ENGINEERING TRIPOS   PART IIB

Wednesday 11 May 2005   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:
   Special datasheets (11 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   A former industrial site is to be redeveloped for new residential houses. During the site investigation, it was found that hydrocarbons leaked from an abandoned underground storage tank. The tank is located above the water table and the spill contaminated the vadose zone.

(a)   The spilled hydrocarbons included both petrol (gasoline) and diesel fuel. Which fuel is likely to migrate deeper into the subsurface? Describe the differences in composition and discuss the effects of their physical properties on migration in the subsurface.   [20%]

(b)   Toluene was the major component found in the soil samples taken.

(i)   The vapour concentration of toluene was 100 ppmV. Assuming equilibrium between the gas and aqueous phases, what is the aqueous concentration of toluene in the soil moisture in mg/l?   [15%]

(ii)   Assuming linear adsorption, what is the sorbed concentration in mg/kg? The organic carbon content of the soil is 0.1%. Assume that the temperature is 20 degrees.   [15%]

(iii) The soil sample has the following characteristics: porosity = 0.4, degree of water saturation = 50% and bulk density of soil = 1.8 g/cm^3. If there is no free phase, estimate the total amount of toluene inside the sample per kg of soil.   [15%]

(c)   Calculate the retardation factor of toluene in this soil and hence the average velocity of toluene in the groundwater. The groundwater flows with a hydraulic gradient of 0.015. The hydraulic conductivity of the aquifer is 40 m/day.   [15%]

(d)   Describe two remediation methods that can be used to remove the free-phase hydrocarbons from the subsurface before the housing construction starts. Discuss the removal mechanisms.   [20%]

2   (a)   Draw an unsaturated and saturated zone of a subsurface system and list hydrological inputs and outputs of the system.   [25%]

(b)   What are chlorinated solvents? How do they tend to migrate in the subsurface? Discuss why they are difficult to find in the subsurface in relation to their physical properties.   [25%]

(c)   What does a cancer risk of 10^{-6} mean? How does this value relate to the maximum contamination level in drinking water?   [25%]

(d)   Describe the differences in dose-response models adopted for carcinogens and non-carcinogens. Discuss how these models are determined.   [25%]

3   (a)   Explain what types of reactions can occur between the clay liner of a landfill and the waste disposed in it.   [10%]

(b)   What is a 'diffused double layer' of water in between clay particles? How can this effect the performance of a clay liner if hydrocarbons are present in the waste?   [20%]

(c)   A vertical slurry wall is to be constructed in a clayey silt layer with a saturated unit weight of 19.6 kN/m^3 and an undrained shear strength of 30 kPa. The permeability of the clayey silt was determined to be 2.4×10^{-6} m/s. Calculate the theoretical limit on the unsupported vertical cut that can be made in this soil.   [10%]

(d)   It is anticipated that the construction plant required to cut the trench for the slurry wall will exert a bearing pressure of 50 kPa next to the trench. How will this effect your calculation in part (c)?   [10%]

(e)   The depth of the slurry wall required to form a vertical barrier against contaminant migration was determined to be 12 m excluding the keying depth. Estimate the unit weight of the soil-bentonite slurry required to maintain stability of the trench,

       (i)   if water table is well below the 12 m depth of the slurry wall.

       (ii)   if water table is at the ground surface.   [20%]

(f)   The soil bentonite slurry inside the trench hardens with time. The permeability of the hardened soil bentonite is determined to be 1.6×10^{-7} m/s. The thickness of the slurry wall is to be 1.5 m. Assuming that a 4 mm thick filter cake with a permeability of 2.8×10^{-10} m/s forms on both sides of the wall, estimate the overall permeability of the slurry wall. Briefly comment on the important factors that govern the stability of the slurry wall.   [30%]

4. (a) A landfill with a plan area of 400 m × 500 m is to be constructed near London. The rainfall in London is approximately 1200 mm/yr and 20% of this is expected to be infiltrated through the top cover the landfill. You may assume that an equal amount of leachate will be produced due to the reactions within the waste.

The thickness of the drainage layer at the base is 1.2 m and its permeability is 1.0×10^{-2} m/s. You may assume that the level of leachate will be kept just below the top surface of the drainage layer. PVC pipes with an outer diameter of 420 mm and wall thickness of 10 mm are available at this site. The natural slope at the site is 1:1000 in the width direction as shown in Figure 1.

Design a suitable Leachate Collection and Removal (LCR) system for this landfill. Sketch the plan view of the landfill showing the LCR system. [60%]

(b) Explain how continental shelves and continental slopes affect the area of spread of the waste deposited in the Ocean. [20%]

(c) Describe briefly how waste can be disposed into underground caverns formed by solution mining

(i) if the waste is lighter than brine solution.

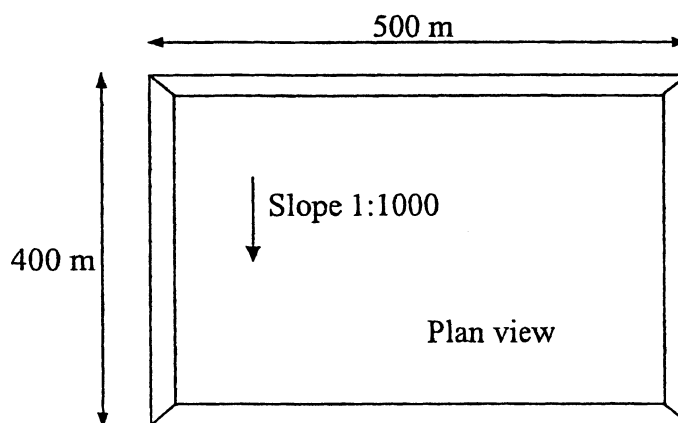(ii) if the waste is heavier than brine solution. [20%]

Fig. 1

END OF THE PAPER

Part IIB

4D14 Contaminated Land and Waste Containment

DATABOOK

2004/2005 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 = 1.013×10^5 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 = 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 ($X = K_p C$, 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 Some analytical solutions

[Case 1] Pulse injection of Mass M into an one-dimensional flow field

Boundary and initial conditions

$C(x, 0) = 0$	$x \geq 0$	Initial condition
$C(0, t) = M\delta(x)/An$	$t = 0$	Boundary condition; $\delta(x)$ is a Dirac delta function; A is the cross-sectional area; n is porosity
$C(\infty, t) = 0$	$t \geq 0$	Boundary condition

Solution

$$C(x,t) = \frac{M/A}{2nR\sqrt{\pi \frac{D_L}{R}t}} \exp\left(-\frac{\left(x - \frac{v_x}{R}t\right)^2}{4\frac{D_L}{R}t} \right)$$

where v_x = average linear water velocity

x = flow distance

D_L = hydrodynamic dispersion coefficient in the longitudinal direction

R = retardation factor

[Case 2] Continuous injection into an one-dimensional flow field

Boundary and initial conditions

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

Solution

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

[Case 3] 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

$$C(x,y,t) = \frac{C_0 A}{4\pi t(D_L D_T)^{0.5}} \exp\left(-\frac{(x - v_x t)^2}{4D_L t} - \frac{y^2}{4D_T t} \right)$$
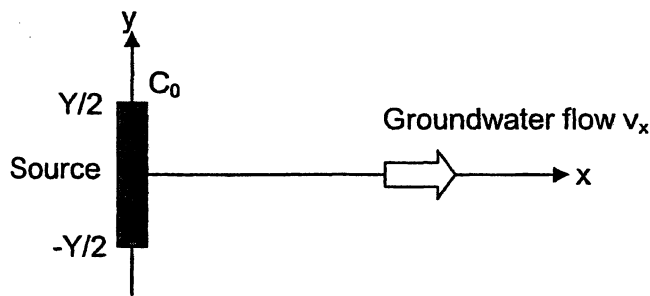
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where D_L = hydrodynamic dispersion coefficient in the longitudinal direction

              D_T = hydrodynamic dispersion coefficient in the transverse direction

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

Boundary and initial conditions

$C(x, y, 0) = 0$	$-\infty < x, y < +\infty$	Initial condition
$C(0, -Y/2<y<Y/2, t) = C_0$	$t \geq 0$	Boundary condition
$C(x, y<-Y/2, y>Y/2, t) = 0$	$t \geq 0$	Boundary condition

Solution (for $t>5a_x/v_x$, $x/a_x>30$ only)

$C(x,y,t)$

$$= \frac{C_0}{4} \exp\left[\frac{x}{2a_x}\left(1-\sqrt{1+\frac{4\lambda a_x}{v_x}}\right)\right] \cdot erfc\left[\frac{x-v_xt/R\sqrt{1+4\lambda a_x/v_x}}{2\sqrt{a_xv_xt/R}}\right] \cdot \left[erf\left(\frac{y+Y/2}{2\sqrt{a_yx}}\right)-erf\left(\frac{y-Y/2}{2\sqrt{a_yx}}\right)\right]$$

where a_x = longitudinal dispersivity (i.e. $D_x = a_xv_x$)

          a_y = transverse dispersivity (i.e. $D_y = a_yv_x$)

          λ = decay constant

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

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

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;

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

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

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

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)

Error Functions

$$\mathrm{erf}\,(\beta) = \frac{2}{\sqrt{\mu}} \int_0^{\beta} e^{-\epsilon^2}\, d\epsilon$$

$$\mathrm{erf}\,(-\beta) = -\mathrm{erf}\,\beta$$

$$\mathrm{erfc}\,(\beta) = 1 - \mathrm{erf}\,(\beta)$$

β	$\mathrm{erf}\,(\beta)$	$\mathrm{erfc}\,(\beta)$
0	0	1.0
0.05	0.056372	0.943628
0.1	0.112463	0.887537
0.15	0.167996	0.832004
0.2	0.222703	0.777297
0.25	0.276326	0.723674
0.3	0.328627	0.671373
0.35	0.379382	0.620618
0.4	0.428392	0.571608
0.45	0.475482	0.524518
0.5	0.520500	0.479500
0.55	0.563323	0.436677
0.6	0.603856	0.396144
0.65	0.642029	0.357971
0.7	0.677801	0.322199
0.75	0.711156	0.288844
0.8	0.742101	0.257899
0.85	0.770668	0.229332
0.9	0.796908	0.203092
0.95	0.820891	0.179109
1.0	0.842701	0.157299
1.1	0.880205	0.119795
1.2	0.910314	0.089686
1.3	0.934008	0.065992
1.4	0.952285	0.047715
1.5	0.966105	0.033895
1.6	0.976348	0.023652
1.7	0.983790	0.016210
1.8	0.989091	0.010909
1.9	0.992790	0.007210
2.0	0.995322	0.004678
2.1	0.997021	0.002979
2.2	0.998137	0.001863
2.3	0.998857	0.001143
2.4	0.999311	0.000689
2.5	0.999593	0.000407
2.6	0.999764	0.000236
2.7	0.999866	0.000134
2.8	0.999925	0.000075
2.9	0.999959	0.000041
3.0	0.999978	0.000022

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
1,1,1,2-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	20
1,1,1-Trichloroethane	133.4	14.4	100		2.49	4400	30
1,1,2-Trichloroethane	133.4	1.17	32		2.47	4500	20
Trichloroethylene	131.4	9.1	60		2.38	1100	20
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