd = 4.759 x 10^{-9}/20.02 = 2.377 x 10^{-10}.

The diffusion coefficient will also reduce by 20.02.

Both solutions to the diffusion and dispersion equations can be used again with the revised values. By inspection the time for the contaminant to reach the aquifer in both cases will simply be 20 times longer than calculated in parts (a) and (c). Hence with diffusion only it will take 374 years for the contaminant to reach the aquifer and for the dispersion case, it will take 233 years. For the dispersion case, the 50% concentration point will also reduce by 20 times down to 0.0875m. Hence the effect is retardation of the profile by 20 times, as show on both figures above.   [20%]

(e)
- Physically solidify the liquid contaminant to reduce their availability for leaching
- Chemically stabilize to reduce leaching, e.g. precipitate the contaminant into solids.
- Introduce a form of liner at the base of the impoundment to form a barrier.
- Grout the clay surface to convert to a lower permeability horizontal barrier.
- Reduce the thickness of the impoundment to reduce the hydraulic gradient, to reduce the flow velocity.
- Inject a sorbent into the clay to sorb contaminants that leach out into the clay.
- Any other feasible solutions would be acceptable.   [10%]