ENGINEERING TRIPOS   PART IIB

Wednesday 5 May 2004   9 to 10.30

Module 4D14

CONTAMINATED LAND AND WASTE CONTAINMENT

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is
indicated in the right margin.*

Attachments: 4D14 datasheets (10 pages)

You may not start to read the questions
printed on the subsequent pages of this
question paper until instructed that you
may do so by the Invigilator

1.   Gasoline has been leaking from an underground storage tank of a shipyard. Soil sampling was conducted at the site and the measured hydrocarbon soil concentrations are listed in Table 1. The sample mean and biased standard deviation are also listed in the table. The bulk density of the soil is 1800 kg/m^3 and the soil contained 2% of organic carbon. The subsurface temperature is 20 °C.

(a)   Using the maximum value test, show that the largest value in the table should not be treated as an outlier.   [10%]

(b)   Calculate the normalised upper bound concentration for 95 percentile confidence.   [10%]

(c)   Benzene is the major component of the spilled contaminants. Estimate the aqueous phase concentration in the soil (in mg/L) assuming that the soil concentration evaluated in (b) is the sorbed benzene concentration. Use the linear adsorption isotherm model.   [20%]

(d)   Estimate the vapour phase concentration (in ppmV) based on the aqueous phase concentration determined in (c).   [20%]

(e)   The total volume of the contaminated soil is estimated to be 200 m^3. Assuming that the volumetric water and air contents are 0.05 and 0.3, estimate the total mass of benzene in the soil. It is assumed that there is no non-aqueous phase liquid (NAPL).   [20%]

(f)   If NAPLs are present in the ground, what are possible remediation technologies to remove them? Identify two potential technologies and describe the removal mechanisms.   [10%]

(g)   Monitored natural attenuation (MNA) is proposed to remediate the benzene in the groundwater. Discuss why MNA is suitable for benzene remediation.   [10%]

Table 1. Measured soil concentrations of soil samples

No.	1	2	3	4	5	6	7	8
Conc. (mg/kg) X	80	350	150	160	130	90	210	120
Log(Conc.) Y = log(X)	1.90	2.54	2.18	2.20	2.11	1.95	2.32	2.08

X mean = 161 mg/kg, X standard deviation = 87 mg/kg
Y mean = 2.16, Y standard deviation = 0.204

2. Groundwater contamination by Trichloroethylene (TCE) was found in a sandy aquifer near an industrial site and Fig. 1 shows the extent of the plume. The aquifer thickness is 25 metres. The bulk density and the porosity of the sand are 1800 kg/m^3 and 0.35, respectively.

(a) What are the potential industrial applications of TCE? [15%]

(b) The free phase of TCE is often difficult to find in the ground. Why? [10%]

(c) List two potential remediation technologies to remove the free phase of TCE. Discuss the removal mechanisms. [15%]

(d) List mechanisms of the fate and transport of TCE contaminant in the dissolved plume. [10%]

(e) Calculate the retardation factor. The sand contained 1 % of organic carbon. [20%]

(f) The hydraulic conductivity and gradient of the sandy aquifer are found to be 40 m/day and 0.005, respectively. Estimate when the spill initiated. [15%]

(g) A pump-and-treat operation is proposed to avoid the plume from moving downstream further. Using two groundwater extraction wells with a pumping rate of 0.2 m^3/min, estimate the geometry of the capture zone. Sketch the optimal well locations in relation to the location of the plume. [15%]
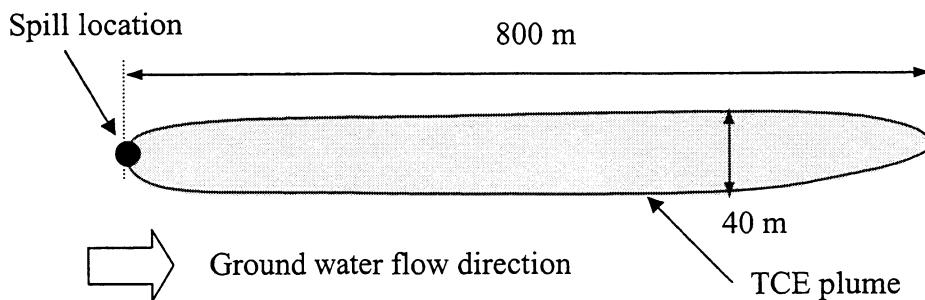

Fig. 1

3. (a) Give examples of geosynthetic materials used in the design of landfill components. Discuss briefly the function they serve.   [20%]

(b) A landfill was constructed with its side slope consisting of a single clay liner overlain by a HDPE geomembrane that is 4 mm thick. The weight of this geomembrane is 18 kg/m^2. The depth of the landfill is 15 m and the side slope of a landfill is constructed at 70° to the horizontal as shown in Fig. 2. The height of the waste deposited is also 15 m as shown in Fig. 2. The friction angle between the underside of the geomembrane and the clay liner is 9°. Estimate the self-weight stress induced in the geomembrane.   [20%]

(c) Laboratory experiments determined that the friction angle between the upper side of the geomembrane and the waste is 6°. The waste was compacted poorly and as a result had a unit weight of 6 kN/m^3. Estimate the down-drag stress induced in the geomembrane lining of the side slope due to the settlement of the waste. For the purposes of this estimation you may ignore the shear strength of the waste. Without calculations explain what will be the effect of considering the shear strength of waste on the estimated down-drag stress.   [30%]

(d) Hazardous waste is disposed of by underground injection wells. Describe the siting criteria that are used in locating such injection wells. How would you determine the radial extent over which the injected waste is disposed of by considering the volumetric method? How is this radius affected if you consider the dispersion of injected waste?   [30%]
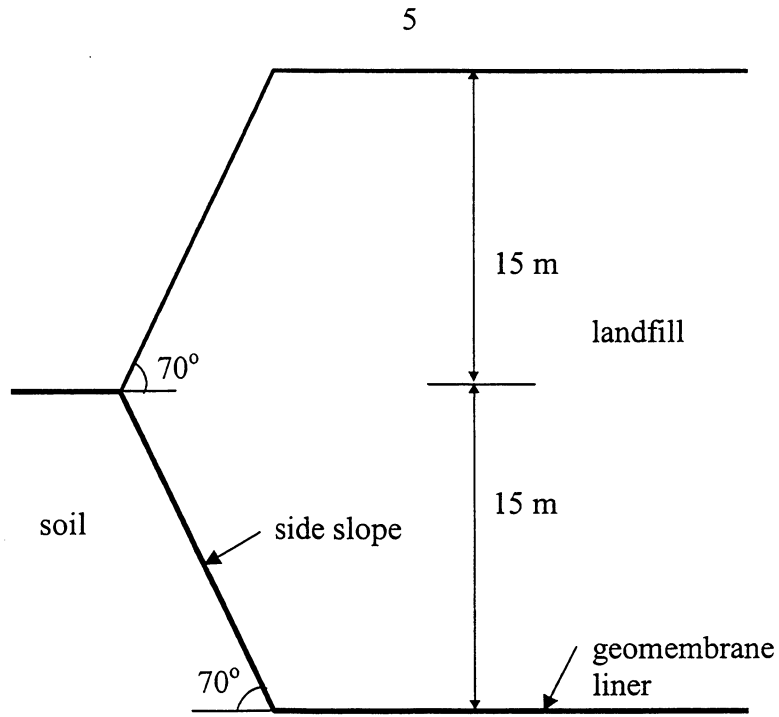
(Cont.

Fig.2

4   (a)   What types of reactions can take place within the waste in a landfill? Give examples of some of the products that can be formed due to these reactions.   [20%]

(b)   What do you understand by the term 'waste-soil interaction'? Why is it important to consider waste-soil interaction while designing waste containment systems?   [20%]

(c)   A new landfill is being planned for a suburban area near London. It was decided that the new landfill will receive waste for 8 years. The construction of the landfill will take one year from the present time. The cost of construction of this landfill is estimated to be £ 1.3 million and running cost of the landfill will be £ 0.45 million per year. New compaction equipment will be used during the operation of the landfill and it is anticipated that the waste fill will be compacted to achieve an average unit weight of 9.0 kN/m^3. The present population of the suburban area is 680,000. Assuming that the average waste produced by each person is 20 kg per week, estimate the following:

(i)   the volume of the landfill that would be required, assuming an increase in population in this area of 10% per year;   [10%]

(ii)   approximate dimensions of the new landfill, assuming the depth of the landfill to be 20 m;   [10%]

(iii)   profit generated by this project, if a flat fee of £28.50 is charged per ton of waste to be disposed in the landfill (excluding landfill tax);   [10%]

(iv)   the government revenue raised in landfill tax if the average landfill tax during the life of the landfill is £8 per ton in addition to the flat fee.   [10%]

(d)   A vertical barrier in the form of slurry walls is planned to protect a fresh water reservoir from ground water contamination. The soil surrounding the water reservoir has sandy silt strata overlying a thick layer of stiff clay. Give an example with help of suitable sketches of the vertical barrier system.   [20%]

END OF PAPER

Part IIB

4D14 Contaminated Land and Waste Containment

DATABOOK

2003/2004 Edition

Cambridge University Engineering Department

1. Contaminated Land

1.1 Basics

Mole   = Mass/Molecular weight

Molarity = Mole per 1 litre of liquid (mol/L)

mg/L   = Molarity (mol/L) x Molecular weight (g/mol) x 10^3 (mg/g)

1 litre = 4.82 x 10^{-5} mole

1.2 Mass and Concentration relationship

Solid phase

1 ppm = one part mass of a compound in one million parts mass of the media containing it.
   [mg/Kg]

1 ppb = one part mass of a compound in one billion parts mass of the media containing it.

Aqueous phase

1 ppm   = one part mass of a compound in one million parts mass of the media containing it.

   = 1 μg in 1 g of water [μg/g]

   = 1 mg in 1 L of water [mg/L]

Gas phase

1 ppmV = 1 ppm by volume

   = MW/22.4 [mg/m^3] at 0 °C

   = MW/24.05 [mg/m^3] at 20 °C

   = MW/24.5 [mg/m^3] at 25 °C

   MW = the molecular weight of the compound

1 atm   = 10^6 ppmV

1.3 Mass of contaminants present in different phases

1.3.1 Total mass of contaminants

$$M_t = V(\phi_w)C + V(\rho_b)X + V(\phi_a)P + \text{free product}$$

where M_t = total mass of contaminant (usually in mg)

   V = Volume of soil (usually in litres)

   ϕ_w = volumetric water content

   ϕ_a = volumetric air content

   ρ_b = density of the soil

   C = aqueous phase concentration (usually in mg/L)

X = soil concentration (usually in mg/Kg)

P = gas phase concentration (usually in mg/L)

1.3.2 Free product – Gas phase

Vapour pressure P^{vap} = the pressure exerted by its gas phase at equilibrium, usually expressed in millimetres of mercury (mmHg)

760 mmHg = 1 atm = 1.013 x 10^5 N/m²

Vapour pressure of a compound in a mixture

$P_A = P^{vap}{}_A \cdot x_A$,   (Raoult's law)

where P_A = partial pressure of compound A in the gas phase

$P^{vap}{}_A$ = vapour pressure of compound A as a pure liquid

x_A = mole fraction of compound A in the free phase

Vapour pressure of a mixture

$P_{mix} = \Sigma P^{vap}{}_i \cdot x_i$ (i – individual compounds)

1.3.3 Free product – aqueous phase

Solubility S = the concentration in the aqueous phase at equilibrium, usually expressed in mg/L

Solubility of a compound in a mixture

$S = S_A \cdot x_A$,   (Raoult's law)

where   S = partial concentration of compound A in the aqueous phase

S_A = Solubility of compound A as a pure liquid

x_A = mole fraction of compound A in the free phase

Solubility of a mixture

$S_{mix} = \Sigma S_i \cdot x_i$ (i – individual compounds)

1.3.4 Aqueous phase – gas phase

Equilibrium between gas concentration P and aqueous phase concentration C

$P_A = H_A \cdot C_A$ (Henry's law)

where P_A = partial pressure of compound A in the gas phase

H_A = Henry's constant of compound A (usually in atm/M, M –solution molarity in (mol/L)

C_A = concentration of compound A in the aqueous phase.

Henry's constant H of compound A

$$H = \text{vapour pressure/solubility at a given temperature}$$

1.3.5 Aqueous phase – Solid phase

Adsorption isotherms

$X = X_{max} KC/(1 +KC)$	The Langmuir isotherm
$X = KC^{1/n}$	The Freundlich isotherm
$X = KC$	The linear isotherm

where X is the sorbed concentration, C is the liquid concentration, K and n are the equilibrium constants, and X_{max} is the maximum adsorbed concentration.

For an organic compound,

$$K_p = f_{oc} K_{oc}$$

where K_p = the partition coefficient ($X = K_pC$, where X and C above)

    f_{oc} = the fraction of organic carbon,

    K_{oc} = the organic carbon coefficient = $f(K_{ow}$ or $S_w)$ (in L/Kg or mL/g)

K_{oc} vs. K_{ow} (K_{oc} in L/kg or mL/g)

$\log K_{oc} = 0.544 (\log K_{ow}) + 1.377$ Aromatics, pesticides (Kanaga and Goring, 1980)

$\log K_{oc} = 1.00 (\log K_{ow}) - 0.21$ Polyaromatic compounds, chlorinated hydrocarbons (Karichhoff, Brown and Scott, 1979)

where K_{ow} = octanol-water partition coefficient, indicator of how an organic compound will partition between an organic phase and water.

1.4 Mass transport in saturated media

1.4.1   Migration speed of dissolved plume

$V_p = V_s/R$

    V_p = the velocity of the dissolved plume

    V_s = groundwater seepage velocity = V (Darcy's velocity)/ϕ (porosity)

    $V = ki$, where k is the hydraulic conductivity and i is the hydraulic gradient

    R = Retardation factor

$R = 1 + (\rho_d K)/\phi$

    ρ_d = bulk density of soil

    K = the partition coefficient (see 1.3.3)

    ϕ = porosity

1.4.2 Analytical solutions to the Advection-Dispersion equation

[Case 1] One-dimensional step change in concentration

Boundary and initial conditions

$C(x, 0) = 0$	$x \geq 0$	Initial condition
$C(0, t) = C_0$	$t \geq 0$	Boundary condition
$C(\infty, t) = 0$	$t \geq 0$	Boundary condition

Solution

$$C = \frac{C_0}{2}\left[erfc\left(\frac{L - v_x}{2\sqrt{D_L t}}\right) + \exp\left(\frac{v_x L}{D_L}\right) erfc\left(\frac{L + v_x}{2\sqrt{D_L t}}\right)\right]$$

where v_x = average linear water velocity

L = flow distance

D_L = hydrodynamic dispersion coefficient in the longitudinal direction

[Case 2] One-dimensional continuous injection into a flow field

Boundary and initial conditions

| $C(x, 0) = 0$ | $-\infty < x < +\infty$ | Initial condition |
| $C(\infty, t) = 0$ | $t \geq 0$ | Boundary condition |

$\int_{-\infty}^{\infty} n_e C(x,t)dx = C_0 n_e v_x t \quad t \geq 0$ Boundary condition (Constant rate injection)

where n_e = effective porosity

Solution

$$C = \frac{C_0}{2}\left[erfc\left(\frac{L - v_x}{2\sqrt{D_L t}}\right) - \exp\left(\frac{v_x L}{D_L}\right) erfc\left(\frac{L + v_x}{2\sqrt{D_L t}}\right)\right]$$

[Case 3] Continuous injection into a uniform two-dimensional flow field

Boundary and initial conditions

Continuous injection at origin of a solute with a concentration C_0 at a rate Q over the aquifer thickness b.

Solution

$$C(x,y,t) = \frac{C_0(Q/b)}{4\pi(D_L D_T)^{0.5}} \int_{\theta=0}^{\theta=\infty} \exp\left[-\frac{(x - v_x\theta)^2}{4D_L\theta} - \frac{y^2}{4D_T\theta}\right]\frac{d\theta}{\theta}$$

where D_T = hydrodynamic dispersion coefficient in the transverse direction

Steady state condition

$$C(x,y,t) = \frac{C_0(Q/b)}{4\pi(D_L D_T)^{0.5}} \exp\left(\frac{v_x x}{2D_L}\right) K_0\left[\left(\frac{v_x^2}{4D_L}\left(\frac{x^2}{D_L} + \frac{y^2}{D_T}\right)\right)^{1/2}\right]$$

where K_0 = the modified Bessell function of the second kind and zero order

[Case 4] Accidental injection into a uniform two-dimensional flow field

Boundary and initial conditions

A contaminant with concentration C_0 is injected over an area A at the origin.

Solution

$$C(x,y,t) = \frac{C_0 A}{4\pi t(D_L D_T)^{0.5}} \exp\left(-\frac{(x - v_x t)^2}{4D_L t} - \frac{y^2}{4D_T t}\right)$$

1.5 Groundwater extraction

1.5.1 Steady-state flow in a confined aquifer

$Q = [2.73Kb(h_2-h_1)]/\log(r_2/r_1)$

where   K = hydraulic conductivity of the aquifer (m/day)

       b = thickness of the aquifer (m)

       h_1, h_2 = static head measured from the aquifer bottom (m)

       r_1, r_2 = radial distance from the pumping well (m)

1.5.2 Steady-state flow in an unconfined aquifer

$Q = [1.366K(h_2^2-h_1^2)]/\log(r_2/r_1)$

where   K = hydraulic conductivity of the aquifer (m/day)

       h_1, h_2 = static head measured from the aquifer bottom (m)

       r_1, r_2 = radial distance from the pumping well (m)

1.5.3 Capture zone (well located at the origin)

Single well

       $y = \pm(Q/2Bu) - (Q/2\pi Bu)\tan^{-1}(y/x)$

where   Q = groundwater extraction rate

       B = aquifer thickness

       u = regional groundwater velocity = Ki

       K = hydraulic conductivity

       i = hydraulic gradient

Multiple wells

No. of wells	Optimal distance between each pair of extraction wells	Distance between the streamlines at the line of the wells	Distance between the streamlines at far upstream from the wells
1	-	0.5Q/Bu	Q/Bu
2	0.32Q/Bu	Q/Bu	2Q/Bu
3	0.40Q/Bu	1.5Q/Bu	3Q/Bu
4	0.38Q/Bu	2Q/BU	4Q/Bu

1.6 Statistical Tables

1.6.1 The upper 95 percentile value

$$US_{95} = \bar{X} + (t\,s)/\sqrt{n}$$

where $\bar{X}$ is the sample mean, t is given in the table below, s is the sample standard deviation, and n is the number of samples.

Table A 1.1 Relationship between sample size (n) and t

n	t	n	t	n	t
-	-	11	1.812	21	1.725
2	6.314	12	1.796	22	1.721
3	2.920	13	1.782	23	1.717
4	2.353	14	1.771	24	1.714
5	2.132	15	1.761	25	1.711
6	2.015	16	1.753	26	1.708
7	1.943	17	1.746	27	1.706
8	1.895	18	1.740	28	1.703
9	1.860	19	1.734	29	1.701
10	1.833	20	1.729	30	1.699

1.6.2 Maximum value test

$$T = (y_{max} - \bar{y})/S_y$$

where $\bar{y}$ is the mean of y (=logx, x is the sample value), $y_{max} = \log(x_{max})$, x_{max} is the value in question, Sy is the standard deviation of y. T is to be compared to T_{crit} as shown in the table below.

Critical values to test for the presence of outliers

Sample no.	4	5	6	7	8	9	10	12	14	16	18	20
5 %	1.46	1.67	1.82	1.94	2.03	2.11	2.18	2.29	2.37	2.44	2.50	2.56
10 %	1.42	1.60	1.73	1.83	1.91	1.98	2.04	2.13	2.21	2.28	2.33	2.38

2.Waste Containment

2.1 Population rise

$$P_{new} = P_{current} \cdot \left[1 + \frac{r}{100}\right]^n$$

where   r is percentage rate of increase of population

n is the number of years.

2.2 Darcy's Law

$$v = Ki$$

where   K is the hydraulic conductivity

i is the hydraulic gradient.

2.3 Manning's formula for flow velocity in Open Channels

$$V = \frac{1.486}{n} R_h^{2/3} . S^{1/2}$$

where R_h is the hydraulic radius defined as Area divided by Wetted Perimeter

n is the Manning's constant

S is the slope

Values of Manning's constant:

Material of pipes	n
PVC	0.01
HDPE	0.009
Concrete	0.016 ~ 0.017
Steel	0.016

2.4 Flow through pipes

$$Q = A.V$$

where   A is the cross-sectional area

V is the velocity of flow.

2.5 Leakage through composite liner, geomembrane in good contact with a low permeability layer

$$Q = 0.7 \, a^{0.1} \, K^{0.88} \, h$$

where   Q is the flow rate (m^3/s)

a is the area of the hole (m^2)

K is the hydraulic conductivity of the low permeability soil (m/sec)

h is the liquid depth above the geomembrane (m)

2.6 LCRS analysis

Assuming leachate will distribute equally between two pipes under gravity flow; we have the following relations;

$$Q = q \cdot \frac{L}{2}$$

$$Q = 2K \cdot \frac{h_{max}^2}{L}$$

$$L = 2h_{max} \sqrt{\frac{K}{q}}$$

where   Q = flow into each pipe

q = flow rate into the drainage layer

K = hydraulic conductivity of the drainage layer

L = spacing between the drainage pipes

h_{max} = maximum height to which leachate is allowed to rise in the drainage layer (usually taken as the thickness of the drainage layer so that at worst location the leachate is just at the interface between the waste and the drainage layer)

Chemical properties of Common Contaminants

Compound	MW (g/mole)	H (atm/M)	P^{vap} (mmHg)	D (cm^2/s)	Log K$_{ow}$	Solubility (mg/L)	T (°C)
Benzene	78.1	5.55	95.2	0.092	2.13	1780	25
Bromomethane	94.9	106		0.108	1.10	900	20
2-Butanone	72	0.0274			0.26	268,000	
Chlorobenzene	112.6	3.72	11.7	0.076	2.84	488	25
Chloroethane	64.5	14.8			1.54	5740	25
Chloroform	119.4	3.39	160	0.094	1.97	8000	20
Chloromethane	50.5	44			0.95	6450	20
Dibromochloromethane	208.3	2.08			2.09	0.2	
1,1-Dichloroethane	99.0	4.26	180	0.096	1.80	5500	20
1,2-Dichloroethane	99.0	0.98	61		1.53	8690	20
1,1-Dichloroethylene	96.9	34	600	0.084	1.84	210	25
1,2-Dichloroethylene	96.9	6.6	208		0.48	600	20
1,2-Dichloropropane	113.0	2.31	42		2.00	2700	20
1,3-Dichloropropylene	111.0	3.55	38		1.98	2800	25
Ethylbenzene	106.2	6.44	7	0.071	3.15	152	20
Methylene chloride	84.9	2.03	349		1.3	16,700	25
Pyrene	202.3	0.005			4.88	0.16	26
Styrene	104.1	9.7	5.12	0.075	2.95	300	20
1,1,2-Tetrachloroethane	167.8	0.381	5	0.077	3.04	200	20
1,1,2,2-Tetrachloroethane	167.8	0.38			2.39	2900	20
Tetrachloroethylene	165.8	25.9		0.077	2.6	150	20
Tetrachloromethane	153.8	23			2.64	785	20
Toluene	92.1	6.7	22	0.083	2.73	515	20
Tribromoethane	252.8	0.552	5.6		2.4	3200	30
1,1,1-Trichloroethane	133.4	14.4	100		2.49	4400	20
1,1,2-Trichloroethane	133.4	1.17	32		2.47	4500	20
Trichloroethylene	131.4	9.1	60		2.38	1100	25
Trichloroflueomethane	137.4	58	667	0.083	2.53	1100	25
Vinyl chloride	62.5	81.9	2660	0.114	1.38	1.1	25
Xylenes	106.2	5.1	10	0.076	3.0	198	20