Q1 b)

$$K = 3.5 \times 10^{-6} \text{ m/s}.$$

From flownet
$$N_f = 5.5$$
$$N_h = 11$$

$$q = K \Delta h \frac{N_f}{N_h}$$

$$\therefore q = 3.5 \times 10^{-6} \times 3 \times \frac{5.5}{11} = 5.25 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}.$$

$$= \underline{453.6} \text{ litres/day/m.}$$

[10%]

c) From flownet $\bar{h}_A = 2.727$ m $\bar{h}_B = 0.2727$ m.

$$y_A = -0.25 \text{ m} \qquad\qquad y_B = -0.25 \text{ m}$$

$$\bar{h}_A = h_A + y_A .$$
$$2.727 = h_A - 0.25$$
$$h_A = 2.977 \text{ m}$$
$$P_A = \underline{29.2} \text{ kPA}$$

$$0.2727 = h_B - 0.25$$
$$h_B = 0.5227 \text{ m}$$
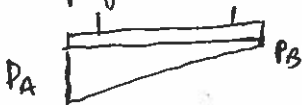$$P_B = \underline{5.127} \text{ kPa}$$

[10%]

d) weight of the building:
$$\text{Area} = 6 \times 4 - \left[3.5 \times \frac{5.25}{2}\right] 2 + 5 \times 0.25 = 6.875 \text{ m}^2.$$
$$\gamma_{conct} = 24 \text{ kN/m}^3.$$
$$\therefore \text{weight of the buildg} = 24 \times 6.875 = 165 \text{ kN/m}$$

Uplift on the buildg:

$$U = \frac{1}{2}[P_A + P_B] \times 5 = 85.8175 \text{ kN/m}$$

$$\therefore \text{Effective weight } W' = W - U = 165 - 85.8175 = 79.1825 \text{ kN/m}.$$
$$\text{Interface friction angle} = 32° \quad \therefore \mu = \tan\phi = 0.625$$

Horizontal force on buildg due to water =

$$H = \frac{1}{2} \times 3 \times 9.81 \times 3 = 44.145.$$

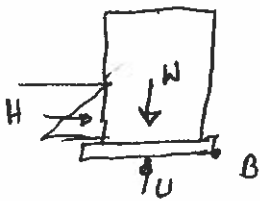$$\therefore \text{FoS against slidg} = \frac{\cancel{W}}{\cancel{W \tan\phi}} = \frac{\cancel{}}{\cancel{}} = \frac{W' \tan\phi}{H}$$

$$= \frac{79.1825 \times 0.625}{44.145} = \underline{1.12}$$
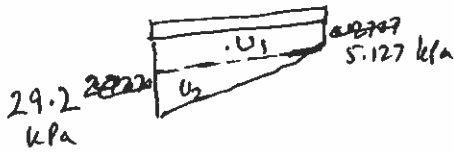
Getting close to sliding!

[20%]

1 e)

Moment due to $N = 165 \times 2.5 = 412.5$ kN-m

Moment due to $H = 44.145 \times \frac{1}{3} \times 3 = 44.145$ kN-m.

Divide uplift into U_1 & U_2.

$U_1 = (5.127 \times \cancel{}) 5 = 25.635$ kN

$U_2 = \frac{1}{2} (29.2 - 5.127) 5 = 60.1825$ kN

29.2 kPa   5.127 kPa

$\therefore$ Moments due to $U_1 = 25.635 \times 2.5 = 64.0875$ kN-m

Moment due to $U_2 = 60.1825 \times \left(\frac{2}{3} \times 5\right) = 200.6083$ kN-m

$\therefore$ FoS against rotation $= \dfrac{412.5}{(44.145 + 64.0875 + 200.6083)}$

$= 1.3356$

Building is more likely to slide than rotate about B.   [20%]

1 f) If the horizontal permeability is higher, than more flood water will leak due to seepage. So leakage rate increases.
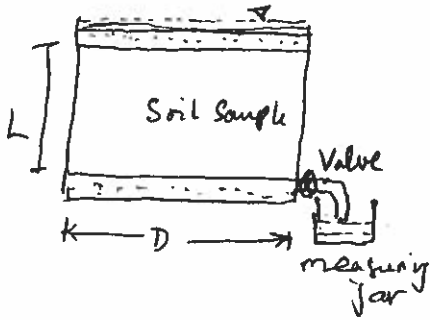
As it is more easy for water to flow, the number of equipotentials N_f will be reduced. This can be verified by drawing a flownet by rescaling the boundary value problem 1:52. The uplift forces can reduce there by increasing the FoS against both sliding & rotation.   [20%]

2 a) Constant Head Permeametre: A soil sample of height 'h' and diametre 'D' is placed in the device, sandwiched between two porous plates. Initially water is admitted from the bottom porous stone and head is raised until the sample is fully saturated. The level of water is always maintained at a constant height above the porous (top) plate. To start the experiment, a valve is open and simultaneously a stop watch is started. The water from the bottom porous plate is collected in a measuring jar in a given time. Using this the flow rate Q is calculated using Darcy's law;

$$Q = K A i \qquad A = \frac{\pi D^2}{4} \qquad i = \frac{\Delta \bar{h}}{\Delta S} = \frac{L}{L} = 1$$

$$\therefore \quad K = \frac{Q}{A \times 1} \qquad \dots (1)$$

The hydraulic conductivity of the soil sample is determined using Eq (1). [20%]

b) As the hydraulic conductivity of clay soils is of the order of 10^{-9} m/s, very little water will come out of the device. Evaporation of the water collected will become a major problem. [20%]

b)

$$Q = 53.2 \text{ ml/min} = 0.886 \text{ ml/s} = 0.886 \times 10^{-6} \text{ m}^3/\text{s}$$

$$Q = K i A$$

$$A = \frac{\pi}{4} \times \left(\frac{50.8}{1000}\right)^2 = 0.002 \text{ m}^2$$

$$i = \frac{d\bar{h}}{ds} = \frac{80 + 60}{80} = \frac{140}{80} = \frac{7}{4}$$

$$K = \frac{0.886 \times 10^{-6}}{\frac{7}{4} \times 0.002} = \underline{2.5 \times 10^{-4}} \text{ m/s}$$

using Hazen's equation

$$K = \frac{1}{100} (D_{10})^2$$

K in m/s, D_{10} in mm.

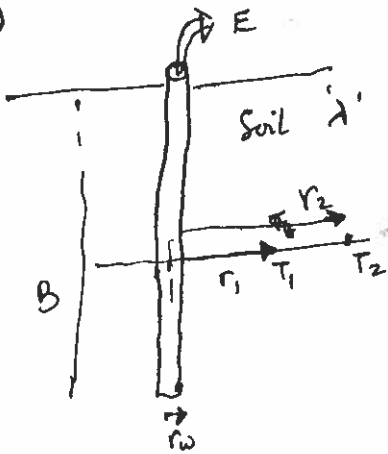$$D_{10}^2 = 100 K = 100 \times 2.5 \times 10^{-4}$$

$$D_{10} = 0.15811$$

$$D_{10} \approx 0.16 \text{ mm}$$

$\therefore$ Average void size $D_{10} = \underline{0.16 \text{ mm}}$ [20%]

2 c)

The heat energy E is extracted from the soil with thermal conductivity of λ.

Using Fourier's law, heat flux

$$H = \frac{E}{2\pi r B} = -\lambda \frac{dT}{dr}$$

For this problem, considering axi-symmetric conditions

$$\frac{E}{2\pi B} \frac{dr}{r} = -\lambda \, dT$$

Integrating between limits.

$$\frac{E}{2\pi B} \int_{r_1}^{r_2} \frac{dr}{r} = -\lambda \int_{T_1}^{T_2} dT$$

$$\frac{E}{2\pi B} \ln \frac{r_2}{r_1} = -\lambda (T_2 - T_1) \implies \lambda = -\frac{E}{2\pi B} \frac{\ln(r_2/r_1)}{(T_2 - T_1)} \quad [20\%]$$

2 d)

Thermal conductivity $= \lambda = 2.9 \; W/m/°c$. $\quad E = 2kW = 2000 \; Watts$

$r_w = \dfrac{0.75}{2} m \quad T_{amb} = 6°c$. $\quad B = 50 \, m$

$$T_2 - T_1 = \frac{2000}{(2\pi \times 50)\lambda} \times 1 \times \ln \frac{r_2}{r_1}$$

$r_1 = 2 + \dfrac{0.75}{2} = 2.375 \, m \qquad r_2 = 5 + \dfrac{0.75}{2} = 5.375 \, m$

$$T_2 - 3 = \frac{2000}{2\pi 50} \times \frac{1}{2.9} \times \ln\left(\frac{5.375}{2.375}\right) = 1.793$$

$$\therefore T_2 = 4.793° c \approx \underline{4.8°c}$$
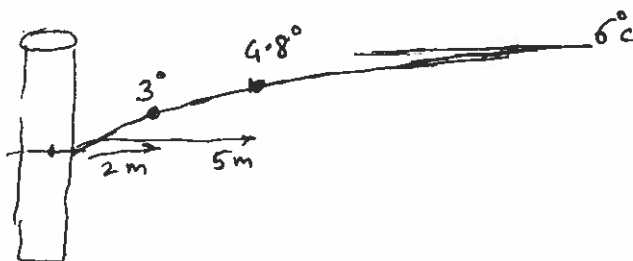
$[20\%]$

2 e) As total heat energy required is 200 kW & each GSHP can extract 2kW, we need 100 GSHP's.

We need to estimate the radius of influence.

$$T_1 = 3°c \text{ at } r_1 = 2.375m$$
$$T_2 = Tamb = 6°c \quad r_2 = ?$$

$$6-3 = \frac{2000}{2\pi \times 50} \times \frac{1}{2.9} \ln\left(\frac{r_2}{2.375}\right)$$
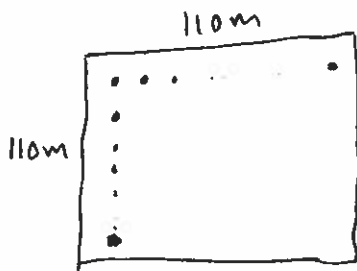
$$\ln\left(\frac{r_2}{2.375}\right) = 1.3665928$$

$$r_2 = 3.9219 \times 2.375 = 9.31466m$$

So choose the radius of influence as 10 m, which should be spacing between GSHP's.

Use a Grid of 10×10 GSHP's with 10 m spacing.

∴ Minimum area required = 11×10 = 110m × 110m

[20%]

Q3   (a) Depth of clay liner for 5% of initial concentration in 50 years' time:
$C/Co = 0.05$, $Dd^* = 2.5 \times 10^{-9} m^2/s$, $t = 50$ years $= 1.577 \times 10^9$ secs.   From erfc table, for $C/Co = 0.05$, $\beta = 1.3874$. Therefore $1.3874 = z/\sqrt{[4 \times 2.5 \times 10^{-9} \times 1.577 \times 10^9]}$, and $z = 5.51m$.   [10%]

(b) If the design life is 100 years, then $t = 3.154 \times 10^9$ secs. β still $= 1.3874$, $1.3874 = z/\sqrt{[4 \times 2.5 \times 10^{-9} \times 3.154 \times 10^9]}$. Therefore $z = 7.78m$.   [5%]

(c) For 10% concentration threshold, from the erfc table, β now becomes: 1.166.
$1.166 = z/\sqrt{[4 \times 2.5 \times 10^{-9} \times 3.154 \times 10^9]}$, therefore $z = 6.55m$.   [5%]

(d) For steady state diffusion, $dc/dt=0$, hence equation (1) becomes: $Dd^* \, d2c/dz2 = 0$, integrating twice gives $C = ax+b$, boundary conditions are: $C(0) = Co$ for $z=0$ and $C(L) = 0$ for $z=L$, hence $b = Co$ and $a = -Co/L$. Hence $C = -Co \, z /L + Co$, and therefore: $C/Co = (L-z)/L$. i.e. a straight line from Co at 0 to 0 at L.   [15%]

(e) Figure:
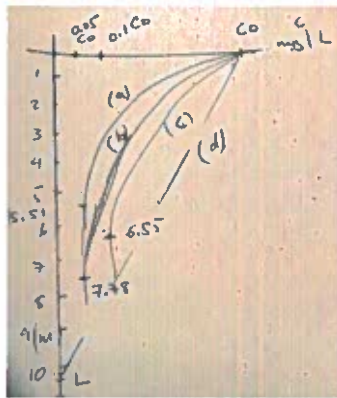
The result from (a) of 5.51m shows that for a single clay liner, quite a large thickness is required. The results from (b) show an even thicker liner of 7.78m is needed for doubling the design life. Doubling the threshold, lightly reduced the depth of liner to 6.55m. Overall, when a single liner is used, a very thick clay layer is needed – This used to be the traditional landfill design, now replaced with a multi-layers thicker set up.   [15%]

(f) If dispersion is also present, this means that there is an advective flow through the liner and hence an advective velocity, and hence an dispersion coefficient. The two coefficients will need to be combined to give the dynamic dispersion coefficient. Also the graph will have more of an 'S' shared at the top to represent the advective/dispersion front.   [10%]

(g) If Kaolin is used instead of bentonite, will lead to a higher diffusion coefficient since Kaolin has a much higher permeability than bentonite. Kaolin is also less sorptive and hence far less effective in binding contaminants. Hence the liner will lose its advantage in being able to retard the movement of contaminants within it.   [10%]

(h) Eq. 1 assume one-dimensional flow and assumes that the soil is homogeneous. Both are not realistic assumptions. The heterogeneity of natural soils will mean that the contaminant transport is likely to include elements of dispersion. This means that the diffusion coefficient will become close to the value of the hydrodynamic dispersion coefficient, which is higher, and hence leaves to faster contaminant transport within the clay liner.   [10%]

(i)   Laboratory scale testing is usually based on more uniform and homogenous conditions and any heterogeneities are usually due to microscopic changes. In the field the clay liner conditions are far less uniform, impacted by macroscale heterogeneities as well as workmanship related issues. Hence, field scale measurements are different from lab scale measurements, sometimes by up to a factor of 10. In addition natural heterogeneous conditions also come into play with dispersion usually expected to play a part and hence the diffusion coefficient will be affected as in (g) above. In addition placement of the liner and its compaction and other workmanship aspects are also likely to impact the results.   [10%]

(j) Reasons for breach of physical integrity of the clay liner: (i) poor construction process leading to a liner with a poor performance, (ii) effect of aggressive landfill contaminants or leachate on the liner clay, could impact thermally, chemically or mechanically, (iii) inadequate safety factors and parameters used in the design, (iv) slope failure. Three remedial measures: (i) injection grouting to repair damage, (ii) injection of sealant to enhance performance of the liner, adding a further layer of protection, (iii) use in-ground barriers if applicable to failure mechanism, (iii) replacing the liner with a more efficient liner system.[10%]

4. (a) The structure of illite and montmorillonite clays [25%]

Montmorillonite is three layer (2:1 type) mineral with gibbsite sheet sandwiched between two silica sheets. The bonds between the sheets are those between O2- and O2- ions, which are weak compared to those between kaolinite layer (O2- and (OH)-). There is also isomorphous substitution, with ~1/6th of the Al3+ in the octahedral sheets replaced by Mg2+ resulting in net negative charge on the surface. The resulting charge deficiency is made up by the adsorption of cations between the montmorillonite crystal sheets. But these are not potassium (as for illite) and are much less effective in keying the sheets together. Water molecules can therefore enter between the montmorillonite sheets, and are the right size to fit into the structure causing large volume change within the crystal itself. Montmorillonite thus exhibits strong swelling characteristics since up to 6 molecules of water can build between the sheets. Because of the poor bonding between adjacent oxygen layers, montmorillonite sheets typically break into extremely small particles of ~0.1-0.5µm in diameter with thickness of ~0.001- 0.005µm. The specific area is between 500 and 800m2/g and the CEC is 100-150 meq/100g clay. There are +ve and -ve charges on broken edges.
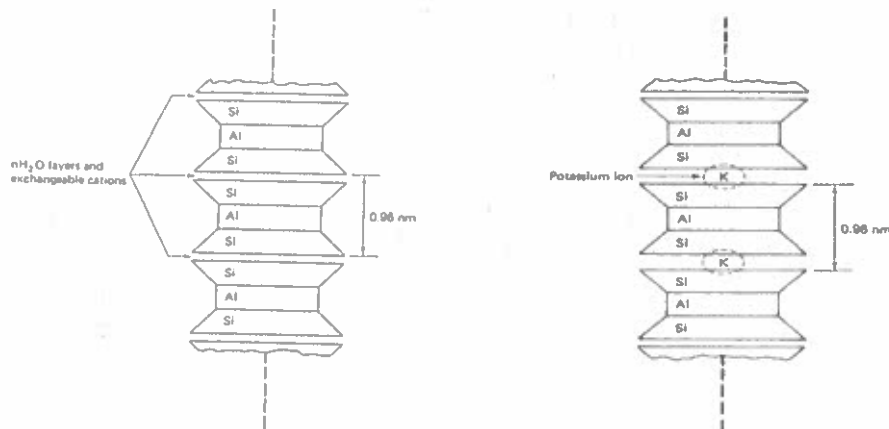
Structure of the clays – left Montmorillonite and right illite

Illite consists of the same structural elements as montmorillonite, so also a three-layered mineral, with the exception that potassium ions occupy positions between the adjacent O2- base planes. The K ions are just the right small size to fit into holes in the silica sheets. Hence the sheets in illite are bonded together more firmly than in montmorillonite. The lattice is as a result much less susceptible to breakage. Illite therefore does not swell so much in the presence of water as does montmorillonite, although it does expand more than kaolinite. Particles are typically ~0.1-0.5 µm and with thickness of ~0.005-0.05µm. Soils containing Illite have properties intermediate between kaolinite and montmorillonite. The CEC is ~20-25meq/100g clay and the specific area is ~80m2/g.

In practice bentonite due to its much higher swelling capacity and CEC is used much more in relevant applications including drilling muds, cut-off wall construction, landfill liners and contaminant sorbents/binders.

(b) The role of pH and redox potential in the fate of contaminants in the groundwater [25%]

pH is a measure of the acidity (values <7) or alkalinity (values >7) of an aqueous solution and neutral at 7. It is based on the concentration of hydrogen ions. Pure water has a hydrogen ion concentration of 10-7 M (pH = 7). Chemicals in water can be affected by pH in different ways. For example, 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.

Eh, in volts, is a measure of the likelihood of chemicals being *oxidised* or *reduced*. A chemical is oxidised if it loses electrons and reduced if it gains them. Many chemical reactions are redox reactions. Oxidation and reduction reactions occur together. For example, iron reacts with oxygen and hydrogen ions: the iron is *oxidised* (Fe becomes Fe^{2+}, losing electrons) and the oxygen reduced (O_2 becomes O^{2-}, gaining electrons,

and reacts with hydrogen ions to form water). An environment with oxygen present will be oxidising, causing materials in it to be oxidised (this will have a *positive* Eh). Conversely, an anaerobic environment (lacking oxygen) is usually reducing, and will have a *negative* Eh. Chemical properties vary depending on if it is oxidised or reduced. Variation in pH can also cause changes in properties. An Eh-pH diagram shows the chemical states an element may take in water with different pH and redox conditions (figure below for manganese). At very low values of Eh, Mn is reduced and is present as the solid metal. Once conditions become more oxidising, it may lose electrons to form the Mn2+ ion and dissolve, if the pH is <7, or it may react with water to form a variety of compounds. Such diagrams allow us to predict the behaviour of a given chemical under different environmental conditions. pH is more commonly used with applications in precipitation and chemical fixation while redox potential is used is used in oxidation/reduction processes.
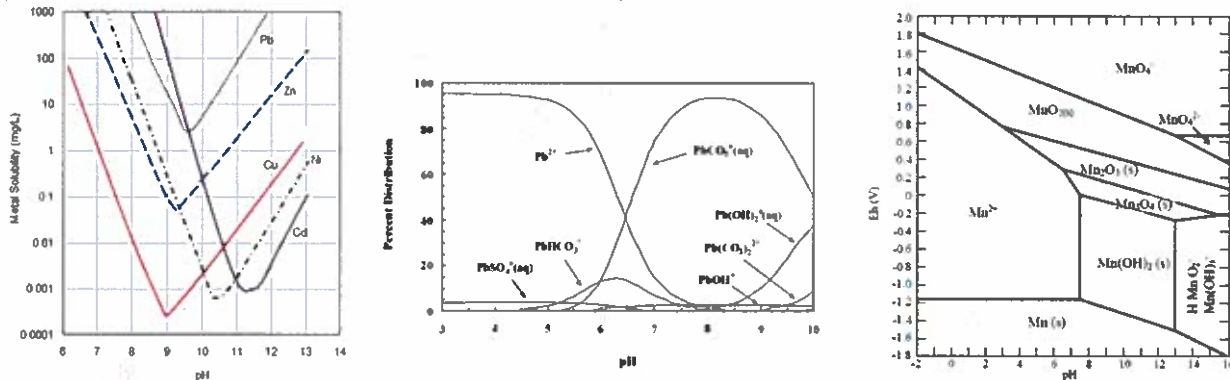
(c) Typical mobility and distribution of heavy metals and organic contaminants in the subsurface.   [25%]

Organic contamination is commonly associated with (i) leakage or hydrocarbon from underground storage tanks, some diffuse source of contamination e.g. application of fertilisers on land. Organic pollution are usually comprised of a large number of compounds, which have different physical properties (boiling point, solubility, Henry's constant). Hence they have different densities and volatilities and in the subsurface, they separate into the different groups. Some remain in the vadose zone and in the unsaturated soil above the groundwater, the more soluble chemicals migrate into the groundwater. LNAPls and DNAPLs, float and sink respectively and remain mainly in the pure phase.

Heavy metals are usually the result of industrial activities, so could be mainly one type of heavy metal or a mix of many e.g. gasworks sites. Their mobility and distribution in the subsurface is dependent on the soil and groundwater conditions. The sorptive capacity of the soil has a dominant factor in the availability and mobility of heavy metals. The cation exchange capacity of any clays present will impact on this. The speciation of the heavy metals is affected by the anions present and the groundwater conditions.

In practice heavy metals generally precipitate within soils and so do not travel very far, but this varies, hence the profile varies within the ground. Usual anions are sulphates and chlorides which have low solubility compared to the nitrates. Organic pollutants are usually in large chemical groups and hence disperse more widely within the subsurface and have a bigger range of properties and hence are more difficult to treat.

 (d) Chemical vs Biological methods of contaminated land clean-up   [25%]

Chemical methods for contaminated land clean-up: Chemical reactions are used to destroy or change the hazardous properties of contaminants or to aid their removal from soil. The range of chemical processes that can be used include:
(i) dechlorination of poly-chlorinated biphenyls (PCBs), (ii) pH adjustment e.g. adding acid to strip adsorbed heavy metal ions such as Cadmium from the soil, (iii) Precipitation, (iv) solvent or surfactant extraction e.g. detergents to aid the removal of DNAPLs, (v) oxidation-reduction reactions, (vi) adsorption

Advantages: (i) the hazardous properties of the contaminants are permanently reduced, (ii) high degree of chemical specificity possible.

Disadvantages: (i) contamination of the soil may increase due to the addition of new material, (ii) the outcome of chemical reactions are not always easy to predict, (iii) in heterogeneous sites different and unexpected reactions may occur.

Biological methods of contaminated land clean-up: In bioremediation, living micro-organisms are used to destroy, remove or transform the hazardous contaminant. It is necessary to optimise the biological activity in anaerobic/aerobic conditions and is applied both *ex-situ* and *in-situ.*

Advantages: (i) the hazardous properties of the contaminants are permanently reduced,(ii) naturally occurring microbes present in the soil can be used, (iii) could be inexpensive, (iv) particularly suited to organic contaminants.

Disadvantages: (i) a more toxic product may be produced, (ii) nutrients and oxygen (for aerobic micro-organisms) need to be supplied, (iii) gas and odours are produced e.g. methane, (iv) some organic pollutants are not easily degraded, (v) the reaction may be slowed by the presence of heavy metals or pesticides, (vi) long treatment times may be necessary

Bioremediation is ideally suited to pure hydrocarbon contamination, the present of some heavy metals could compromise the process. Chemical methods are suitable for easily oxidisable organics, could deal with a mix of heavy metal and organics. Bioremediation is generally more cost effective but is slower.