ENV 6438: Physical & Chemical Processes for Drinking Water Treatment
Department of Civil & Environmental Engineering
University of South Florida
Cunningham **Spring 2020**

Homework #6 **Filtration** Due Mon., March 30

Assignment for 2020: Answer problems 1–6 … but if you don't want to do problem 4, you can substitue #7, #9, or #10 instead of #4.

1. (5 pts) Suppose you are treating water at a flow rate of 10 mgd = 1577 m^3/hr. You are going to filter the water and you want a filter velocity of 10 (m^3/hr)/m^2. You design a set of filters to be used in parallel. Each filter box has a surface area of 25 m^2. How many filters do you need to construct?

2. (35 pts) Consider the same flow conditions as in problem 1, above. Suppose the water temperature is 15 °C, and it contains particles of diameter 1.0 μm and density 1.8 g/cm^3. Your filters consist of a layer of anthracite on top of a layer of sand. Here is the information you have about each of the two media in your filter.

Filter medium	Effective size (mm)	Uniformity coefficient	Grain density (g/cm^3)	Porosity	Layer thickness (m)
Anthracite	?	1.5	1.5	0.50	0.60
Sand	0.7	1.5	2.65	0.40	0.60

a. Select the effective size for the anthracite grains, using equation 11-25. The idea is that, by using this equation, the grains will be compatible for backwashing purposes.
b. Use the Tufenkji-Elimelech model to estimate the single-collector efficiency for an anthracite grain and for a sand grain. Use d_{60}, not the effective size, as the grain diameter in your calculations.
c. What fractional removal would you achieve in the sand layer? What would be the overall removal of these particles? You can assume an adhesion efficiency $\alpha = 0.8$. Optional: graph C/C_I versus filter depth, z, where $z = 0$ corresponds to the top of the upper layer, and $z = 1.2$ m corresponds to the bottom of the lower layer.
d. Repeat the calculations from part (c) for particles of diameter 0.1 μm and 10 μm.
e. Which size particles were removed most effectively? Least effectively? Is this what you expected? Explain briefly (a sentence or two).
f. Which medium (anthracite or sand) is more effective at removing the particles? Why?
g. For each of the three particle sizes, indicate which transport mechanism is most important. Is this what you expected? Explain briefly (a sentence or two).

3. (10 pts) For the scenario and conditions described in problems 1 and 2, estimate the (clean-filter) head loss in each of the two layers, and the overall head loss. Which layer is responsible for more head loss? Is that what you expected? Explain briefly. Hint: what grain diameter should you use for calculations of head loss?

4. (20 pts) For the scenario described in problems 1–3, let's estimate how fast the head loss increases. Suppose you were filtering water that contained 1.0×10^{15} particles/m^3 of diameter 0.1 μm, 1.0×10^{13} particles/m^3 of diameter 1.0 μm, and 1.0×10^{11} particles/m^3 of diameter 10 μm. Assume that the particles are spheres, so you know the volume of each particle. You know the fractional removal of each of those particles in each layer (from problem 2), and you know the rate at which you are applying water to the filters, so you can estimate the rate at which the particles fill up the pore space of the filters. Therefore you can calculate how the pore volume fraction, ε, decreases over time. From that, you can calculate how the head loss in each layer increases over time. Graph head loss versus time for both filter layers. In which layer does head loss increase more rapidly? Why? How long until you think the filter will need to be backwashed? Can we make it 96 hr, like they do at the Tippin plant in Tampa?

5. (20 pts) For the scenario described in problems 1–4, we know that eventually we will have to backwash the filters.
   a. Estimate the backwash velocity required to expand each filter layer by 30%. One of these will probably be higher than the other (i.e., the two layers do not behave the same).
   b. At the *higher* of the two backwash velocities, how much expansion will you get in the "other" layer? Is it within our desired range of 20–50%? If so, that is our desired backwash velocity.
   c. What size of sand grain has a (type I) *settling velocity* equal to the backwash velocity? What size of anthracite grain? Based on this, can you make any estimates of the possibility of washing out our filter media during backwash?
   d. Suppose your typical filter run time is 48 hr and your backwash cycle lasts 30 min. What fraction of your product water must go to backwashing the filters? (I am not sure if 48 hr agrees with the run time found in problem 4, but for this problem, let's assume 48 hr run time.)

6. (10 pts) For the scenario described in problems 1–5, check to see if the filter media will invert at the end of the backwash cycle. Show your calculations. If you find out that the filter media will invert, what would you recommend?

Some of the following problems are copied or adapted from problems created by Paul Roberts (problems 10–14) and Dick Luthy (problem 15) at Stanford University. ***These problems are not required in 2020***.

7. (20 pts) For the filter described in problems 1–4, let's see how head loss depends upon the filter velocity. (Recall that filter "velocity" is not really velocity, it is the volumetric flow rate per cross-sectional area of filter, Q/A.) For simplicity, let's consider just the sand layer, not the anthracite layer. Calculate the clean-filter head loss for filter velocities equal to 1 m/hr, 2 m/hr, 5 m/hr, 10 m/hr, 20 m/hr, and 50 m/hr. At each velocity, determine what fraction of the overall head loss is due to viscous head loss and what fraction is due to inertial head loss. Also estimate a Reynolds number for each velocity based on $Re = \rho_L v_f d_g / \mu$. For what values of Re do viscous losses dominate, for what values of Re do inertial losses dominate, and for what values of Re are both terms important?

8. Look at Figure 11-4 in your text book. Estimate the uniformity coefficient for both the naturally occurring sand and the processed sand. (Note: this is basically the same as example problem 11-1 in the text.)

9. (20 pts) When estimating the effectiveness of a granular-media filter, we usually estimate the single-collector efficiency, η. If we account for three transport mechanisms (as discussed in class), then $\eta = \eta_D + \eta_G + \eta_I$. In class, I gave equations for the collision efficiency of each of these three mechanisms. The equations I gave in class were those presented in the landmark paper by Yao et al. (1971). However, your text book gives different equations for those three collision efficiencies, based on a more recent analysis of filtration (Tufenkji and Elimelech, 2004). I am curious how well the equations agree. Suppose a filter grain of diameter 1.0 mm is being used to remove particles of diameter 3.0 μm. The water temperature is 15 °C, the filter velocity (superficial velocity) is 10 $(m^3/hr)/m^2$, the particle density is 2.6 g/cm^3, and the filter bed porosity is 0.45. Estimate η_D, η_G, η_I, and η for these conditions using the equations given in class and using the equations given in your text. How closely do the two methods agree? Is one set of equations simpler to use than the other?

10. (20 pts) The filter sand for a rapid sand filter has the following sieve analysis:

sieve opening (mm)	cumulative weight passing through sieve opening (%)
0.50	0.0
0.595	1.0
0.707	12
0.841	44
1.00	81
1.19	98
1.41	100

  a. Graph the grain-size distribution on log-normal paper. Do you think this sand follows a log-normal grain-size distribution?
  b. Determine the geometric mean size (d_{50}), the effective size (d_{10}), and the uniformity coefficient (UC) for this sand.

11. (20 pts) A filter is used at low filtration rates to treat relatively dense particles. Estimate the effect of doubling the filter grain size (e.g., from 1 to 2 mm) on the contact efficiency of a single collector for the following two particle sizes: 0.1 μm and 20 μm. Give your answer for each particle size expressed as the ratio of η for large grains compared to smaller grains. Briefly explain/discuss the results in the context of which transport mechanisms are dominant for the different particle sizes. You can use either the Yao model or the TE model for estimating η.

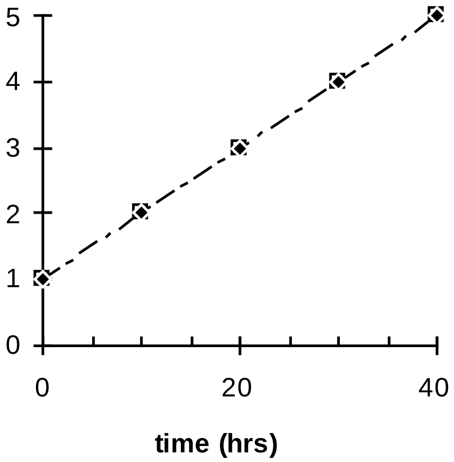
12. For what size range of particles is a granular filter most likely to be more effective in solids removal than conventional gravity sedimentation? Give your answer as a particle size range (either an open or a closed size interval) in units of μm. Justify your answer by discussing transport mechanisms in deep-bed granular filtration; compare the removal of particles having a density $\rho_p = 1.05\times10^3$ kg/m^3 by sedimentation and with deep bed filtration.

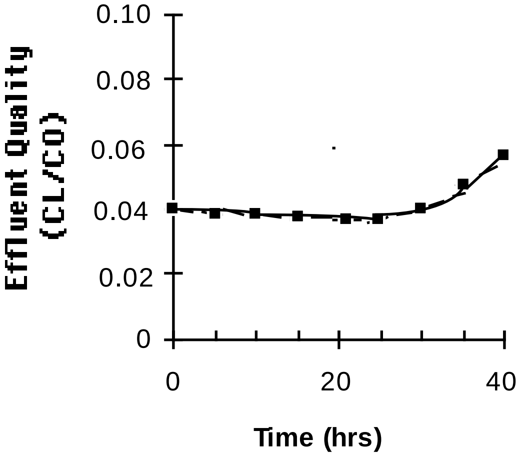
13. Water is to be filtered through a filter bed of 0.7 mm sand grains. The bed depth is 90 cm and the superficial velocity is 10 m/hr. The porosity is 0.4 and the sphericity of the sand grains equals 0.8. The grain density is 2.6 g/cm^3. Water temperature is 20 °C.
    a. Calculate the minimum fluidization velocity of the filter medium. Give your answer in units of m/h.
    b. Calculate the terminal settling velocity (m/h) of the filter medium grains.
    c. Referring to parts (a) and (b), what is the significance of the minimum fluidization velocity and the terminal settling velocity with regard to the backwash velocity (v_{bw})?

14. Water is to be filtered for removal of particulates (mainly alum flocs carried over from a clarifier). A pilot plant filter test was carried out in a downflow sand filter under the following conditions:

    v_0 = 10 m/h (~4 gpm/ft^2) C_0 = 2 mg/L suspended solids
    L = 1.0 m (depth of sand) d_{10} = 0.8 mm (effective size)
    ε = 0.35 (bed porosity)

    The headloss Δh and the effluent quality (C_L/C_0) were measured as functions of time, as shown by the graphs below. The left-hand graph is for head loss, in units of m (the graph is missing a label on the y-axis).





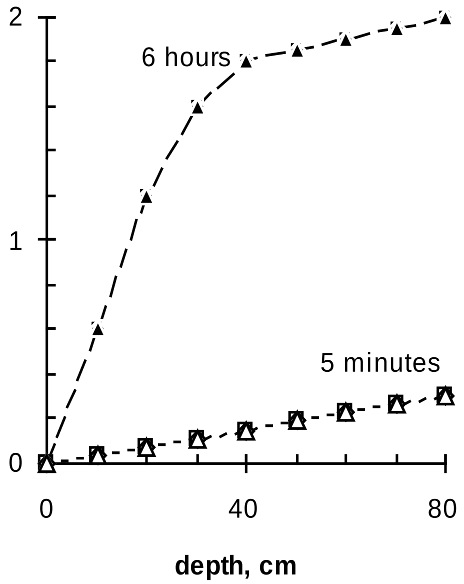
problem 14 continues →

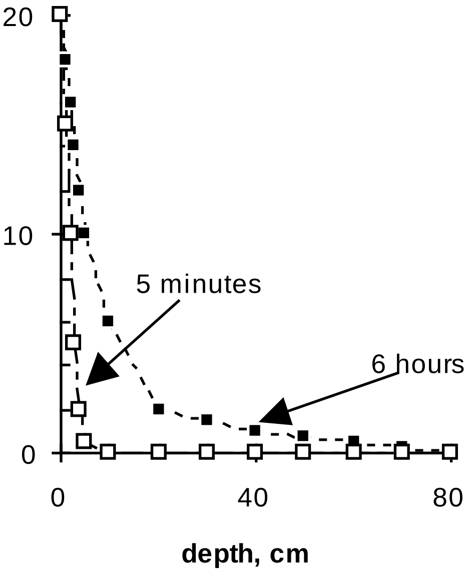
14. continued
    a. Comment on the results in view of the following criteria:
       $\Delta h_{max} = 3$ m H_2O $(C_L/C_0)_{max} = 0.05$ (effluent quality considerations)
       Do you consider the filter performance to be near optimum? Why?
    b. List the changes in concept, design, or conditions that would be most effective in "optimizing" the performance of a down flow filter in this application.
    c. What would be the effect on Δh and C_L/C_0 if a polyelectrolyte (PE) were added to the filter influent ($C_{PE} \approx 0.2$ mg PE/L)? Answer qualitatively. Would you recommend doing so in the light of the experimental results?
    d. From the results above for the entire time period, i.e. 40 hours, calculate the gravimetric specific deposit [g solids removed per m^3 filter volume]. Also, calculate the volumetric specific deposit [m^3 occupied by the solids stored in the filter per m^3 filter volume], assuming that the density of the solids deposited in the filter is 1500 kg/m^3. At the end of the 40-hour filter run,what fraction of the filter's pore volume is occupied by solids deposited during the run?
    e. Suppose that all of the filtered solids are removed from the filter during a 10-minute backwash at a superficial backwash velocity of $v_{bw} = 50$ m/h. What solids concentration (average value) is expected for the backwash water?

15. Water from a eutrophic lake is being treated to remove 20 mg of suspended solids per liter. The filter consists of sand with an effective size of 0.5 mm in a bed 80 cm deep. Polyelectrolyte is being dosed at 1 mg PE per liter to destabilize the algae (because without polyelectrolyte algae are very difficult to remove). The filtration rate is 5 m^3 per m^2 per hour. The profiles of head loss and suspended solids concentration measured are measured 5 minutes after the start of the filter run, and again 6 hours after the start of the filter run. Results are shown on the following page. (The graph on the left is for head loss; the graph on the right is for concentration of suspended solids. The y-axis labels were cut off from the graphs.)

    The maximum allowable headloss is 2 m. The maximum acceptable effluent solids concentration is 2 mg/L.

    a. What fraction of the bed is being used effectively for particulate removal?
    b. What changes in design or operation would you suggest to improve the operation of the filter? How would you test or judge the effectiveness of your suggestions?


2
1
0
6 hours
5 minutes
0
40
80
depth, cm


20
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