Wednesday 10 May 2006   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.*

Attachment: Special Datasheets (10 pages).

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS
Engineering Data Book
CUED approved calculator allowed

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   (a)   Give three examples of hazardous substances you may find in Municipal Solid Waste (MSW). How would the presence of these hazardous substances in MSW influence the design of the top cover of a landfill?   [10%]

(b)   What is a 'diffuse double layer' of water in between clay particles? How can this affect the performance of a clay liner if hydrocarbons are present in the waste.   [10%]

(c)   A new landfill is being planned for a suburban area near Birmingham with a current population of 76,000. It was decided that the new landfill will receive waste for 5 years. The construction of the landfill will take one year from the present time. The construction cost of this landfill is estimated to be £48 million and running cost of the landfill will be £6 million per year. Assume that the waste will be moderately compacted only during the operation of the landfill and that the waste fill will achieve an average unit weight of 7.0 kNm^{-3}. Assuming that the average waste produced by each person is 15 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;

(ii)   approximate dimensions of the new landfill, assuming the total depth of waste in the landfill to be 30 m;

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

(iv)   the government revenue raised in landfill tax if the average landfill tax during the life of the landfill is £8 per tonne in addition to the flat fee.   [40%]

(d)   A slurry wall is to be constructed to protect a drinking water reservoir. The construction site consists of a fine sand stratum with a thickness of 8 m and a hydraulic conductivity of 6.5×10^{-4} m s^{-1} overlying a clay stratum. A 2 m key is to be provided into the clay stratum.

(i)   During construction the side slopes of the trench are to make an angle of 30° with the horizontal. The trench is to be filled with soil-bentonite slurry with a unit weight of 16.5 kN m^{-3} and the backfill soil is to have a unit weight of 19 kN m^{-3}. Estimate the Factor of Safety against sliding assuming that the water table is well below the slurry wall.

(ii) Once the construction of the slurry wall is completed, a filter cake of 4 mm thickness with a hydraulic conductivity of 3.5×10^{-8} m s^{-1} is expected to form. The hydraulic conductivity of the backfill material is estimated to be 5×10^{-6} m s^{-1}. Assuming that the average thickness of the wall is 2 m, calculate the overall hydraulic conductivity of the slurry wall.   [40%]

2   Discuss the following in the context of the UK Contaminated Land Exposure Assessment (CLEA) model:

(a)   The three main exposure pathways included in the model;   [25%]

(b)   Threshold and non-threshold contaminants;   [25%]

(c)   The three generic land-uses employed in the model;   [25%]

(d)   The terms used in determining the average daily exposure to a contaminant by a critical receptor.   [25%]

3   (a)   What organic and inorganic contaminants might be found on the site of a former gas works?   [10%]

(b)   What analytical techniques could be used to detect these contaminants in samples of the groundwater from the site? Briefly discuss the operating principles of three of these techniques.   [40%]

(c)   Two remediation options are being considered for the remediation of the site: soil washing and in-situ bioremediation. The majority of the contaminated soil at the site is silty sand.

(i)   Briefly describe the principles of each of the two remediation techniques.   [40%]

(ii)   Compare and contrast these two options for remediating the site.   [10%]

4. (a) The side slope of a landfill with a clay liner and a geomembrane was constructed to retain waste to a depth of 24 m as shown in Fig. 1. The side slope makes an angle of 60° with the horizontal as shown in Fig. 1. The geomembrane made from HDPE has a thickness of 4 mm and has a mass of 20 kg m^{-2}. The underside of the geomembrane has a friction angle of 8° with respect to the clay liner while the upper side has a friction angle of 5° with respect to the waste. The unit weight of the waste was estimated to be 8 kN m^{-3}. The yield stress of HDPE was determined to be 13 MN m^{-2}.

(i) Estimate the tensile stress created in the geomembrane due to self-weight.

(ii) Estimate the downdrag stress created in the geomembrane due to the settlement of the waste.

(iii) Comment on the design of the geomembrane layer and suggest how you may want to improve the design. [30%]
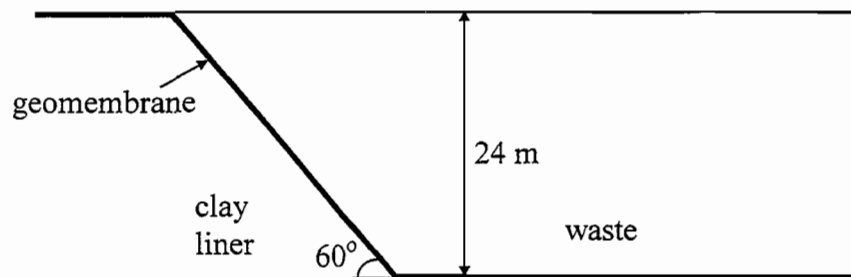

Fig. 1

(b) Liquid waste from a Petroleum refining plant is to be injected into the ground using a Class II well. The total volume of the liquid waste to be disposed off is estimated to be 1.6 million m^3. A suitable sedimentary rock formation with a thickness of 8 m and unlimited lateral extent was identified to site this well. The sedimentary rock formation is sandwiched between impermeable strata. The porosity n and the diffusion co-efficient (D_d) of the sedimentary rock were determined to be 0.4 and 1.2 m s^{-1} respectively. Estimate the radius of influence of this well immediately after the pumping is completed and after a long time has elapsed. Comment on your calculations and how the estimated radii may differ from the actual zone of influence. [30%]

(c)   Explain briefly the term 'pycnocline'. How does the presence of a pycnocline and the oxygen minimum zone affect the ocean disposal of waste?   [20%]

(d)   Describe the siting conditions required for an underground waste repository. Why are domal salt formations considered a suitable host rock for siting a hazardous waste repository?   [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

$M_t = V(\phi_w)C + V(\rho_b)X + V(\phi_a)P$ + 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 = 1.013×10^5 N/m^2

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
$\int_{-\infty}^{\infty} n_e C(x, t) dx = C_0 n_e v_x t$	$t \geq 0$	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

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

where $\overline{X}$ 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

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

where $\overline{y}$ 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

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

8

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;

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

$$Q = 2K.\frac{h^2_{max}}{L}$$

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

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 (cm²/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
1,1,1,2-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