Updated: 15 November 2019

Print version

CEE 370
Environmental Engineering Principles

Lecture #28

Water Treatment II: Softening, Settling, Filtration

Reading M&Z: Chapter 8

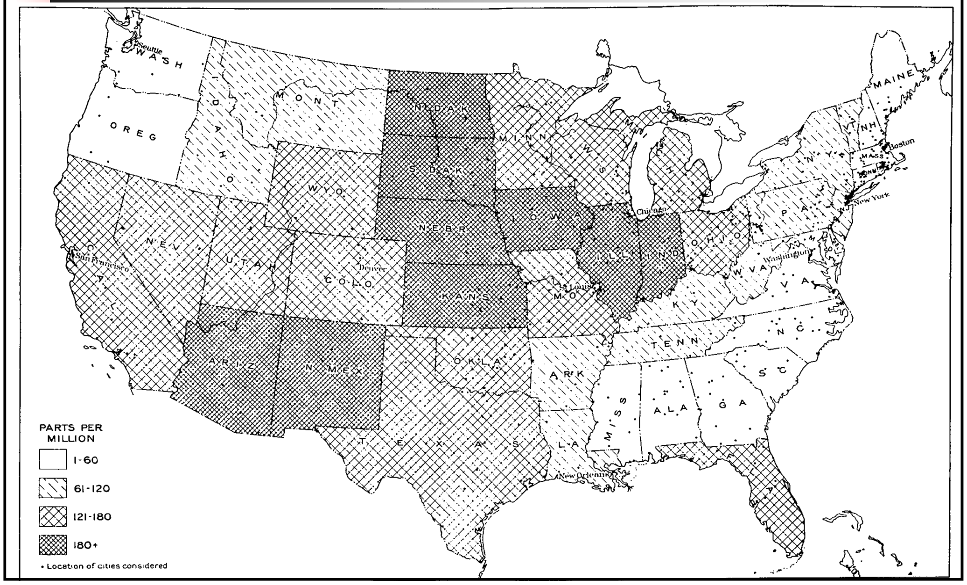
Reading: Davis & Cornwall, Chapt 4-4 to 4-7

Reading: Davis & Masten, Chapter 10-4 to 10-6

Hardness

- Sum of divalent cations: Ca^{+2} and Mg^{+2}
  - Expressed as equivalents in mg-$CaCO_3$/L
    - 100 mg-$CaCO_3$/L = 10^{-3} moles-divalent cations/L
- Problems
  - Consumes soap
  - Cases deposition of “scale” deposits
- Levels:
  - Low: 0-60 mg/L
  - Moderate: 60-120 mg/L
  - High: 120+

National Distribution of Hardness



Removal of Hardness

- Precipitative Softening
  - Raise pH to ~10 to precipitate calcium as the carbonate and magnesium as the hydroxide
  - Addition of Lime (CaO) and soda ash (Na_2CO_3)
    - Both are inexpensive
    - Lime elevates pH; soda ash adds carbonate if needed
    - Lime must be converted to a $Ca(OH)_2$ slurry prior to injection
  - Usually pH must be re-adjusted downward after
    - Common to use CO_2

Softening Chemistry

Stoichiometry

$$Ca(OH)_2 + 2HCO_3^- + Ca^{+2} \rightarrow 2CaCO_3\downarrow + 2H_2O$$

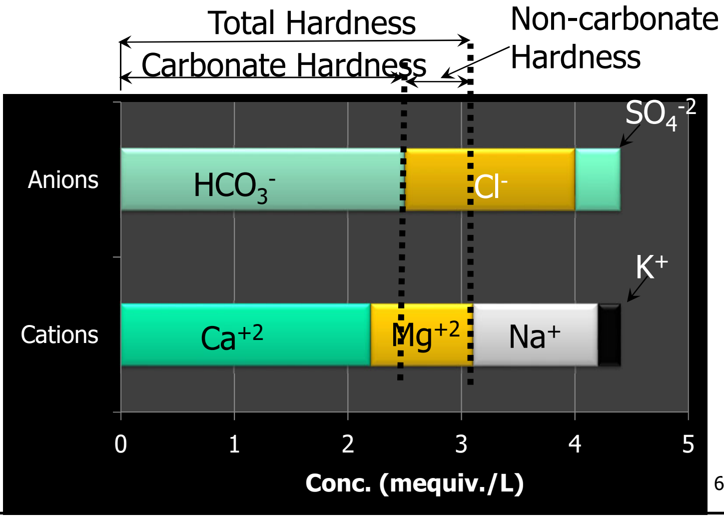
$$Mg^{+2} + Ca(OH)_2 \rightarrow Mg(OH)_2\downarrow + Ca^{+2}$$

Thermodynamics

$$[Ca^{+2}][CO_3^{-2}] = 10^{-8.15}$$

$$[Mg^{+2}][OH]^2 = 10^{-9.2}$$

Anion-Cation Balance



Softening: Process Chemistry I

- Equilibria (Thermodynamics)
  - $[Ca^{+2}][CO_3^{-2}] = 10^{-8.15}$
  - $[Mg^{+2}][OH^-]^2 = 10^{-9.2}$

$$Ca^{+2} + CO_3^{-2} \leftrightarrow CaCO_3 \downarrow$$
$$Mg^{+2} + 2OH^- \leftrightarrow Mg(OH)_2 \downarrow$$

- Theoretical Doses (moles/L)
  - [Lime Dose] = $0.001 + [Mg^{+2}] + 0.5*[HCO_3^-]$
    - = Magnesium Hardness + Carbonate Hardness + excess
  - [Soda Ash Dose] = $0.001 + [Mg^{+2}] + [Ca^{+2}] - .5*[HCO_3^-]$
    - =Non-carbonate hardness + excess

Excess isn't needed if the objective is to remove Ca^{+2} only

- Kinetics
  - Slow, even with excess doses
  - Days, but residence times in WTPs are hours
    - Solution: stabilize water after treatment by lowering pH

1 mole = 100 g-$CaCO_3$

Softening: Process Chemistry II

- How does it actually work?
  - Calcium precipitation

$$Ca^{+2} + 2HCO_3^- + Ca(OH)_2 \rightarrow 2H_2O + 2CaCO_3 \downarrow$$
$$Ca^{+2} + SO_4^{-2} + Na_2CO_3 \rightarrow Na_2SO_4 + CaCO_3 \downarrow$$

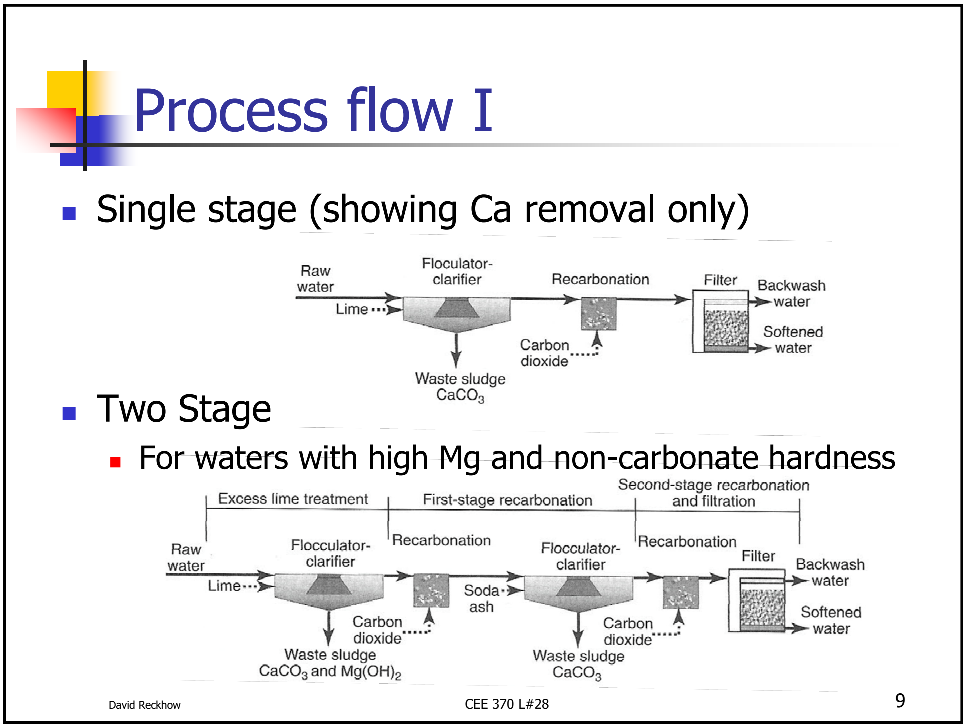
  - Magnesium precipitation

$$Mg^{+2} + 2\ HCO_3^- + 2Ca(OH)_2 \rightarrow 2H_2O + 2CaCO_3 \downarrow + Mg(OH)_2 \downarrow$$

  - Re-carbonation

$$CO_3^{-2} + CO_2 \rightarrow 2\ HCO_3^-$$

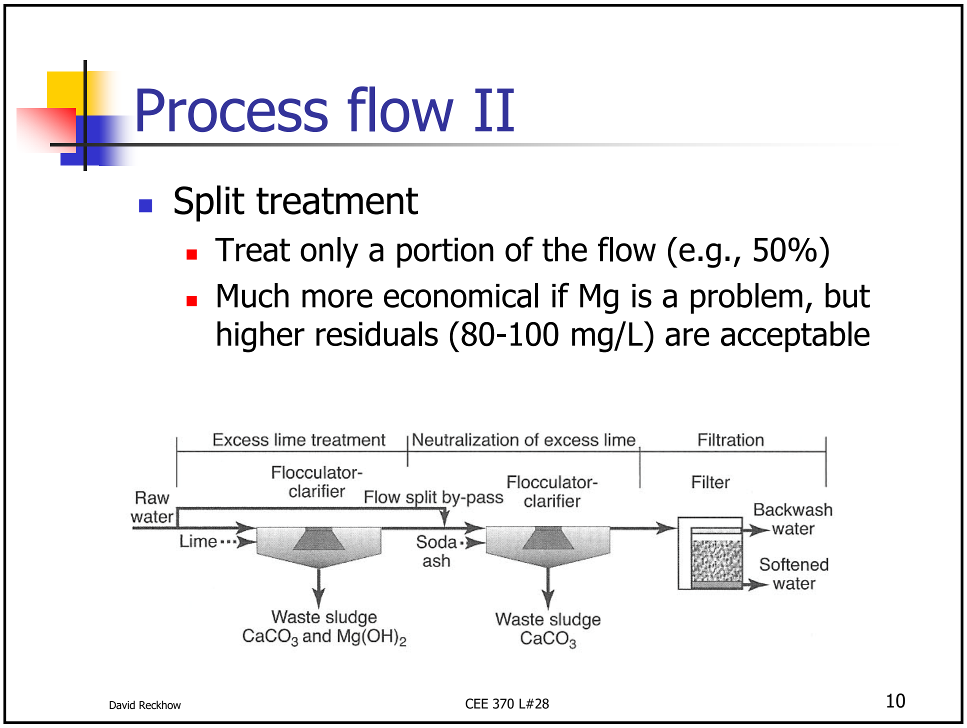
- Level of efficiency
  - Down to about 30 and 10 mg/L (as $CaCO_3$) of Ca and Mg



Process flow I

- Single stage (showing Ca removal only)

- Two Stage
  - For waters with high Mg and non-carbonate hardness



Process flow II

- Split treatment
  - Treat only a portion of the flow (e.g., 50%)
  - Much more economical if Mg is a problem, but higher residuals (80-100 mg/L) are acceptable

Softening

- Iowa City

Lime Softening

- Lime hopper

Lime feeders

3 Feb 09

DSCN6202 , Providence

Lime Storage

3 Feb 09

Lime Tanks and hoppers: DSCN6205; Providence

Question

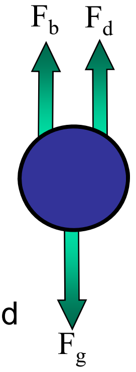
- You want to treat your water for complete removal of all hardness. If you have 2 mM calcium, 1 mM magnesium and 3 mM bicarbonate in the raw water, how much lime do you need to add?
  a) 1 mM lime = 56 mg-CaO/L
  b) 2 mM lime = 112 mg-CaO/L
  c) 3 mM lime = 168 mg-CaO/L
  d) 3.5 mM lime = 196 mg-CaO/L
  e) 6 mM lime = 336 mg-CaO/L

Sedimentation Principles

Settling Type	Description	Applications
Discrete	Individual particles settle independently, neither agglomerating or interfering with the settling of the other particles present. This occurs in waters with a low concentration of particles.	Grit chambers
Flocculant	Particle concentrations are sufficiently high that particle agglomeration occurs. This results in a reduction in the number of particles and in increase in average particle mass. The increase in particle mass results in higher settling velocities.	Primary clarifiers, upper zones of secondary clarifiers.
Hindered (Zone)	Particle concentration is sufficient that particles interfere with the settling of other particles. Particles settle together with the water required to traverse the particle interstices.	Secondary clarifiers
Compression	In the lower reaches of clarifiers where particle concentrations are highest, particles can settle only by compressing the mass of particles below.	Lower zones of secondary clarifiers and in sludge thickening tanks.

Discrete Settling

Discrete settling, which occurs in grit chambers at wastewater treatment facilities, can be analyzed by calculating the settling velocity of the individual particles contained within the water.



F_g = gravity force in the downward direction
F_d = drag force
F_b = buoyancy force due the water displaced by the particle

Discrete Settling (cont.)

Equating the forces gives: $\boxed{F_g = F_d + F_b}$

The gravitational force can be expressed as:

$$\boxed{F_g = m_p g}$$

where,
g = gravitational constant, [9.8 m/s^2]
m_p = particle mass, [Kg]

Using the density and volume of the particle, this becomes,

$$\boxed{F_g = \rho_p V_p g}$$

where,
ρ_p = density of the grit particle, [Kg/m^3]
V_p = particle volume, [m^3]

Discrete Settling (cont.)

- And using the equation for the volume of a sphere: $F_g = \rho_p \left(\frac{\pi}{6} D_p^3 \right) g$

Discrete Settling (cont.)

The drag on the particle can be calculated by the drag equation from fluid mechanics:

$$\mathbf{F_d = \frac{1}{2} C_d A \rho_w v^2}$$

where,

C_d = drag coefficient, dimensionless

A = particle cross-sectional area, [m^2]

ρ_w = density of water, [Kg/m^3]

v = velocity, [m/s]

The buoyant force acting on the particle is:

$$\mathbf{F_b = m_w g}$$

where,

m_w = mass of water displaced, [Kg]

Discrete Settling (cont.)

Substituting the particle volume and density of water,

$$F_b = \boxed{V_p \rho_w g} = \frac{\pi}{6} \rho_w D_p^3$$

When these relationships are substituted into the force balance equation, we obtain,

$$\rho_p V_p g = \frac{1}{2} C_d A \rho_w v^2 + \boxed{\rho_w V_p g}$$

Solving for the settling velocity, v,

$$v = \left[\frac{2(\rho_p - \rho_w) V_p g}{C_d A \rho_w} \right]^{\frac{1}{2}}$$

Discrete Settling (cont.)

If the relationships for particle area and volume are inserted into the equation, it becomes,

$$v = \left[\frac{4}{3} \frac{(\rho_p - \rho_w) D_p g}{C_d \rho_w} \right]^{\frac{1}{2}}$$

At low Reynolds Numbers (for $Re_d < 1$), which would be expected for sand particles settling in water, the drag coefficient, C_d can be approximated by:

$$\mathbf{C_d = \frac{24}{Re_d}}$$

Discrete Settling (cont.)

The Reynolds number is,

$$\mathbf{Re_d} = \frac{\rho v d}{\mu}$$

where,

μ = absolute viscosity of the fluid, in this case, water, [centipoise or 10^{-2} gm/cm-s]

Using these relationships, the particle settling velocity can be estimated as a function of the properties of the particle and water, and the particle diameter,

$$v = \frac{(\rho_p - \rho_w)D_p^2 g}{18\mu}$$

See Table 8.15, pg 404 in M&Z

Discrete Settling (cont.)

This relationship is known as Stoke's Law, and the velocity is known as the Stokes velocity. It is the terminal settling velocity for a particle.

The vertical velocity of water in a grit chamber or settling basin is often described as the overflow rate. It is usually expressed as m/s, m^3/m^2-day or Gal/ft^2-day. It is calculated as:

$$\left[OFR \equiv v_s\right] = \frac{Q}{A_s}$$

See Equ #8.10, pg 407 in M&Z

where,

OFR or v_s	=	overflow rate, [m^3/m^2-day]
Q	=	flow rate, [m^3/day]
A_s	=	clarifier surface area, [m^2]

Overflow Rate

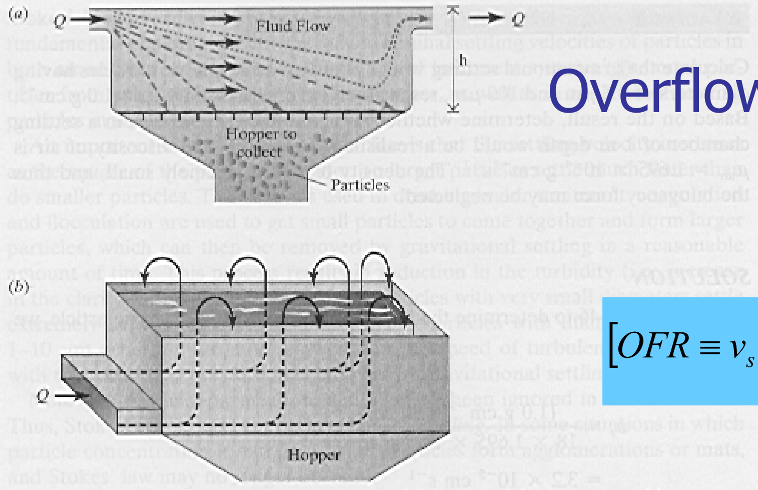
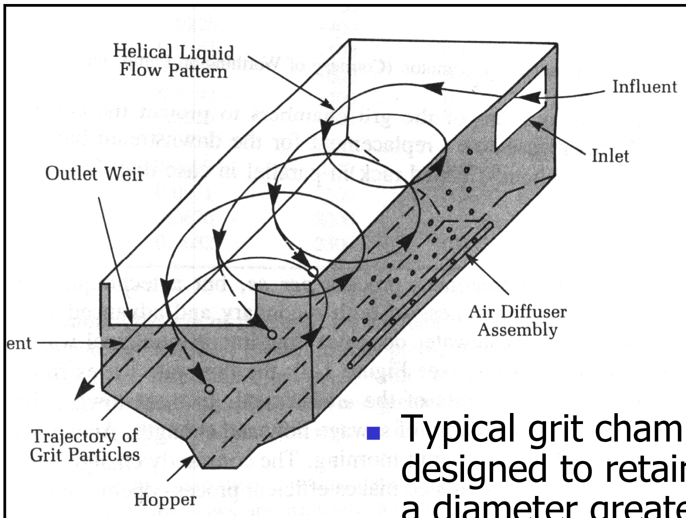


Figure 4-17. Two approaches to determining minimum particle size removed in a nonturbulent chamber. (*a*) The fluid (water or air) travels smoothly from left to right across the settling chamber. Large particles fall rapidly while traveling through the chamber, resulting in a steep trajectory, as indicated by dashed lines; small particles fall slowly, resulting in a shallow trajectory, as indicated by dotted lines. (*b*) The inflow enters near the bottom of the chamber and flows upward, exiting by overflowing out of the open top. Particles that fall faster than the water rises have a net downward velocity and eventually reach the hopper. Particles with settling velocities less than the upward water velocity rise, and are carried out with the effluent flow.

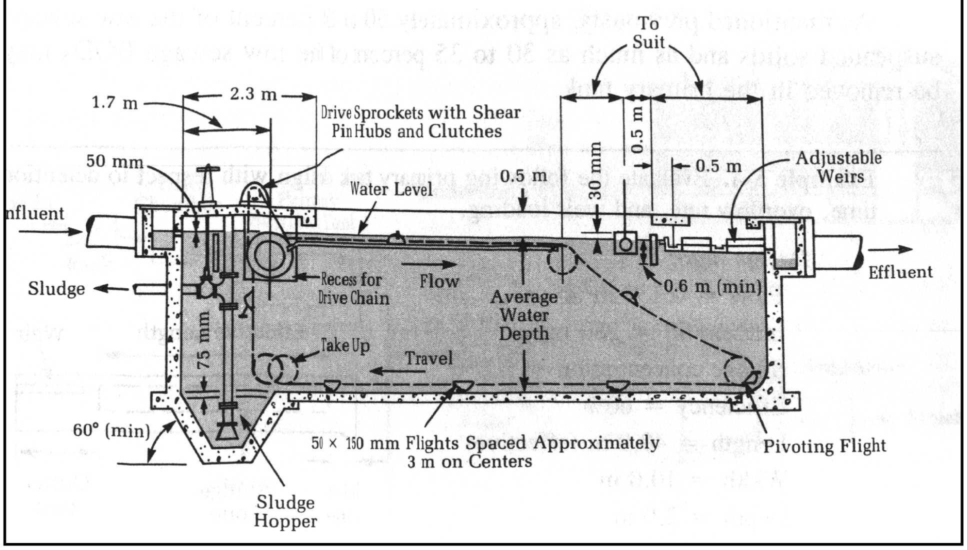
$$\left[OFR \equiv v_s\right] = \frac{Q}{A_s}$$

Grit Chamber

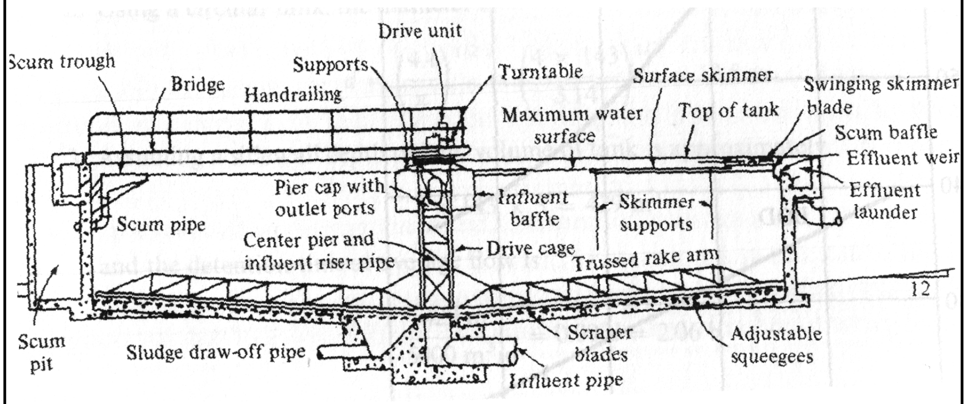


- Typical grit chambers are designed to retain particles with a diameter greater than 0.21 mm or 0.0083 in. The odd dimension corresponds to a standard U.S. Mesh of 65.

Primary Sed. Tank



Primary Clarifier: Center Feed

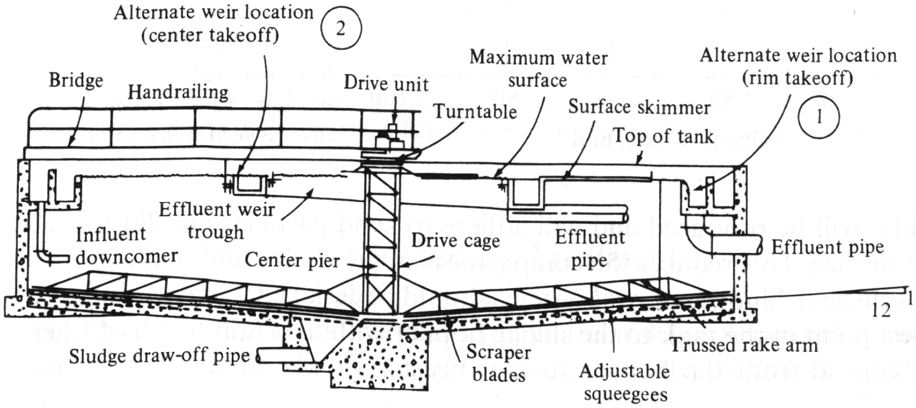


Settling

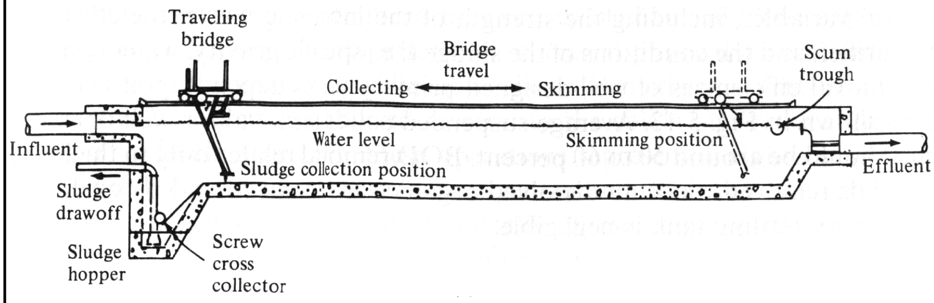
- 1965 addition

MWDSC
Weymouth Plant
12 Dec 05

Primary Clarifier: Rim Feed



Primary Clarifier: Rectangular



Settling Example #1

Estimate the settling velocity of sand (density = 2650 Kg/m^3) with a mean diameter of 0.21 mm. Assume the sand is approximately spherical. Using a safety factor of 1.4 to account for inlet and outlet losses, estimate the area required for a grit chamber to remove the sand if the flow rate is 0.10 m^3/sec.

The density of water at 20C is 998 Kg/m^3. Also, the viscosity of water at 20C is 1.01 x 10^{-3} N-sec/m^2 (Newton = Kg-m/s^2). The Stoke's settling velocity can now be calculated (see prior slides or Table 8.15, pg 404, in M&Z):

Solution to Example #1

$$v_s = OFR = \frac{(2650\ \frac{Kg}{m^3} - 998\ \frac{Kg}{m^3})(2.1\ x\ 10^4\ m)^2\ (9.8\ \frac{m}{sec^2})}{18(1.01\ x\ 10^3\ \frac{Kg}{msec})}$$

$$v_s = OFR = 0.039\ m/sec = 3.9\ cm/sec$$

Knowing the overflow rate, we can now calculate the area required for the grit chamber,

$$A = \frac{Q}{OFR}\ x\ SF = \frac{0.10\ m^3/sec}{0.039\ m/sec}\ x\ 1.4$$

where SF is the safety factor, 1.4.

$$\mathbf{A = 3.6\ m^2}$$

Thus, the area required for the grit chamber is 3.6 m^2 to remove 0.21 mm grit from the wastewater.

Primary Sedimentation

- Primary Treatment
- Removes ~50% of suspended solids

Parameter	Design Range	Typical Value
Overflow Rate	35-45 m/d 800-1200 gal/ft^2/d	40 m/d 1000 gal/ft^2/d
Detention Time	1.5-2.5 h	2 h
Weir loading rate	125-500 m^2/d 10,000-40,000 gal/ft/d	275 m^2/d 20,000 gal/ft/d

Settling Example #2

Estimate the size of two primary clarifiers that must treat a WW flow of 16MGD. $Q = A_s\left(OFR\right)$

$$A_s = \pi r^2$$
$$= \tfrac{1}{4}\pi d^2$$

$$A_s = \frac{Q}{OFR}$$
$$= \frac{(0.5)(8{,}000{,}000\,gal/d)}{1000\,gal/d/ft^2}$$
$$= 8{,}000\,ft^2$$

$$d = \sqrt{\frac{4A_s}{\pi}}$$
$$= \sqrt{\frac{4(8000\,ft^2)}{\pi}}$$
$$= 101\,ft$$

For Prefab units, go to 105 ft as next larger size

Example #2 (cont.)

Next using the design criteria for retention time, we can determine the tank depth (h)

$$\theta = \frac{V}{Q} = \frac{A_s h}{Q}$$

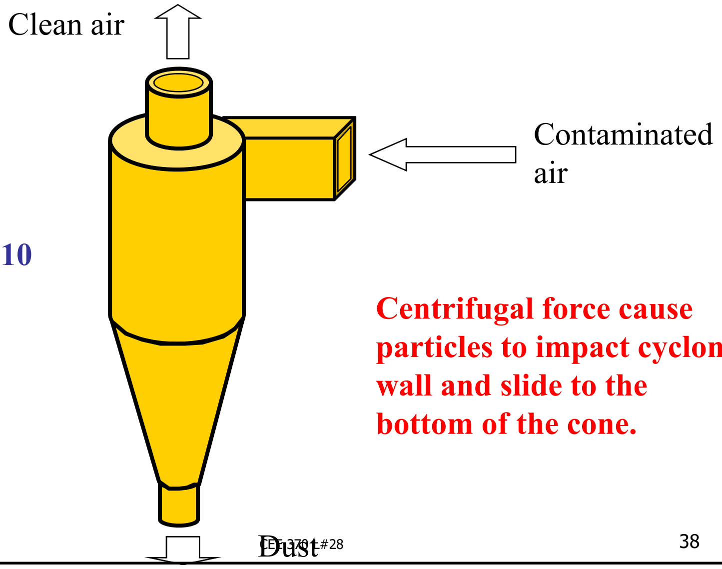
So:

$$h = \frac{\theta Q}{A_s} = \frac{\theta Q}{\pi\left(d/2\right)^2}$$
$$= \frac{2h\left(8{,}000{,}000\,gal/d\right)\frac{1d}{24h}\,\frac{1\,ft^3}{7.48\,gal}}{\pi\left(105/2\right)^2}$$
$$= 10\,ft$$

Other Applications

- Air pollution particulate removal
  - Electrostatic precipitators
    - Force balance includes electric force of attraction/repulsion
  - Cyclones
    - Force balance include centrifugal force against drag forces

Particulate Control: Cyclones



Especially effective for particle sizes greater than 10 µm.

Centrifugal force cause particles to impact cyclone wall and slide to the bottom of the cone.

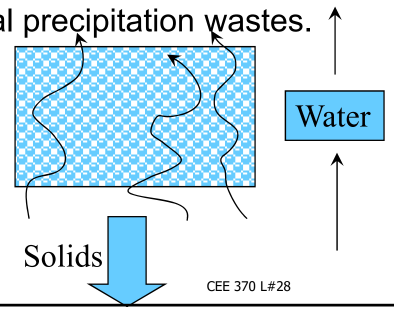
Flocculent Settling

Flocculant settling occurs when the concentration of particles is sufficiently high to allow the particles to agglomerate. The agglomeration is the result of gentle mixing induced by paddles in some sedimentation basins and from differential settling velocities of particles of different mass and size. This agglomeration results in larger particles, often with entrained water, but with higher settling velocities than would occur without agglomeration. Since the particle size and mass continually changes, it is not possible to use Stoke's Law to estimate the settling velocity. Flocculent settling is normally the predominant removal process in primary wastewater clarifiers.

Flocculant settling is analyzed or estimated by using laboratory settling experiments. The laboratory data is then used to estimate the removal versus settling time in the settling basin.

Hindered Settling

Hindered settling occurs as the concentration of solids increases above that for flocculent settling. This results in such high concentrations that the particles settle as a structured mass with the water moving between the particles. This type of settling occurs in the lower regions of clarifiers used to settle primary and secondary wastewater and in some clarifiers used for settling chemical precipitation wastes.



Compression Settling

Compression settling occurs in the bottom of many water and wastewater clarifiers where concentrations are so high that settling cannot occur without the compressive influence of the solids above. The solids at the bottom are compressed due to the weight of the mass above.

Filtration & disease control

resorted to chlorination before adding coagulation, sedimentation, and

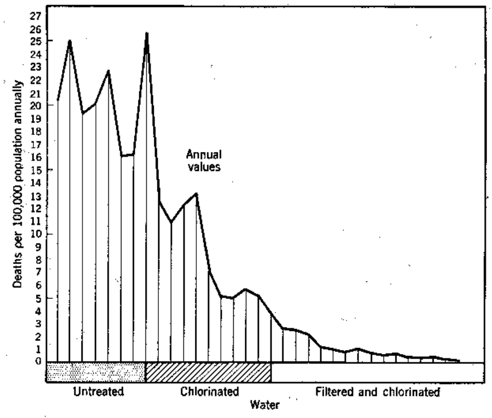


Figure 1-3. Effect of water purification on the death rate from typhoid fever in a city drawing water from a clear lake.

rapid sand filtration. Again the effects are clearly manifest. Both

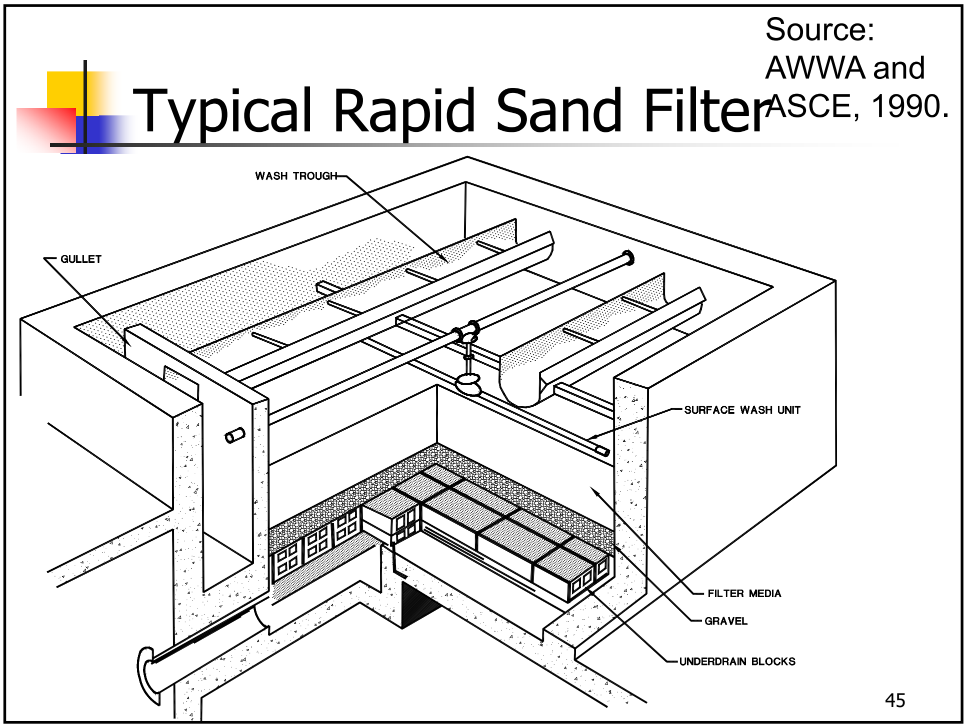
Pg 25, from Fair & Geyer, 1954

Filtration

- A "polishing" solid/liquid separation step
- Intended to remove particles
- Other impacts
  - biodegradation
  - organics adsorption (especially to GAC)
  - Mn and Fe adsorption

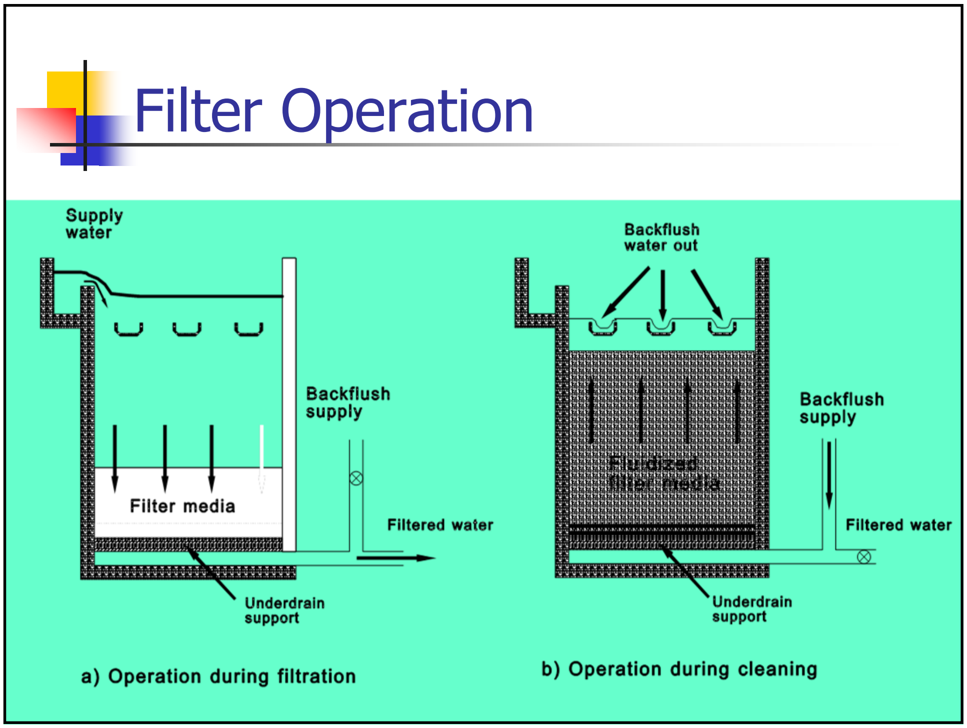
Types of Filtration

- Granular media filters
  - slow sand filters
  - rapid sand filters
  - high-rate granular media filters
- Membrane filters
  - microfiltration, ultrafiltration, nanofiltration
- Cake filtration
  - diatomaceous earth



Typical Rapid Sand Filter

Source: AWWA and ASCE, 1990.



Filter Operation

a) Operation during filtration

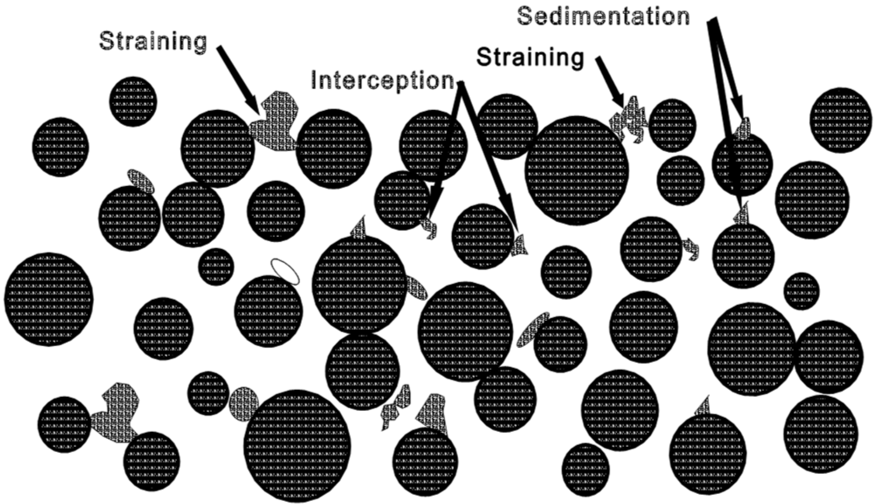
b) Operation during cleaning

Filtration: Mechanisms

- Interception
  - lines of flow strike media
- sedimentation
- diffusion
- straining
  - too large to fit between spaces
- flocculation
  - promoted by increased turbulence

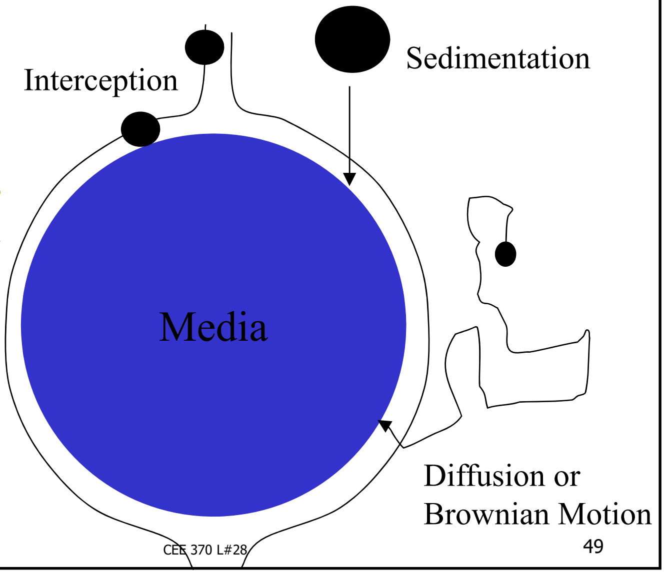
The transport mechanisms

Deposition in a Filter



Filtration transport mechanisms

In addition, particles must be able to stick. This requires chemical destabilization (i.e. coagulation).



- To next lecture