1   (a)   <u>Site X</u>   <u>Site Y</u>

	Volume		Mass		Volume		Mass

Site X

	Volume		Mass
0.166	Air	0
0.494	Water	0.494
1	Solids	2.70

Site Y

	Volume		Mass
0.349	Air	0
0.233	Water	0.233
1	Solids	2.65

Dry density = 2.7/(1+e)

e = 0.66

Volume air = 0.1 x 1.66 = 0.166

Mc = 0.494/2.7 = 18.3%

LI = (18.3 – 17)/(30-17) = 0.1

Deg of Sat. 0.4 = 0.233/(0.233+Va)

Va = 0.349

e = 0.233+0.349 = 0.582

Relative density = (0.85-0.582)/(0.85-0.35)

= 0.536

The sand is likely to be more widely contaminated due to its higher permeability, but it is easier to clean up, e.g. using soil washing, contamination in clay is unlikely to be wide spread, but more difficult to clean up.

[6]

(b) (i) For horizontal flow the flow in each layer is independent.

$$Q_1 \neq Q_2 \quad \text{but} \quad Q = Q_1 + Q_2 \Rightarrow v_1 \neq v_2$$

$$\Delta \overline{h} = \Delta \overline{h_1} = \Delta \overline{h_2} \quad \therefore i = i_1 = i_2, \quad A = L \times 1$$
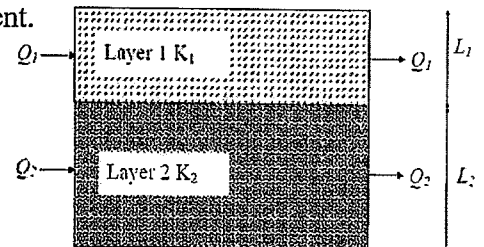
The volumetric flow rate through layer 1 is:

$$Q_1 = v_1 L_1 = K_1 L_1 i$$

where i is the horizontal hydraulic gradient driving the flow. Similarly:

$$Q_2 = v_2 L_2 = K_2 L_2 i$$

Therefore,

$$Q_1 + Q_2 = (K_1 L_1 + K_2 L_2)i$$

and the specific discharge for the deposit as a whole is:

$$v = \frac{Q}{L_1 + L_2} = \left(\frac{K_1 L_1 + K_2 L_2}{L_1 + L_2}\right)i$$

so the effective horizontal hydraulic conductivity is:

$$K_{horizontal} = \frac{K_1 L_1 + K_2 L_2}{L_1 + L_2}$$

Effective horizontal permeability of the soil strata = (2 x 10^{-7} x 2 + 5 x 10^{-5} x 3)/(2 + 3)

= 3 x 10^{-5} m/s

Ratio between the quantity of water flowing through each layer = Q1/Q2 = 4 x 10^{-7}/1.5 x 10^{-4}

= 1/375   [7]

(ii) For vertical flow, continuity of mass flow rate requires that the volumetric flow rate of water through layer 1 be the same as that through layer 2. Assume unit length into the page.

$$Q = Q_1 = Q_2 \qquad A = A_1 = A_2 = v \text{ constant}$$

$$\Delta \overline{h_1} \neq \Delta \overline{h_2} \quad \text{but} \quad \Delta \overline{h_1} + \Delta \overline{h_2} = \Delta \overline{h}$$

Darcy's Law for layer 1 gives the specific discharge:

$$v = \frac{Q}{W} = K_1 \frac{\Delta \bar{h_1}}{L_1} \qquad \Delta \bar{h_1} = v \frac{L_1}{K_1}$$

where $\Delta \bar{h_1}$ is the difference in potential head between the top and bottom of layer 1. Similarly for layer 2:

$$\Delta \bar{h_2} = v \frac{L_2}{K_2}$$

$$\Delta \bar{h_1} + \Delta \bar{h_2} = v \left[\frac{L_1}{K_1} + \frac{L_2}{K_2} \right]$$

$$v = \frac{L_1 + L_2}{\left(\frac{L_1}{K_1} + \frac{L_2}{K_2} \right)} \left(\frac{\Delta \bar{h_1} + \Delta \bar{h_2}}{L_1 + L_2} \right)$$

but $\left(\frac{\Delta \bar{h_1} + \Delta \bar{h_2}}{L_1 + L_2} \right)$ is the average or effective vertical hydraulic gradient across the whole deposit, and so the effective vertical hydraulic conductivity of the deposit is:
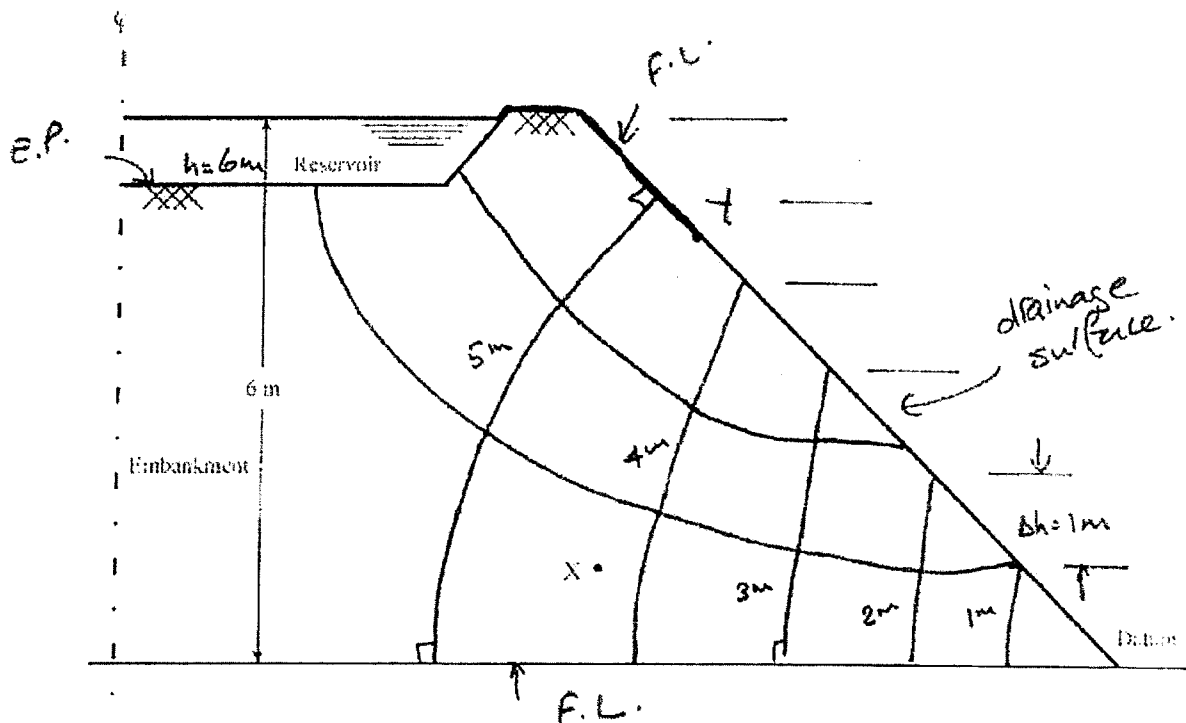
$$K_{vertical} = \frac{L_1 + L_2}{\left(\frac{L_1}{K_1} + \frac{L_2}{K_2} \right)}$$

Effective vertical permeability of the soil strata = $(2 + 3)/[(2/2 \times 10^{-7}) + (3/5 \times 10^{-5})]$
$$= 5 \times 10^{-7} \text{m/s}$$
Ratio of the head losses in each layer = $h_1/h_2 = L_1 K_2/K_1 L_2 = 2 \times 5 \times 10^{-5}/ 2 \times 10^{-7} \times 3 = 166/1$ [7]
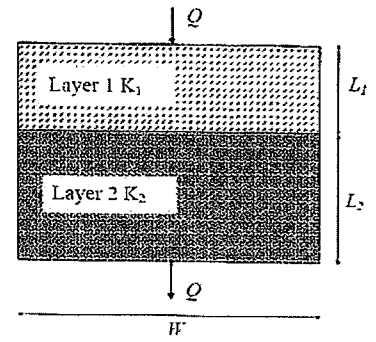
2   (a) See flow net

Darcy's law: $v = k\,i = k\,\Delta h/\Delta L$

$Q_1 = A_1\,v_1 = b_1\,v_1 = b_1\,k_1\,\Delta h_1/\Delta L_1$ etc

If $b = L$ i.e. a square flownet then $Q_1 = k_1\,\Delta h_1$

$Q_2 = Q_3$ because of same flow channel and $Q_1 = Q_2$ because k and Δh are the same.

Therefore total discharge is $Q = N_f\,k\,\Delta h$ or $N_f\,k\,H/N_d$

where N_f is the number of flow channels, Δh is the potential head drop across a square, N_d is the number of equipotential drops and H is the potential head across the whole seepage zone.

The potential head drop across each flownet square is 1.0m, hence the flow in each channel is:

$Q = k\,\Delta h = 0.5 \times 10^{-7} \times 1.0 = 1.5 \times 10^{-7}$ m^3/sec.

There are 3 channels, so the long term seepage quantity is 1.5×10^{-7} m^3/sec/m = 4.73 m^3/year/m [10]

(b) (i) Provide drainage at the base of the embankment or underneath it
   (ii) Widen the crest of the embankment.
   (iii) Ensure that the level of the water does not rise significantly above the based by increasing the area of the reservoir. [2]

(c) The pore water pressure at position X within the embankment is:
   $(h-z)\,\gamma_w = (4.2 - 1.25) \times 10 = 29.5$kPa. [2]

(d) (i) Stabilise the waste water in the reservoir with a binder, e.g. cement.
   (ii) Inject a chemical oxidant depending on the contaminants present.
   (iii) Install an impermeable wall around the perimeter of the reservoir [2]

(e) First appearance at point Y will be along the top flow line.

$v = k\,i = k\,\Delta h/\Delta L$

$t = \Delta L/v_f$ where v_f is the mean linear pore fluid velocity and $v_f = v/n$ where n is the porosity of the embankment material.

Therefore $t = n\,\Delta L/v = n\,(\Delta L)^2 / k\,\Delta h$

$(\Delta L)^2 = (2.4)^2 + (0.65)^2 = 6.18$ m^2 measured from the flownet diagram.

Hence $t = (0.3 \times 6.18) / (0.5 \times 10^{-7} \times 1.0) = 37080000$ secs = 1.17 years [4]

3   More coverage is included here than would be required from the students.

   (a) (i) **Physical treatments** exploit differences in physical properties between contaminants and soil/water system. These include hydraulic properties, electrical properties, sorptive properties. Physical technologies can treat a wide range of inorganic and organic contaminants under different site conditions. Common physical treatment technologies include: (i) Pump and treat and solvent extraction, (ii) Soil vapour extraction and air sparging, (iii) Soil washing and (iv) Electrokinetics. Pump & Treat/Solvent Extraction: Extraction of groundwater and its treatment, may reduce contaminant concentrations in soil due to flushing, treated groundwater may then be either reinfiltrated into the aquifer or surface water, given regulatory approval, P&T technologies can be used for recirculation of ground-water to effect an in-situ treatment referred to as in-situ flushing, range of process enhancements are available including use of surfactants, solvents, fracturing and innovative well design, P&T can be used as containment strategy to prevent plume spreading Soil Vapour Extraction (SVE): In-situ technique of inducing airflow through soil to enhance volatilisation in vadose zone into soil atmosphere, recovered soil air is usually collected for subsequent treatment, airflow is induced in the substrate, by applying a pressure gradient (negative) via a blower or a vacuum pump connected to wells placed in contamination zone resulting in movement of soil air and vapour-phase contaminants towards wells, problem with making all contamination in treatment volume fully accessible to the treatment regime.

Soil Washing: Ex-situ process that employs either mechanical separation (volume reduction) and/or aqueous leaching to remove contaminants from contaminated soils, fundamental principles simple and exploit number of physical properties of contaminant and soil, not usually associated with other

remedial techniques except disposal to landfill – but could form part of sequential treatment methodology e.g. stabilisation/solidification and bioremediation, currently limited to soil types which do not contain significant proportions of organic matter or clay, most effective if fine soil content does not exceed 30%.

Advantages: (i) Contaminants are removed from the soil, (ii) Uses familiar technology, (iii) Flexible, (iv) Can contain the contaminant during clean-up so preventing further advective movement

Disadvantages: (i) Expensive and long-term (may take decades), (ii) Inefficient as clean water also extracted, (iii) Surface treatment necessary, (iv) Needs good hydro-geological survey, (v) Pump-and-treat is effective in highly permeable soils only, and does not flush contaminants either sorbed or trapped in heterogeneities   [4]

(ii) **Chemical treatments** utilise range of chemical reactions to destroy, mobilise, immobilise or neutralise contaminants. Most common chemical treatment technologies for soil remediation include: Oxidation, Reduction and Dechlorination. With most inorganics treatment results in reduced availability (solubility) or reduced toxicity (reduction), reactions involved usually reversible and contaminants not completely destroyed. With organics, chemical treatment leads to destruction or degradation to less toxic compounds

Oxidation: Entails loss of electrons leading to higher valence state e.g. $As^{+3} \rightarrow As^{+5} + 2e-$, or addition of oxygen, Reduction: Entails gain of electrons leading to lower valence state e.g. $Cr^{+6} + 3e- \rightarrow Cr^{+3}$ or addition of hydrogen Oxidation and reduction (redox reaction) occur simultaneously

Oxidising agents: (i) Substances that cause another substance to be oxidised, (ii) Substance that is reduced in a redox reaction, (iii) Typical oxidising agents include hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), which is cheaper, and Ozone (O_3) (gas so difficult to use)

Reducing agents: (i) Substances that cause another substance to be reduced, (ii) Substance that is oxidised in a redox reaction, (iii) Typical reducing agents include iron powder and aluminium.

Advantages: (i) 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) outcome of chemical reactions are not always easy to predict, (iii) in heterogeneous sites different and unexpected reactions may occur.   [4]

(iii) **Biological treatments**: Use of natural bacteria and fungi to treat contaminants, micro-organisms degrade naturally occurring organics, Synthetic organics treated with specific micro-organisms or pre-treated, many micro-organisms can also sorb heavy metals. Biological degradation involves oxidation & other processes used by living organisms to metabolise carbon-bearing substrates to generate energy for growth and reproduction. Bioremediation uses one or more of four basic processes: Biodegradation, Biotransformation, Bioaccumulation, Mobilisation/Immobilisation

Two means of manipulating conditions to effect bioremediation:

Biostimulation: involves the addition of nutrients, oxygen and/or moisture to stimulate micro-organisms in contaminated soils to enhance biological processes. Bioaugmentation: involves the addition of specially prepared 'cultures' of micro-organisms to carry out biodegradation. Biostimulation typically accompanies bioaugmentation. Biostimulation is the most frequently applied and verified approach. Bioavailability is a key limiting factors for bioremediation

Biodegradation: Decomposition of compound into smaller chemical subunits – does not necessarily result in complete mineralisation, usually via enzyme activity on compounds absorbed into cells or through activity of enzymes active outside confines of cell, either aerobic (requires oxygen) or anaerobic (proceeds in absence of oxygen), aerobic biodegradation could lead to complete mineralisation: $C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O$

Anaerobic degradation includes a range of reduction processes: (i) Nitrate reduction to nitrogen, (ii) Iron reduction – iron III to iron II, (iii) Sulphate reduction to hydrogen sulphide, (iv) Methanogenesis – carbon dioxide reduction to methane.

Ex-situ Bioremediation includes Treatment beds: simplest form of ex-situ bioremediation, consists of a treatment area (lined with an impermeable liner) for complete collection of leachate, layer of contaminated soil is spread on top, conditions for bioremediation enhanced by periodic turning or mixing of soil to introduce oxygen, nutrients, water or other additives may be also introduced

In-situ Bioremediation: In-situ bioremediation systems are based on in-situ movement of air (bioventing and biosparging) and water (using passive amendments or through in situ flushing) to simulate biodegradation of organic contaminants. Include Bioventing (similar to SVE): Movement of air through vadose zone stimulates in-situ biodegradation of organics – using either extraction or injection wells, is an application of SVE, movement of air is controlled to maximise rate of in-situ biodegradation and should be accompanied by reduction in extracted VOCs in the exhaust air from the process – generally uses lower air flow rates than SVE. Biosparging (similar to air sparging): Used to optimise biodegradation in saturated zone, air is pumped in small bubbles into the groundwater, encourages bio-degradation of organics both in groundwater and also sorbed onto soil. Advantages: (i) 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, and suitable containment-specific micro-organisms may be available. 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) reaction may be slowed by the presence of heavy metals or pesticides, (vi) long treatment times may be necessary.   [4]

(iv) **Thermal Treatments**: Use of elevated temperatures to achieve rapid physical and chemical processes such as volatilisation, combustion and/or pyrolysis (incomplete combustion in the absence of air) of contaminants. Most common for treatment of soils contaminated with organics.
Can also be used to treat asbestos (decomposition at 900oC), but not applicable for most other inorganic. Most treatments are ex-situ. Typical methods include: Thermal desorption, Incineration.
Thermal desorption: Physical separation process in which wastes are heated to desorb (from soil) and volatilise organic contaminants, not designed to destroy contaminants, vapour and gases are collected and treated, high temperature thermal desorption heats waste to 320-560°C & targets SVOCs, PAHs, PCBs, pesticides & high boiling point petroleum products.
Low temperature thermal desorption heats waste to 90-320°C and targets nonhalogenated VOCs & low boiling point petroleum products.
Advantages: (i) hazardous properties of contaminants are permanently reduced, (ii) Uses well-established technology, (iii) Treatment residue or end product is usually soil-like.
Disadvantages: (i) Generally very expensive, (ii) May produce gas and particle emissions, (iii) Metals are not destroyed.   [4]

(b) Historical land remediation is dealt with through risk-based management where the site contamination is assessed in terms of the risk that a receptor is exposed to. There are various models and softwares that will assess the risk to either human health or protected waters. Remediation of the site is hence based on reducing the risk to acceptable levels rather than removing the risk completely and hence removing all contamination from the site. New land contamination is likely to be subject to the Integrated Pollution and Prevention and Control (IPPC) legislation which will require complete clean up of the site and returning the site to its pre-contamination status. With the introduction of the EU Landfill task it is now very difficult to send contaminated soil to landfill and hence most contaminated soils are retained on sites in one way or another. This is increasing the treatment of contaminated soil in site for use in various applications on the site such as backfill. [4]

4. $z = 2m$, $v_f = 0.5 \times 10^{-8}$ m/s, $D_d = 0.5 \times 10^{-9}$ m²/s, $\tau = 0.45$, $\alpha = 0.35$.

(a) $D_d^* = 0.5 \times 10^{-9} \times 0.45 = 0.225 \times 10^{-9}$ m²/s
$c/c_o = 0.00$ 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 $t = 4.938 \times 10^8$ secs $= 15.6$ years   [4]

(b) $c/c_o = 0.01$, 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 $t = 1.33 \times 10^9$ secs $= 42.3$ years   [2]

(c) $D_l = D_d^* + v_f \alpha = 0.225 \times 10^{-9} + 0.5 \times 10^{-8} \times 0.35 = 1.975 \times 10^{-9}$ m^2/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 secs = 1.4 years   [6]

(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.   [4]

(e) (i) The cement grout could also include a reactive additive which will remove the contaminants as they move through the wall.

(ii) A permeable reactive barrier wall section could be constructed around the site to clean up contaminated groundwater.   [2]

(f) (i) Check lists of classification for inert and hazardous wastes for compliance

(ii) Perform the appropriate leaching test.

(iii) compare leachate concentrations against published values for inert, hazardous and non-hazardous landfill criteria.   [2]

Dr A Al-Tabbaa
January 2011

ENGINEERING TRIPOS PART IIA 2011

MODULE 3D6: ENVIRONMENTAL GEOTECHNICS

Numerical Answers

1.   (a)   (i) 18.3%, 0.1.
           (ii) 0.582, 0.536
     (b)   (i) 3×10^{-5} m/s, 1/375
          (ii) 5×10^{-7} m/s, 166/1

2.   (a) 4.73 m^3/year/m
     (c) 32kPa
     (e) ~1.2 years

4.   (a) 156 years
     (b) 423 years
     (c) 1.53 years

Dr A Al-Tabbaa
Principal Assessor
20 May 2011