Exam 2018 - Solution

Problem 1: soil vapor extraction

Contaminant: benzene $C_{i,s} = 50\, mg/kg$
Extraction well = diameter 20 cm, screened height 6m, pressure 0.7 atm
Monitoring well = distance 10m, pressure 0.99 atm

From the data given in the problem, prior answering the question, we can already work out some important variables that will be useful later.
We will use the following notations:

$$\rho_{wb} = soil\ wet\ bulk\ density \frac{g}{cm^3}$$
$$\rho_b = soil\ dry\ bulk\ density \frac{g}{cm^3}$$
$$\epsilon = soil\ porosity$$
$$\rho_w = water\ density \frac{g}{cm^3} = 1 \frac{g}{cm^3}$$

Contaminated area: surface 1200 m^2, depth 3m

So $V_T = 3600\, m^2$, and $V_T = V_L + V_G + V_S$

And we also have $V_L + V_G = \epsilon \times \mathrm{V_T}$

In addition, to find V_L: $\rho_{wb} = \frac{M_S}{V_T} + \frac{M_L}{V_T} = \rho_b + \frac{M_L}{V_T} = \rho_b + \frac{\rho_w \times \mathrm{V_L}}{V_T}$

Hence, $V_L = \frac{V_T}{\rho_w} \times (\rho_{\mathrm{wb}} - \rho_b) = 720\, m^3$

And then, $V_G = \epsilon \times \mathrm{V_T} - V_L = 540\, m^3$

Then, $M_S = \rho_b \times \mathrm{V_T} = 1.6 \frac{g}{cm^3} \times 3{,}600\mathrm{m}^3 \times \frac{10^6\ cm^3}{1\ m^3} \frac{1\ kg}{1{,}000\ g} = 5{,}760{,}000\ kg$

In addition, we have: $m_{benz,tot} = m_{benz,aq} + m_{benz,g} + m_{benz,s} \quad (eq\ 1)$

$$m_{benz,tot} = C_{benz,aq} \times \mathrm{V_L} + C_{benz,g} V V_G + C_{benz,s} M_S \quad (eq\ 2)$$

But $K_D = \frac{C_{benz,s}}{C_{benz,aq}} \frac{g\ sorbed/g\ dry\ solid}{g\ in\ solution/m^3 liquid}$, and $K_H' = \frac{C_{benz,g}}{C_{benz,aq}} \frac{mol/L}{mol/L}$

Hence, we can write eq 2 as follows and access to $C_{benz,aq}$:

$$m_{benz,tot} = C_{benz,aq} \times \mathrm{V_L} + C_{benz,aq} \times \mathrm{K_H'} \times \mathrm{V_G} + C_{benz,aq} \times \mathrm{K_D} \times \mathrm{M_S}$$

The aim of the problem is to determine:

A- how many SVE wells are needed to treat the contaminated area?

B- how long do we need to apply the remediation solution for to remove 90% of the contaminant?

1) Calculation of the gas concentration of benzene $C_{benz,g}$

By calculating first $C_{benz,aq}$, we will access to $C_{benz,g}$ using the Henry's Law constant K'_H.

For $C_{benz,aq}$ we can use K_D as we know that $C_{benz,aq} = 50\ mg/kg$

We can calculate Ko thanks to the Karickhoff's relationship:

$$K_D = K_{ow} \times \mathrm{f_{oc}} \times 0.63 \times 10^{-6} \frac{m^3}{g}$$

$K_D = 300 \times 0.05 \times 0.63 \times 10^{-6} \frac{m^3}{g} = 9.45 \times 10^{-6} \frac{m^3}{g} \times \frac{1{,}000\mathrm{L}}{1\mathrm{m}^3} \times \frac{1000\mathrm{g}}{1\mathrm{kg}} = 9.45 \frac{L}{kg}$

So, $C_{benz,aq} = 5.29 \frac{mg}{L}$

And from K'_H we get: $C_{benz,g} = 1.22 \frac{mg}{L}$

2) Calculation of the radius of influence R_I.

The pressure at the radial distance r is given by the relationship:

$$P_r^2 - P_W^2 = (P_{R_I}^2 - P_W^2) \times \frac{\ln\left(\mathrm{r}/\mathrm{R_w}\right)}{\ln\left(R_I/R_w\right)}$$

We have: $P_r = 0.99\ atm; P_w = 0.7\ atm; P_{R_I} = 1\ atm; R_W = 0.1\ m; r = 10\ m$

Px = 0.99 atm; P. = 0.7 atm; P.. = 1 atm; R. = 0.1m; r = 10m.

We can write the previous equation as follows:

$$\ln\left(\frac{R_I}{R_w}\right) = \frac{P_{R_I}^2 - P_W^2}{P_r^2 - P_W^2} \times \ln\left(\frac{r}{R_w}\right) = 4.79$$

Hence, $R_I = 12\ m$

3) Calculation of the flow rate needed peer well $Q\left(\frac{m^3}{d}\right)$

The vapor flow rate needed is given by:

$$Q = H\left[\frac{\pi k}{\mu}\right] \times \left[\frac{\mathrm{P_w}}{\ln\left(\frac{R_w}{R_I}\right)}\right] \times \left[1 - \left(\frac{\mathrm{P_{R_I}}}{P_w}\right)^2\right]$$

We have $k = 9 \times 10^{-8} cm^2; \mu = 1.8 \times 10^{-4}\ N/(m^2 s)$

So, $Q = 6m\left[\frac{3.14 \times 9 \times 10^{-8} cm^2 \times \frac{1\mathrm{m}^2}{10^4 cm^2}}{1.8 \times 10^{-4} \times \frac{N}{m^2 s} \times \frac{1\mathrm{atm} \times \mathrm{m}^2}{1.103 \times 10^5 N}}\right] \times \left[\frac{0.7\mathrm{atm}}{\ln\left(\frac{0.1}{12}\right)}\right] 1\mathrm{atm} \times \left[1 - \left(\frac{1}{0.7}\right)^2\right] = 1{,}253\ m^3/d$

4) Number of wells needed

The number of well nedded to to cover the area can be calculated as follows:

$$N = \frac{1.2 \times \mathrm{A}}{\pi \times \mathrm{R}_\mathrm{I}^2} = 3.16$$

N = 3.16 wells, which we round up to **N = 4 wells**

5) Time needed to remove 90% of the contaminant

First, the mass which can be removed per day $M_{removal\,rate}$ using SVE is:

$$M_{removal\,rate} = 1{,}253\,\frac{m^3}{d} \times 1.22\,\frac{\text{mg benzene}}{\text{L}} \times 4\text{wells} \times \frac{1\text{kg}}{10^6 mg} = 6.1\,kg/d$$

Second, the total mass of benzene m_{benz} at the site can be calculated as follows:

The mass of benzene at the site is given by:

$$m_{benz} = 5.76 \times 10^6 kg\ soil \times \frac{50\text{mg}}{\text{kg soil}} \times \frac{1\text{kg}}{10^6 mg} = 288\,kg$$

90% removal of benzene corresponds to $m_{benz,90\%} = 0.9 \times 324\text{kg} = 259.2\text{kg}$.

Assuming instantaneous equilibrium, the number of days n_d needed for the removal of 90% benzene is:

$$n_d = \frac{m_{benz,90\%}}{M_{removal\,rate}} = 43\,d$$

Problem 2 : Soil washing

The (wet) soil to treat is:

$V_T = 150\,m^2 \times 3\,m = 450\,m^3$

We have the soil wet bulk density, the porosity, and the water content, so we can calculate the total dry mass (wet mass minus liquid mass):

$$\rho_{wb} = \frac{M_S + M_L}{V_T}$$

$$M_{S,total} = \rho_{wb} V_T - M_L = \rho_{wb} V_T - \rho_w V_L = \rho_{wb} V_T - \rho_w V_T \theta$$
$$= 1{,}800\,\frac{kg}{m^3} \times 450\ \mathrm{m}^3 - 997\,\frac{kg}{m^3} \times 450\ \mathrm{m}^3 \times 0.15 = 742{,}702\,kg$$

- **Soil washing part :**

$$C_{s,initial} = 300\,\frac{mg}{kg_{soil}}$$

$$C_{s,target} = 10\,\frac{mg}{kg_{soil}}$$

$K_D = 10^{-4}\frac{m^3}{g}$

$V_{T,reactor} = 800\ m^3$

$C_{ss} = 10\frac{kg}{m^3}$

$\rho_{wb} = 1.8\frac{g}{cm^3}$

Residence time in reactor: 1 day (equilibrium reached)

<u>The question is:</u> How many consecutive batch reactor runs are needed to reach the target contaminant concentration in the soil?

We need to calculate after 1 day of equilibration the remaining concentration of contaminant in the soil.

$$C_{aq,eq} = \frac{C_{s,initial}M_{s,batch}}{V_L + K_D M_{s,batch}}$$

$$V_L = V_T - \frac{M_{s,batch}}{\rho_{wb}} = 800\ m^3 - \frac{8{,}000\ kg}{1.8\frac{g}{cm^3}\frac{1kg}{1{,}000g}\frac{10^6 cm^3}{1m^3}} = 796\ m^3$$

$$C_{ss} = \frac{M_{s,batch}}{V_{T,reactor}} \rightarrow M_{s,batch} = 10\frac{kg}{m^3} \times 800\ \mathrm{m}^3 = 8{,}000\ kg$$

$$C_{aq,eq} = \frac{300\frac{mg}{kg} \times 8{,}000\ kg}{796m^3 + \frac{10^{-4}m^3}{g} \times 8{,}000{,}000\ \mathrm{g}} = 1{,}504\frac{mg}{m^3}$$

The concentration in the solid after equilibration is:

$$C_{s,eq} = K_D C_{aq,eq} = \frac{10^{-4}m^3}{g} \times 1{,}504\frac{mg}{m^3} = 150\frac{mg}{kg}$$

$C_{s,eq} > 10\frac{mg}{kg}$ → We need to run a second batch.

Let's try to anticipate how many batches will be needed, **i** represents a batch:

$$C_{s,i} = K_D \times C_{aq,eq,i} = K_D \times C_{s,i-1} \times \frac{M_{s,batch}}{V_L + K_D M_{s,batch}} = \frac{C_{s,i-1}}{2}$$

After **n** batches we have:

$$C_{s,n} = \frac{C_{s,initial}}{2^n}$$

$C_{s,target} = 10\frac{mg}{kg} \rightarrow n = 5$

For each run, will need to do 5 consecutive batches to lower the soil concentration under 10 mg/kg.

For each batch, the solid and aqueous concentrations at equilibrium are:

Batch	$C_s\ (\frac{mg}{kg})$	$C_{aq}\ (\frac{mg}{m^3})$
1	150	1,500
2	75.0	750
3	37.5	375
4	18.8	188
5	9.38	93.8

The number of run needed to decontaminate the entirety of the soil is:

$$N = \frac{M_{s,total}}{M_{s,batch}} = \frac{742{,}702\ kg}{8{,}000\ kg} = 92.8 \sim 93$$

Finally, the total number of batches needed is: 5 × 93 = 465. The total duration of the process will be 465 days.

- **GAC part:**

Dimensions of the barrels: $D = 0.8\ m$ and $H = 2\ m \rightarrow V_{barrel} = 1\ m^3$

$\rho_{b,GAC} = 485 \frac{kg}{m^3} \rightarrow M_{GAC,barrel} = 485\ kg$

$$SLR = 300 \frac{L}{min.\,m^2}$$

<u>The questions are:</u>

1) How many drums do we need in parallel and in series?
2) How long before changing the GAC?

<u>Number of rums in parallel and in series:</u>

According to previous results, the water flow is: $Q = 796 \frac{m^3}{day} = 552.8\ L/min$

$$SLR = \frac{Q}{A} \rightarrow A = \frac{Q}{SLR} = \frac{552.8 \frac{L}{min}}{300 \frac{L}{min.m^2}} = 1.8\ m^2$$

The number of drums in parallel needed is:

$N_{parallel} = \frac{A}{A_{drum}} = \frac{1.8\ m^2}{\pi \times 0.4^2} = 3.7 \rightarrow$ we need 4 drums in parallel

The number of drums in serries needed is:

We assume EBCT = 12 min.

$$L = EBCT \times \mathrm{SLR} = 12\ min \times 300 \frac{L}{min.\,m^2} \times \frac{1\ \mathrm{m}^3}{1{,}000\ \mathrm{L}} = 3.6\ \mathrm{m}$$

The number of drums in serries needed is:

$N_{series} = \frac{L}{H} = 1.8 \rightarrow$ we need 2 drums in serries

In total, we need 4 × 2 = 8 drums.

Time before drum exchange:

$\Gamma = 25C_{aq}^{0.36}$ → to be conservative, we assume 50% efficiency: $\Gamma_{50\%} = 12.5C_{aq}^{0.36}$

The barrels can hold:

$$m_{contaminant,barrel} = \Gamma_{50\%} \times N_{barrel} \times M_{GAC.barrel} = 12.5C_{aq}^{0.36} \times 8 \times 485{,}000 = 48{,}500{,}000\ C_{aq}^{0.36}$$

Careful with the unit, C is in mg/L, and $M_{GAC,barrel}$ is in g!

The amount of contaminant that reaches the drums every day is:

$$R_{contaminant} = Q \times C_{aq} = 796 \frac{m^3}{day} \times C_{aq}$$

The time before drum exchange is:

$$t = \frac{m_{contaminant,barrel}}{R_{contaminant}}$$

For the aqueous concentrations previously calculated:

Batch	$C_{aq}\ (\frac{mg}{m^3})$	$m_{contaminant}\ (kg)$	$R_{contaminant}\ (\frac{g}{day})$	$t\ (days)$
1	1,500	56.1	1,190	47
2	750	43.7	597	73
3	375	34.1	299	114
4	188	26.6	149	179
5	93.8	20.7	74.6	277

Depending of the batch, the time before GAC exchange varies a lot. We recommend to run the 93 first batch 1 first, then batch 2 etc.

Problem 3 : partitioning

$$K_{NW} = \frac{C_{SRB,NAPL}}{C_{SRB,aq}}$$

$$K_{D(SRB)} = \frac{C_{SRB,s}}{C_{SRB,aq}}$$

$$m_{SRB,tot} = m_{SBR,NAPL} + m_{SBR,aq} + m_{SBR,s}$$

$$m_{SRB,tot} = K_{NW}\, C_{SRB,aq}\, V_{NAPL} + C_{SRB,aq}\, V_L + C_{SRB,aq}\, K_D M_S$$

$$m_{SRB,tot} = C_{SRB,aq} * (K_{NW}\, V_{NAPL} + V_L + K_D M_S)$$

$$\frac{m_{SRB,tot}}{C_{SRB,aq}} = K_{NW}\, V_{NAPL} + V_L + K_D M_s$$

$$V_{NAPL} = \frac{\frac{m_{SRB,tot}}{C_{SRB,aq}} - V_L - K_D M_s}{K_{NW}}$$

$$V_{NAPL} = \frac{\frac{2000g}{0.003289\frac{g}{L} \times \frac{1000L}{1m^3}} - 498m^3 - 5.5 \times 10^{-6}\frac{m^3}{g} \times 20{,}000kg \times \frac{1000\ g}{kg}}{0.06}$$

$$V_{NAPL} = 1.46\ m^3$$

$$m_{NAPL,ph} = V_{NALP} \times \rho_{NAPL} = 1.46m^3 \times 1{,}100\frac{kg}{m^3} = 1{,}605\ \mathrm{kg}\ NAPL$$

$$m_{NAPL,tot} = m_{NAPL,ph} + m_{NAPL,aq} + m_{NAPL,s} + m_{NAPL,g}$$

$$m_{NAPL,tot} - m_{NAPL,ph} = C_{NAPL,aq}\, V_L + C_{NAPL,aq}\, K_D\, M_s + C_{NAPL,aq}\, K_H\, V_G$$

$$C_{NAPL,aq} = \frac{m_{NAPL,tot} - m_{NAPL,ph}}{V_L + K_D M_S + K_H V_G}$$

$$C_{NAPL,aq} = \frac{2000\ kg - 1{,}605\ kg}{498m^3 + 0.09\frac{cm^3}{g} \times \frac{10^{-6}m^3}{1\ cm^3} \times \frac{1000g}{1\ kg} \times 20{,}000kg + 0.6 \times 2\ m^3}$$

$$= 0.79\ \frac{kg}{m^3} = 0.79\ \frac{g}{L}$$