Lecture 5 - Sedimentation and flocculation

Lecture examines the transport (and specifically the downward settling) of particles in water. It further looks at flocculation as a process to enhance settling

Primary emphasis is on particles in water and wastewater treatment, but particles are also important in the natural environment:

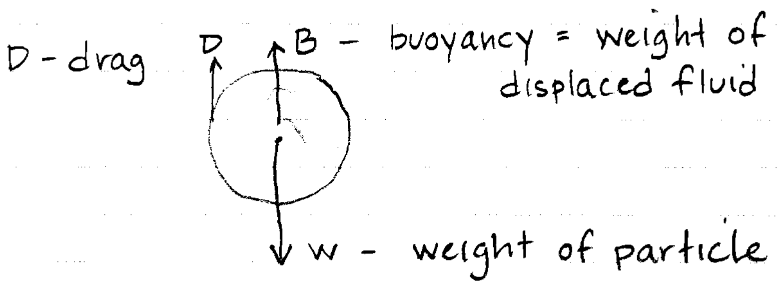
Particles are a pollutant in and of themselves with adverse impacts to aquatic life (damage fish gills, smother coral reefs)

Particle settling clogs rivers, fills up reservoirs (Lake Mead on Colorado River is filling rapidly

Particles may carry adsorbed chemicals - e.g. PCBs in Hudson River

Key parameter is settling velocity - determines how fast particles will settle and thus how large (how much residence time) treatment systems require

Determine settling velocity, V_s, for spherical particle based on force balance:



W = gravitational force on particle (i.e. weight)

$$= -\rho_1 g \frac{4}{3}\pi r^3 = -\rho_1 g \frac{\pi}{6} d^3 \qquad \left[\frac{ML}{T^2}\right]$$

ρ_1 = density of sphere (M/L^3)
d = diameter of sphere (L)
r = radius of sphere (L)
g = gravitational acceleration (L/T^2)

B = buoyancy force on sphere due to displaced fluid

$$= \rho g \frac{4}{3}\pi r^3 = \rho g \frac{\pi}{6} d^3$$

ρ = density of water

Archimedes principle - body wholy or partially immersed in a fluid is buoyed by force equal to the weight of the displaced fluid

D = drag on (moving) sphere

$$= \frac{1}{2}\rho C_D \underbrace{\left(\frac{\pi}{4} d^2\right)}_{\text{frontal area of sphere}} V_s^2$$

C_D = drag coefficient (dimensionless)
V_s = particle velocity

vertical momentum for sphere

$$\underbrace{\rho_1 \frac{\pi}{6} d^3}_{\text{mass}} \underbrace{\frac{\partial V_s}{\partial t}}_{\text{acceleration}} = W + B + D$$

In practice, particle accelerates only a short while, so we can consider the "terminal" velocity when drag, weight, and buoyancy are in equilibrium

$$\frac{\partial V_s}{\partial t} = 0 \longrightarrow W + B + D = 0$$

$$-\rho_1 g \frac{\pi}{6} d^3 + \rho g \frac{\pi}{6} d^3 + \frac{1}{2} \rho C_D \left(\frac{\pi}{4} d^2\right) V_s^2$$

$$\rightarrow V_s^2 = \frac{(\rho_1 - \rho) g \frac{\pi}{6} d^3}{\frac{1}{2} \rho C_D \frac{\pi}{4} d^2}$$

$$V_s = \left[\frac{4}{3}\left(\frac{\rho_1 - \rho}{\rho}\right) \frac{g d}{C_D}\right]^{1/2}$$

C_D = function of Reynolds number

$$\mathbb{R}\mathrm{e} = \frac{\rho V_s d}{\eta} = \frac{V_s d}{\nu}$$

η = dynamic viscosity of water (often written as μ)

ν = kinematic viscosity of water = $\frac{\eta}{\rho}$

See chart of C_D vs. $\mathbb{R}\mathrm{e}$ on page 4

Source for chart: Reynolds, T.D. and P. A. Richards, 1996.

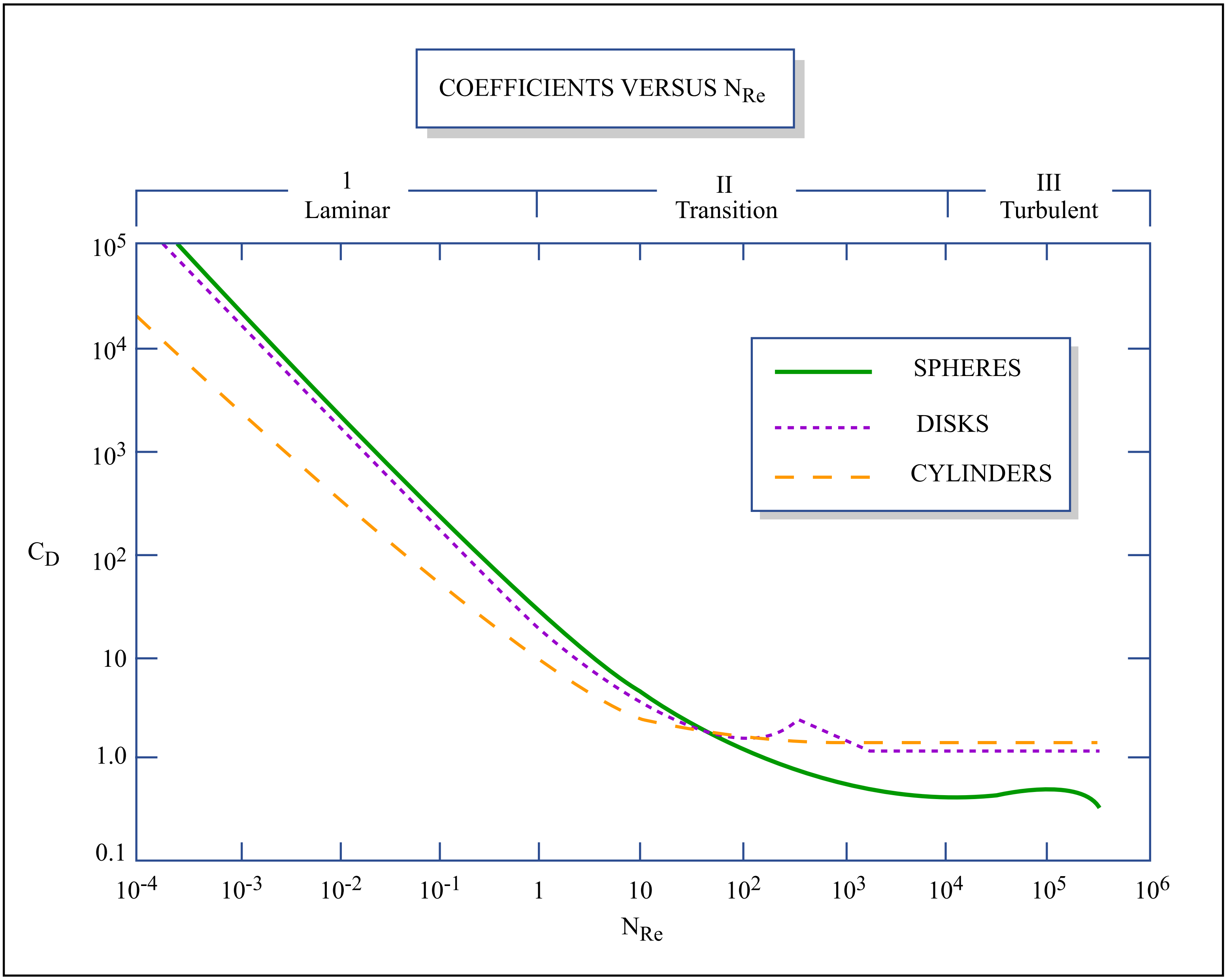


Figure by MIT OCW.

Adapted from: Reynolds, T. D., and P. A. Richards. *Unit Operations and Processes in Environmental Engineering*. 2nd ed. Boston, MA: PWS Publishing Company, 1996.

Three regions in graph:

I. Laminar flow $\mathbb{R}e < 1$ viscous force >> inertial force

$C_D = 24/\mathbb{R}e$ for sphere

This is exact relation since drag is due to viscous stress only - no form drag.

$$V_s = \frac{g d^2 (\rho_1 - \rho)}{18 \eta}$$

Stoke's Law for creeping flow

Consider quartz particle with $d = 10\ \mu m$, $\rho_1 = 2.6\ g/cm^3$ ($30\ \mu m$ is smallest particle visible to the eye)

$\nu = 10^{-6}\ m^2/s$ $\rho = 1\ g/cm^3 = 1000\ kg/m^2$

$\eta = \nu\rho = 10^{-3}\ kg/m \cdot s$

$\rightarrow V_s = 9 \times 10^{-5}\ m/s = 1\ m/day$

(Need to check assumption of laminar flow by computing $\mathbb{R}e$: $\mathbb{R}e = 9 \times 10^{-4} \ll 1$ ✓)

If we did this for typical sand grain with $d = 1\ mm$ predicted velocity is fast, no longer in laminar flow region

II Transition flow $1 < \mathbb{R}e < 10^4$ viscous ≈ inertial force

$$C_D = \frac{24}{\mathbb{R}e} + \frac{3}{\sqrt{\mathbb{R}e}} + 0.34$$

Can only solve for V_s by iteration:

Guess C_D, compute V_s, compute $\mathbb{R}e$, compute C_D

Keep iterating until V_s converges

For typical sand grain ($D = 1$ mm, $\rho_s = 2.6$ g/cm^3)
iteration yields:

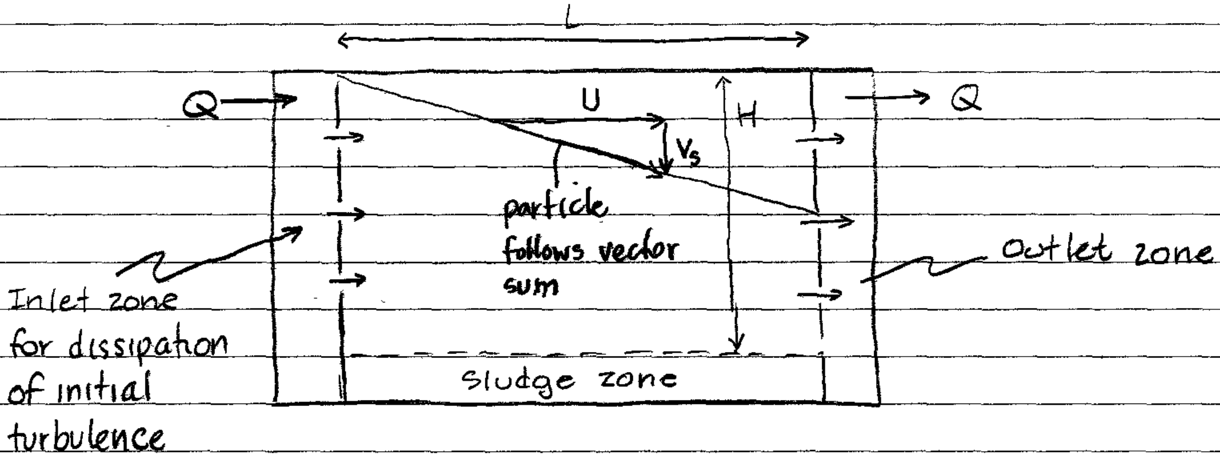
$$C_D = 0.71, \quad Re = 170, \quad V_s = 0.17 \frac{m}{s}$$

III Turbulent flow $Re > 10^{-4}$

$$C_D = 0.4$$

How does this work in a reactor?

Consider rectangular settling basin:



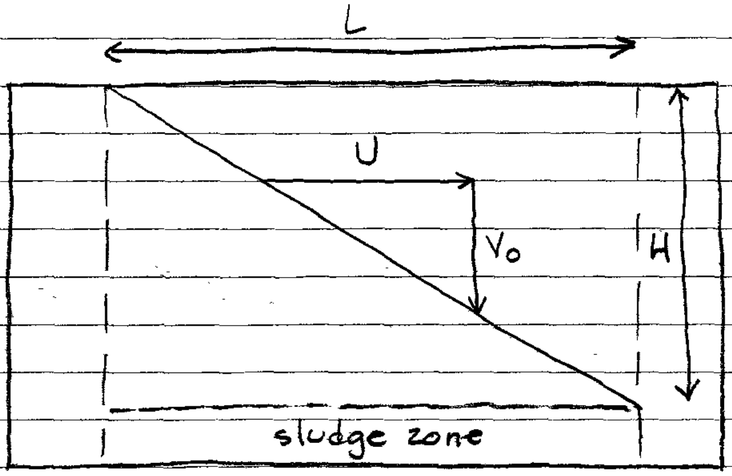
$$\text{settling time} = t_s = \frac{H}{V_s}$$

$$\text{Detention time} = t_R = \frac{L}{U}$$

$U = \dfrac{Q}{HW}$ W = width of tank

To get desired settling with most efficient tank size want

$$t_R = t_s$$



V_o is known as overflow rate

Note that $\frac{V_o}{U} = \frac{H}{L}$

$$V_o = \frac{HU}{L} = \frac{H\left(\frac{Q}{HW}\right)}{L}$$

$$= \frac{Q}{LW} = \frac{Q}{A_p}$$

A_p = plan area of tank

$V_o = \frac{Q}{A_p}$ = overflow rate of tank

Camp (1953) shows removal efficiency is solely a function of V_o

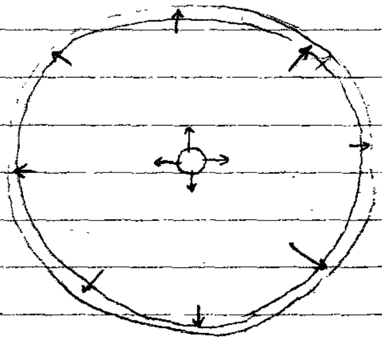
Camp, T.R., 1953 Studies of sedimentation basin design. Sewage and Industrial Wastes. Vol 25, No. 1, pp. 1-12.

Camp Fig 1 shows removal ratio (fraction of influent particles removed) is equal to V_s/V_o

Fig 3 shows effect of halving depth without changing $A_p = LW$ – removal ratio is unchanged

Fig 2 shows effect of adding a settling tray (in effect, halving depth while doubling area) removal ratio doubles

Often sedimentation tanks are circular with inflow at center and outflow along outer edge:

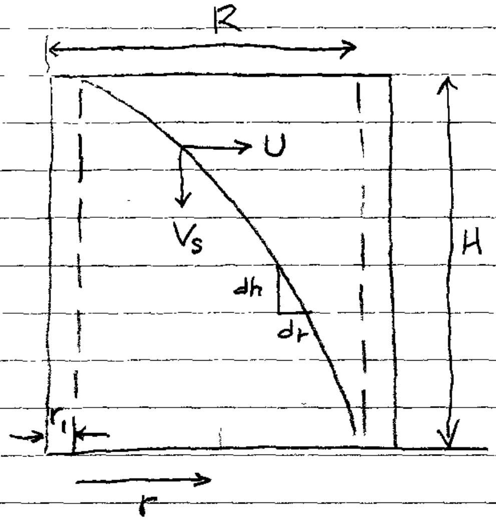


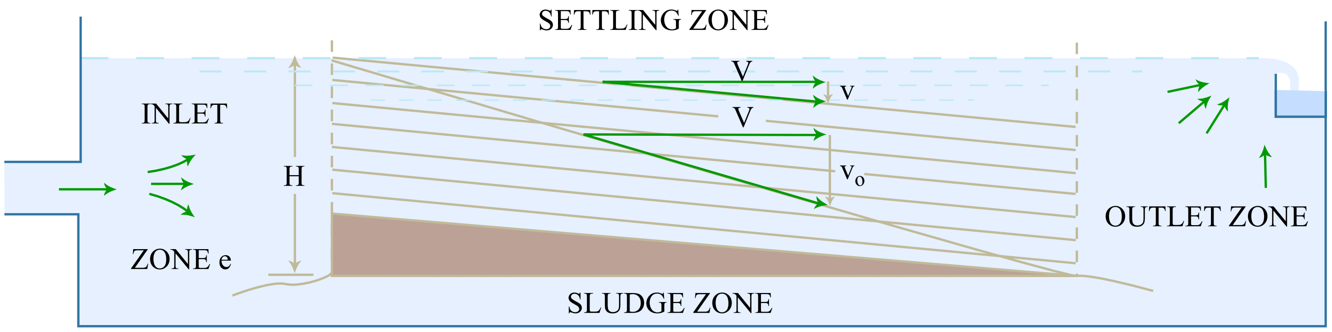
At radius r

$$U = Q / 2\pi r H$$

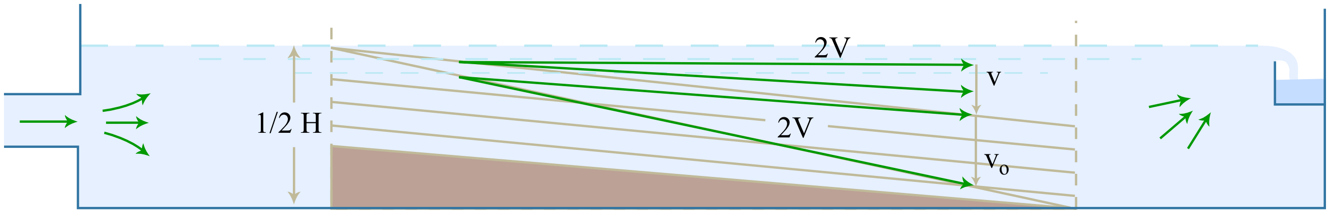
$$\text{Slope of curve} = \frac{dh}{dr}$$

$$= \frac{V_s}{U}$$

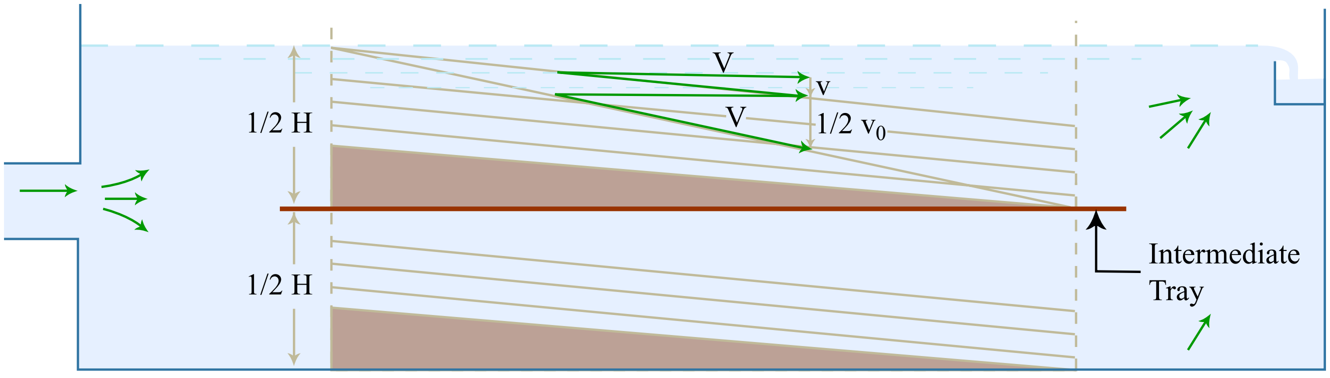




Zones of a rectangular, horizontal, continuous-flow sedimentation basin.



Reduced tank depth does not increase removal ratio.



Tray in tank provides added floor area & increases solids removal

Figure by MIT OCW.

Adapted from: Camp, T. R. "Studies of Sedimentation Basin Design." *Sewage and Industrial Wastes* 25, no. 1 (1953): 1-12.

$$\frac{dh}{dr} = \frac{V_s}{U} = \frac{V_s\, 2\pi r H}{Q}$$

$$\int_0^H dh = \frac{V_s 2\pi H}{Q} \int_{r_1}^R r\,dr$$

$$H = \frac{V_s 2\pi H}{Q} \left.\frac{r^2}{2}\right|_{r_1}^{R} = \frac{HV_s}{Q} 2\pi \left(R^2 - r_1^2\right)$$

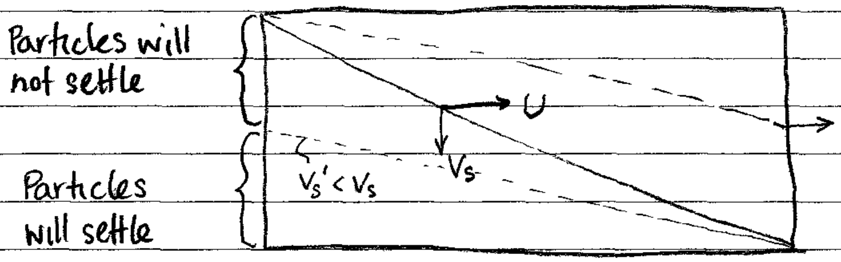
$$= \frac{HV_s}{Q} A_p$$

$\rightarrow \quad V_s = \dfrac{Q}{A_p}$ overflow rate same as for rectangular tank

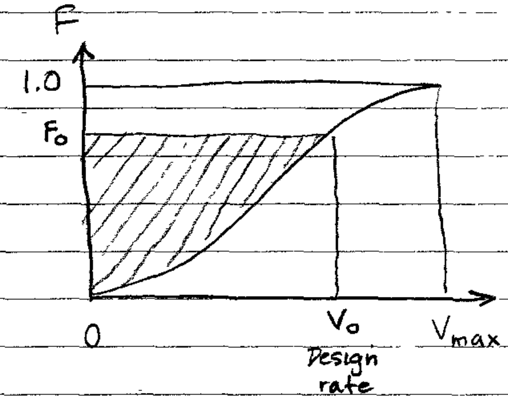
Depth of tank $H = V_s t_R$

Calculations assume uniform settling velocity, which never happens.

Particles smaller than assumed will have $V < V_s$ and will not all settle out in time. Some will settle out - if they enter the tank from a low enough height:



If particle velocity distribution is represented by $F(V_s)$ where F is the fraction of particles with settling velocity $\leq V_s$



Fraction settled for particular overflow rate V_0 is:

$$(1-F_0) + \int_0^{F_0} \frac{V}{V_0}\, dF = \text{Fraction removed}$$

$$\begin{array}{cc} \uparrow & \uparrow \end{array}$$

all particles that settle faster than V_0

fraction of particles slower than V_0 that will settle

Flocculation

Discrete (Type 1) settling discussed above is relatively rare in water and especially wastewater treatment

In treatment, many particles are present. As a particle falls, it collides with other particles and they stick together to form larger particles

Also, chemicals and polymers are added to enhance coagulation and flocculation

Definitions:

Coagulation - destabilization and initial coalescing of colloidal particles

Flocculation - formation of larger particles (flocs) from smaller particles

Chemicals are added to (quickly) cause coagulation, which then (slowly) flocculate

Page 11 shows pictures of typical flocs

Coagulation

Colloids persist as small particles because they carry negative surface charge and therefore repel each other

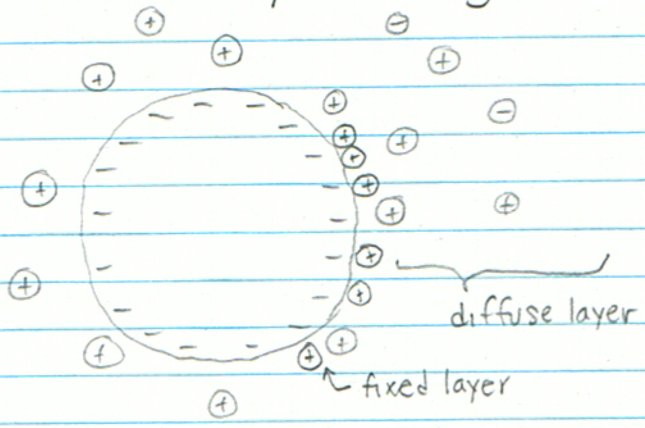
Colloids, by definition, do not settle and colloid removal requires that they be agglomerated into larger particles - this requires surface charge to be destabilized by one of these methods

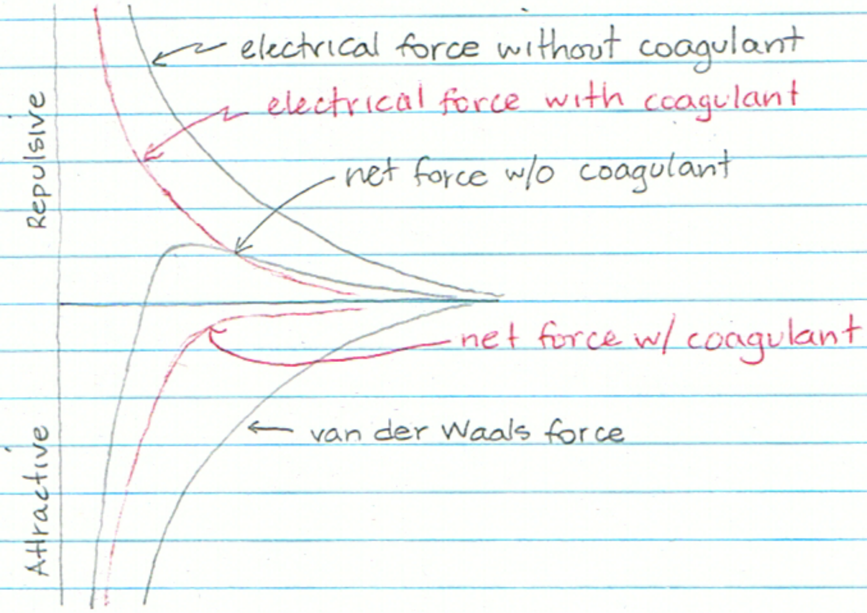
1. Double layer compression

Addition of electrolyte to water shrinks the layer of charged ions around the particle. If reduced enough, the attractive Van der Waals force (which acts close to particle) can overcome repulsive electrical force.

This phenomenon occurs at fresh - salt water zone in estuaries.

Diffuse double layer created by cations attaching to negatively charged particle (fixed layer) and cations and anions loosely attaching in outer diffuse layer:





Diffuse double layer modifies force balance as above. Coagulant creates net attractive force by neutralizing negative electrical charge (and force) of particle

2. Charge neutralization

   Adding positively charged ions that adsorb to particle surface can reduce surface charge and repulsion

3. Entrapment in precipitate

   Al and Fe salts added at right pH will precipitate as flocs with colloids as nuclei

4. Particle bridging

   Large organic molecules (both anionic and cationic) attach to multiple particles "bridging" them (Often used in addition to metal salts)

Once particles are coagulated, they can be flocculated

Flocculation occurs by:

1. Brownian motion - important for small particles ($< 0.5\,\mu m$)
2. Stirring - mechanical stirring strong enough to cause particle collisions but not so strong as to break up particles
3. Differential settlement - larger, faster particles catch up with smaller, slower particles

Flocculated settling is sometimes called Type II settling

Since particles become larger as they fall, settling velocity keeps increasing

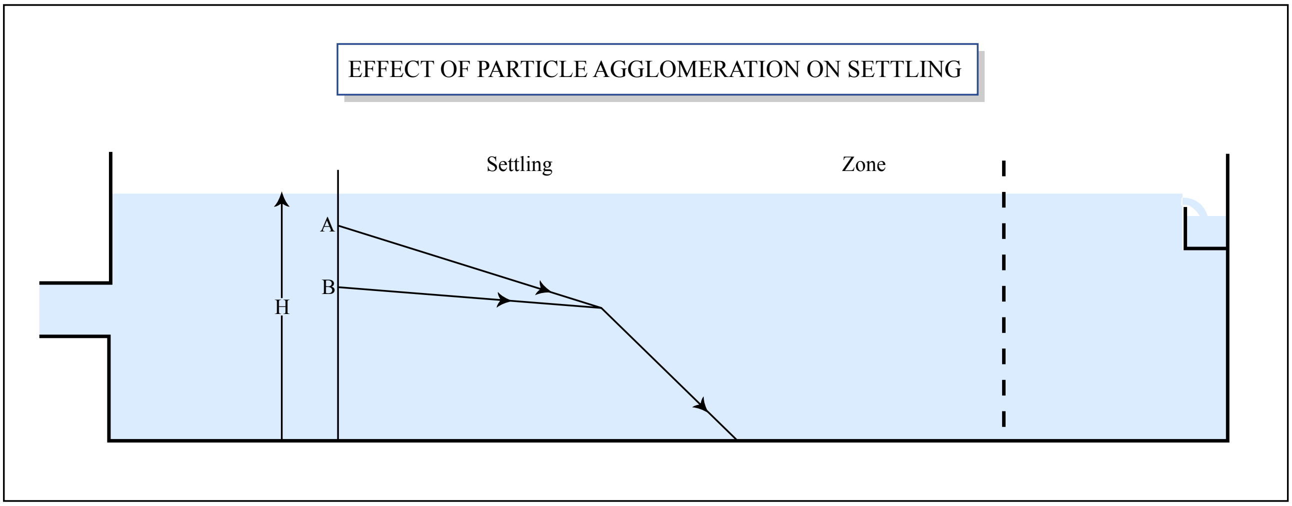


Figure by MIT OCW.

Adapted from: Camp, T. R. "Studies of Sedimentation Basin Design." *Sewage and Industrial Wastes* 25, no. 1 (1953): 1-12.

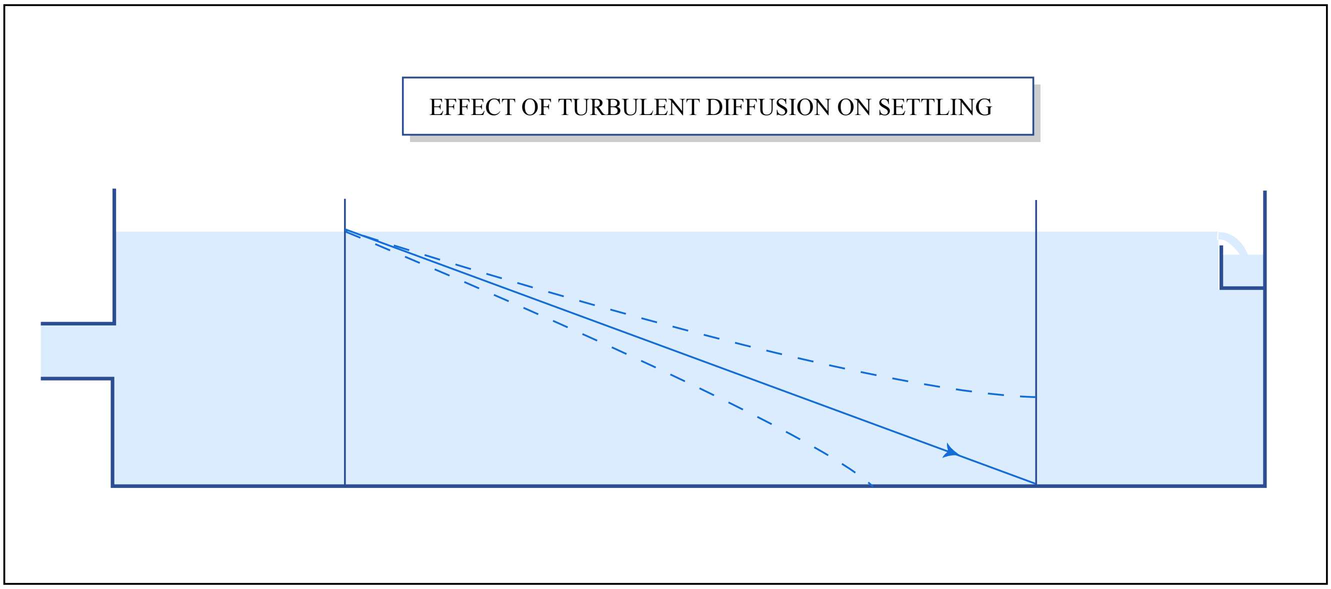
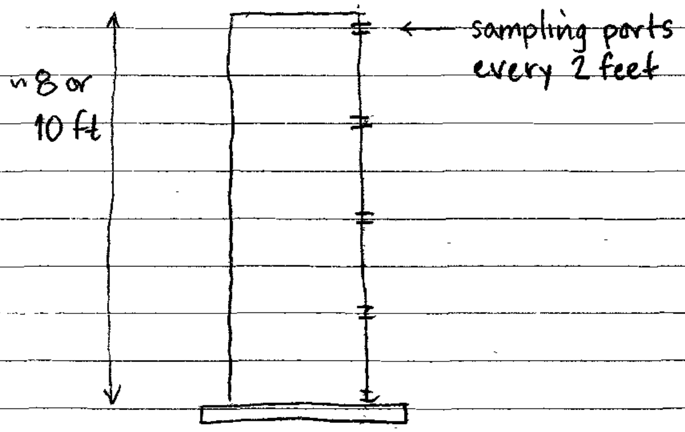


Figure by MIT OCW.

Adapted from: Camp, T. R. "Studies of Sedimentation Basin Design." *Sewage and Industrial Wastes* 25, no. 1 (1953): 1-12.

Design of clarifier for Type II (flocculant) Sedimentation requires knowledge of settling velocity distribution

Lab apparatus is column of depth similar to prototype tank and with diameter ≥ 5 in to reduce wall effects



see illustration pg 14

Initially, suspended sediment is well mixed, then allowed to settle

Samples are taken at each port at selected time intervals e.g. 5, 10, 20, 40, 60, 120 minutes and c/c_0 determined

Removals are then charted on depth vs. time plot (see pg 15) and removal isolines determined

The fraction removed at detention time t (e.g. t_2 on pg 15) comes from chart by reading Δdepth between removal isolines reading vertically from x-axis

$$\%\text{ removed} = \underbrace{\frac{\Delta h_1}{h_5} \times \frac{R_1+R_2}{2}}_{\text{percent removed from } \Delta h_i \text{ interval}} + \frac{\Delta h_2}{h_5} \times \frac{R_2+R_3}{2} + \frac{\Delta h_3}{h_5} \times \frac{R_3+R_4}{2} + \frac{\Delta h_4}{h_5} \times \frac{R_4+R_5}{2}$$

Apparatus For Quiescent Settling Analyses

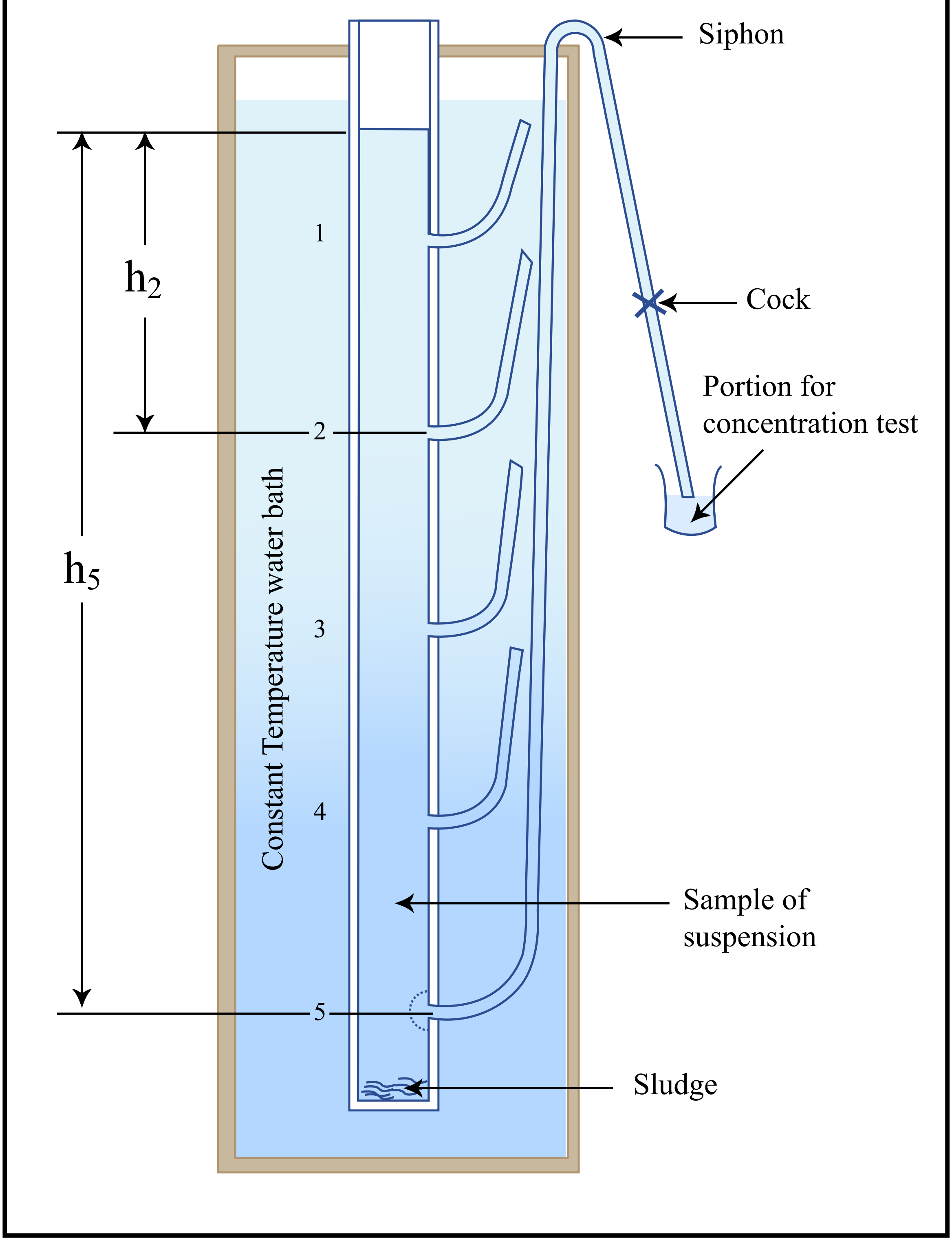


Figure by MIT OCW. Adapted from Camp, T. R., 1946. Sedimentation and the design of settling tanks. *Transactions ASCE*. Vol. 111, Pg. 895-936.

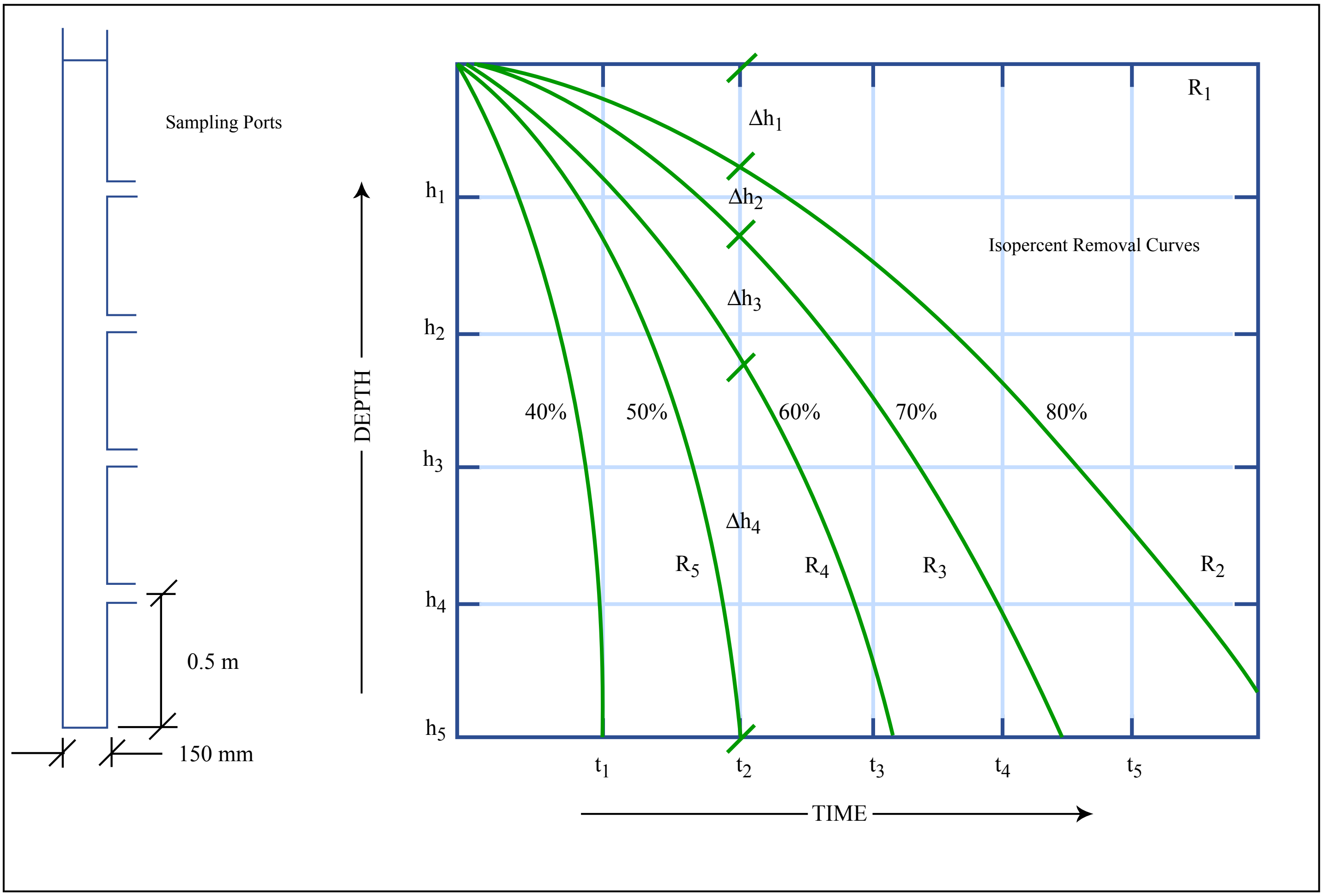


Figure by MIT OCW.

Adapted from: G. Tchobanoglous, F. L. Burton, and H. D. Stensel. *Wastewater Engineering: Treatment and Reuse*. 4th ed. Metcalf & Eddy Inc., New York, NY: McGraw-Hill, 2003, p. 369.

% removed at time t_2 =

$$\frac{\Delta h_1}{h_5} \times \frac{R_1+R_2}{2} + \frac{\Delta h_2}{h_5} \times \frac{R_2+R_3}{2} + \frac{\Delta h_3}{h_5} \times \frac{R_3+R_4}{2}$$

$$+ \quad \frac{\Delta h_4}{h_5} \quad \frac{R_4+R_6}{2}$$

Questions to consider:

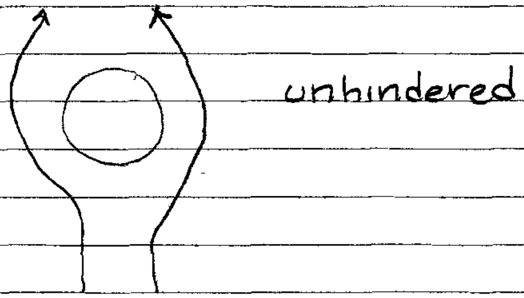
Why do removal isolines curve downwards?

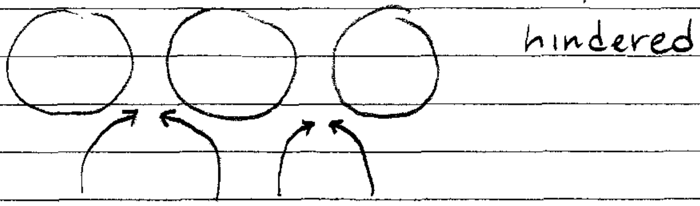
How would isoline curves look with discrete particle settling?

Note that calculation procedure above is not needed for discrete particle settling - can develop curve of fraction removed vs. V as shown on page 9 instead.

Type III settling is called hindered or zone settling

At high particle concentrations, inter-particle repulsion interferes with settling. Also, there is less room for flow to go around particles, creating hydrodynamic forces keeping particles from settling:



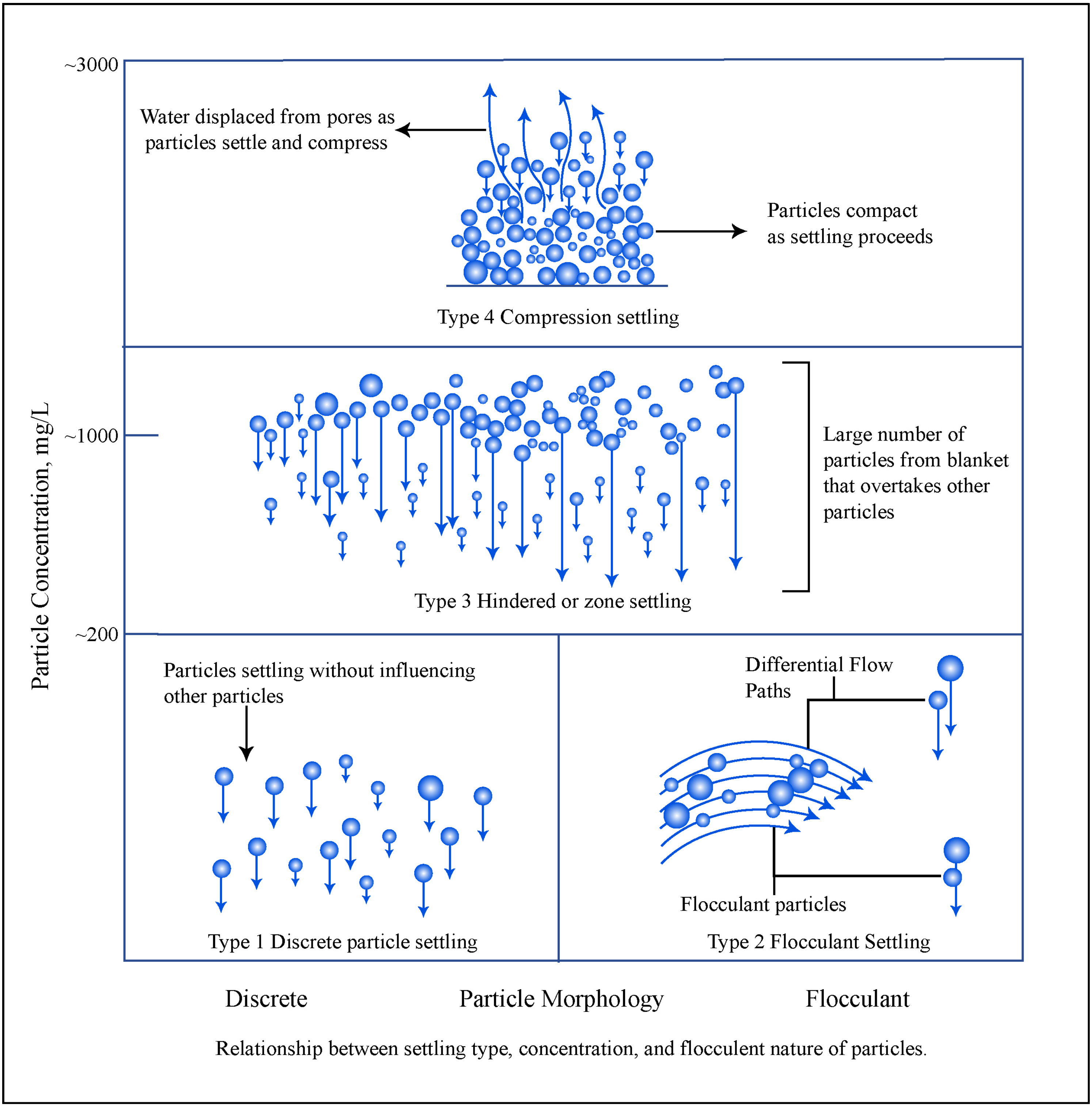


Called compression settling or Type IV settling

Type IV settling is called compression settling

Water gets squeezed out of sludge

See summary of types of settling in figure on pg 14



Relationship between settling type, concentration, and flocculent nature of particles.

Figure by MIT OCW.

Adapted from: MWH, J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous. *Water Treatment: Principles and Design*. 2nd ed. Hoboken, NJ: John Wiley & Sons, 2005, p. 781.

Choice of coagulants is typically site specific and determined by jar tests with different additives

Possible additives:

Aluminum sulfate (alum) forms $Al(OH)_3$ flocs
Ferrous sulfate
Ferric salts eg ferric chloride
Polymers - many proprietary products

Choice depends on local cost and efficacy
Some metal salts may be inexpensively available as industrial by-product

Typical designs

	t_R	overflow rate
Water treatment (VH, p.374)	2 - 4 hr	20-40 m^3/m^2-d
Wastewater (M&E)		
Grit chamber (p. 385)	0.75 - 1.5	~ 60
Primary clarifiers (p. 398)	1.5 - 2.5	30 - 50
Primary with AS return (p 398)	1.5-2.5	24 - 32
Secondary clarifiers (p. 687) (& VH 378)	2-3	16 - 28

Rectangular tanks - usually have chain-drive scrapers to bring sludge to withdrawal trough in tank bottom
Typically 3 m deep for water treatment
See illustration pg 24
(from Reynolds & Richard, pg 249)

Circular tanks - inflow at center, outflow along perimeter weir or radial collection troughs
circular rake arm to rake sludge to center (water treatment) or with suction pipes (wastewater)
See illustrations, pg. 25-27
Depths usually 3 m or more

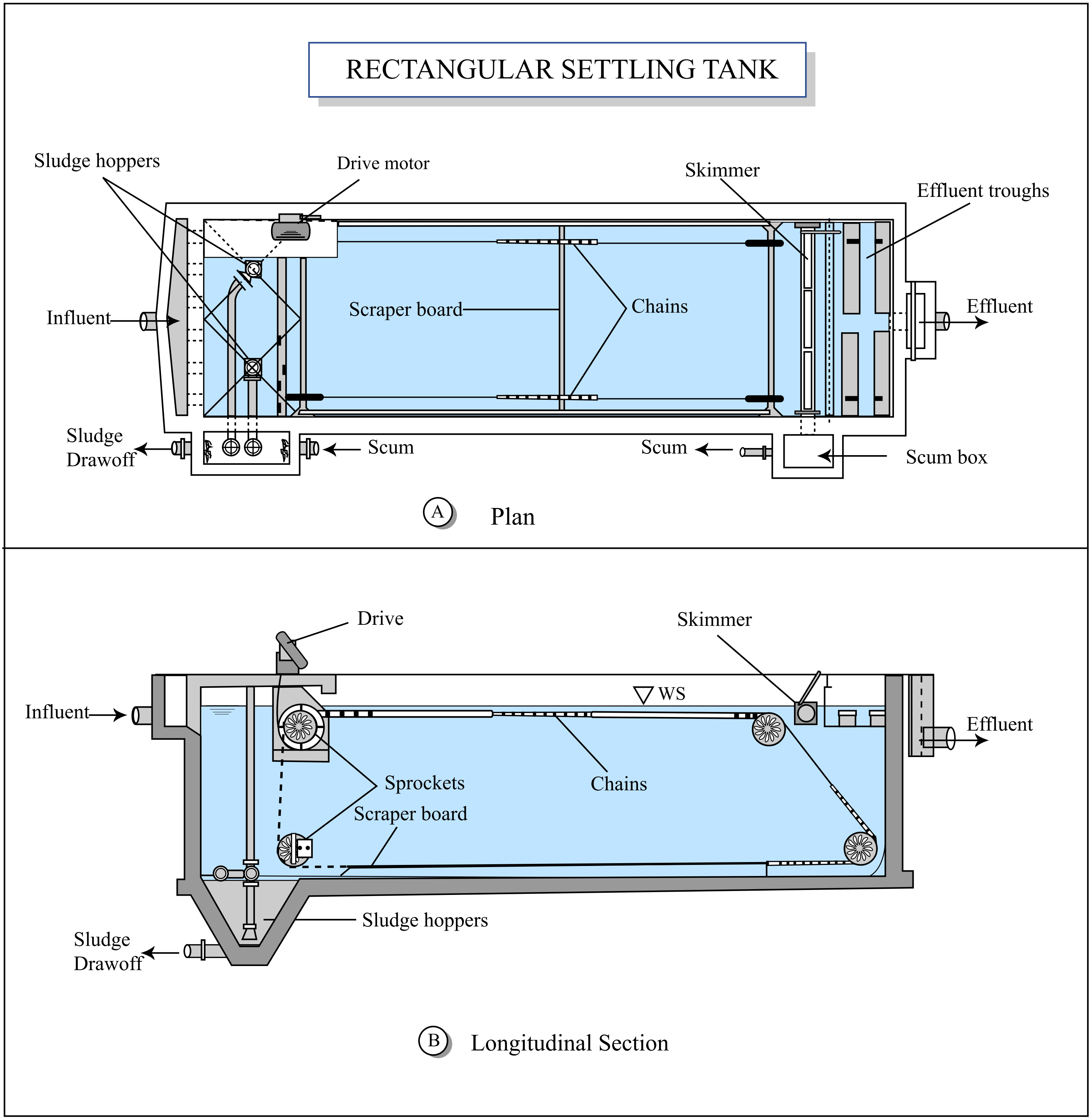
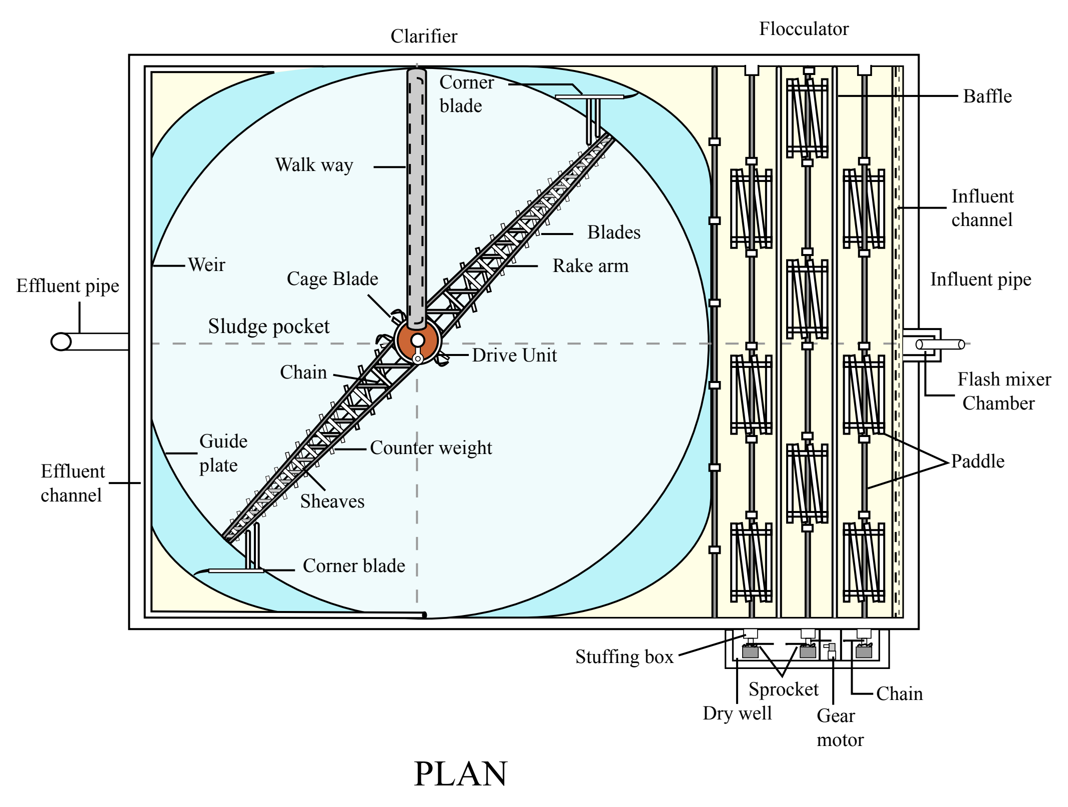


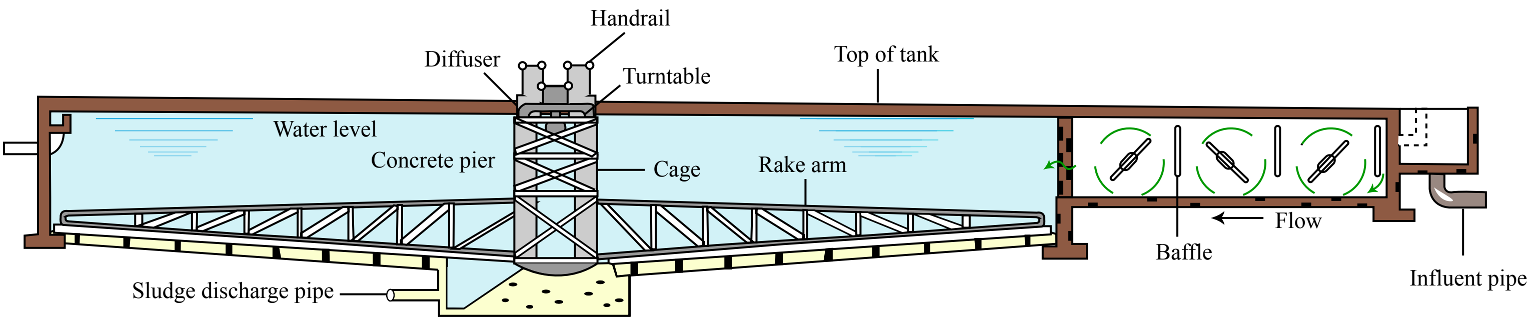
Figure by MIT OCW.

Adapted from: Reynolds, T. D., and P. A. Richards. *Unit Operations and Processes in Environmental Engineering*. 2nd ed. Boston, MA: PWS Publishing Company, 1996, p. 249. ISBN: 0534948847.

Better hydraulic characteristics in long, narrow settling tank

Less short circuiting





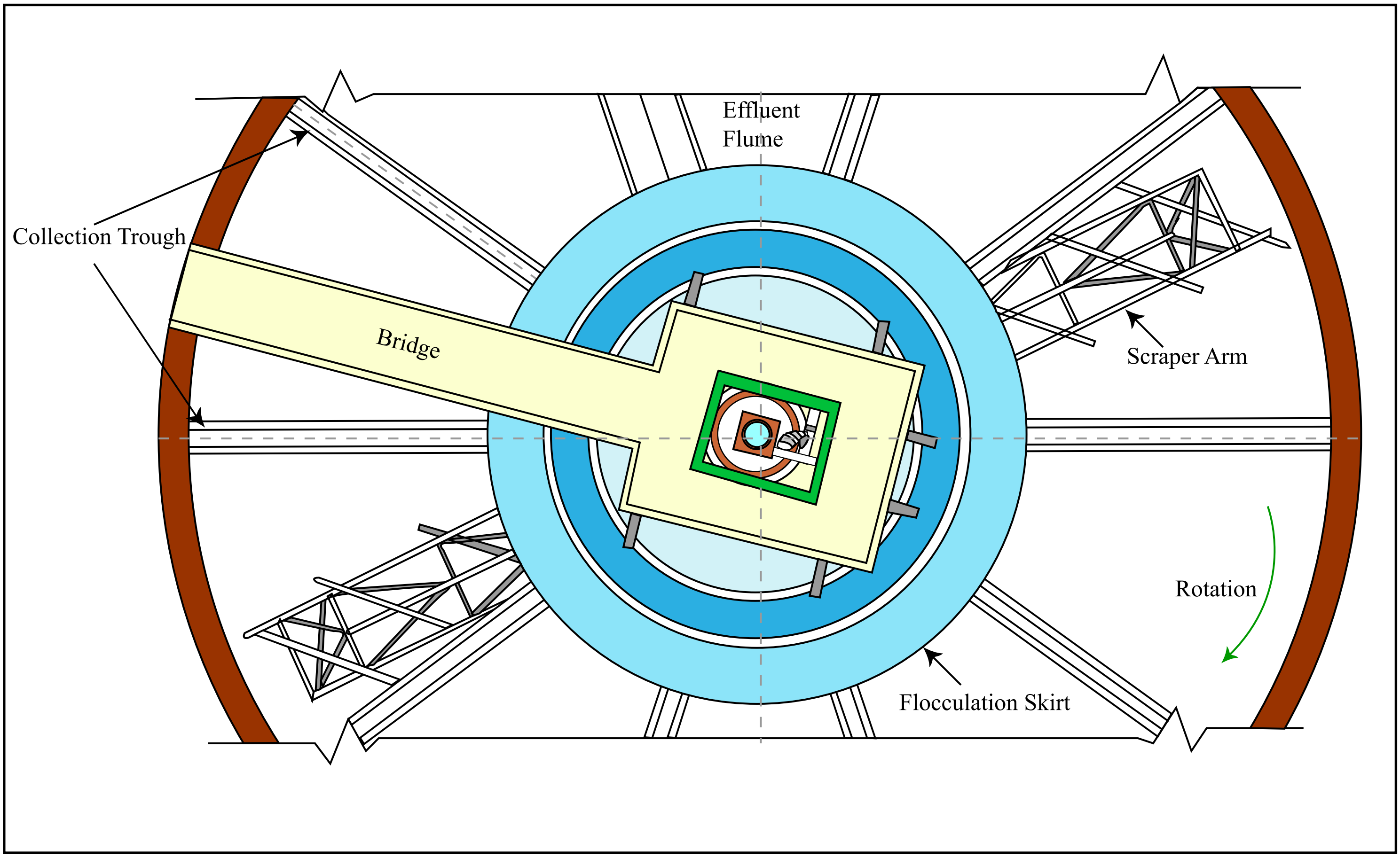
Flocculator & square sedimentation tank for water clarification, illustrating ceoss-flowoperation.

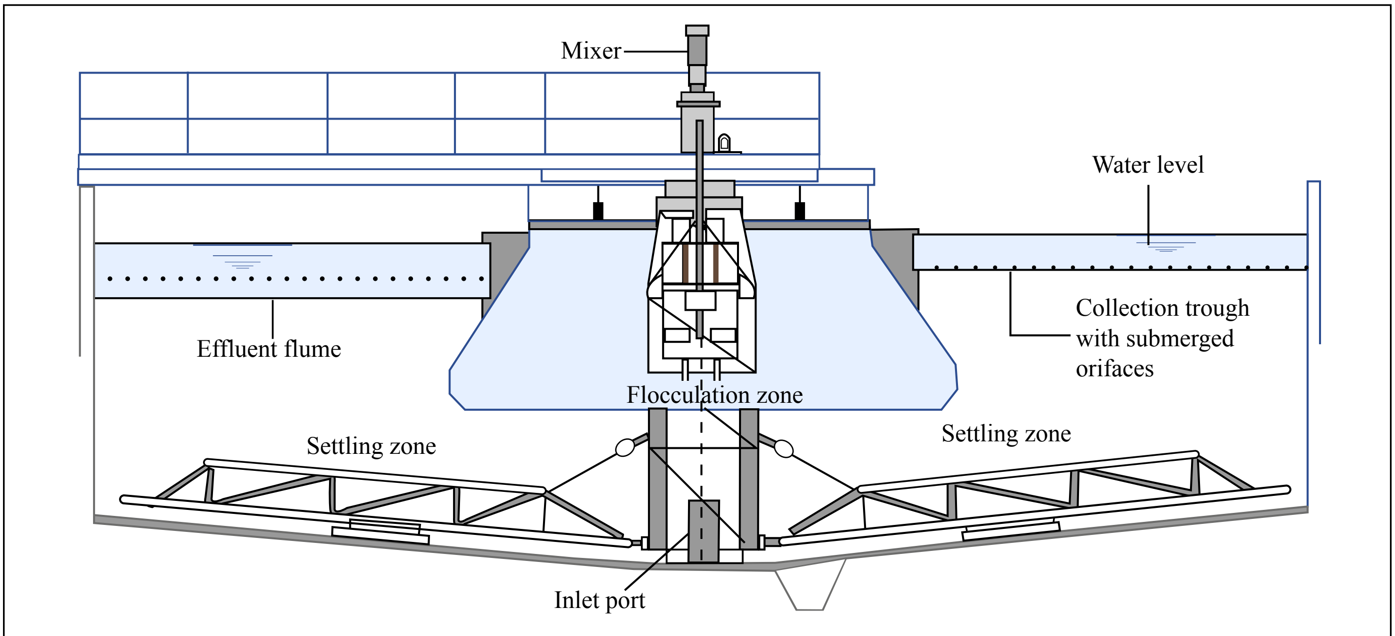
Figure by MIT OCW.

Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment*. Hoboken, NJ: John Wiley & Sons, 1997.

less expensive since side walls can be shared
Circular sludge collectors are relative trouble free
but corner sweeps are problematic
More weir length in corners leads to non-uniform
radial flow - sludge collects in corners

MWH 817





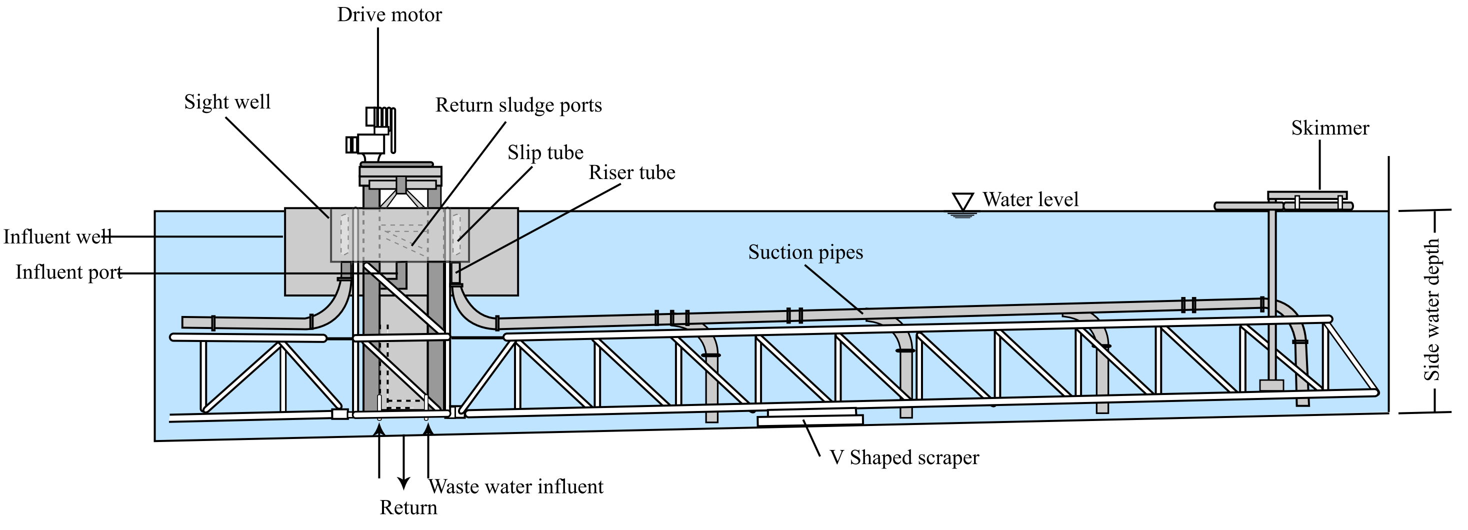
Flocculator-clarifier provides mixing, flocculation, & sedimentation in a compartmented concentric circular tank.

Figure by MIT OCW.

Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment*. Hoboken, NJ: John Wiley & Sons, 1997.

lower capital cost than rectangular tank
Circular sludge sweep is relatively trouble free

MWH 817



Ⓑ SLUDGE OUTLET

Final clarifier designed for use with activated-sludge processes. Return sludge is withdrawn through suction (uptake) pipes located along the collector arm for rapid return to the aeration tank. Sludge flowing from each pipe can be observed in the sight well.

Figure by MIT OCW.
Adapted from: Droste, R. L. *Theory and Practice of Water and Wastewater Treatment*.
Hoboken, NJ: John Wiley & Sons, 1997.

Rakes sludge to suction pipes

Earlier analysis of discrete particle settling shows that a shallow tank would be more efficient in settling particles

But usually, sedimentation tanks are about 3 m deep or more – why?

Answers: to take advantage of floc formation
shallow tanks can be more easily disrupted by turbulence
need space to accumulate sludge

A "shallow" depth design is the inclined plate separator – see illustration pg 29
(from Droste, pg 306)

Analysis of reactors showed a long rectangular tank is better than a circular tank – so why so many circular tanks?

Answers: less expensive construction
sludge collection is easier

LAMELLA CLARIFIER

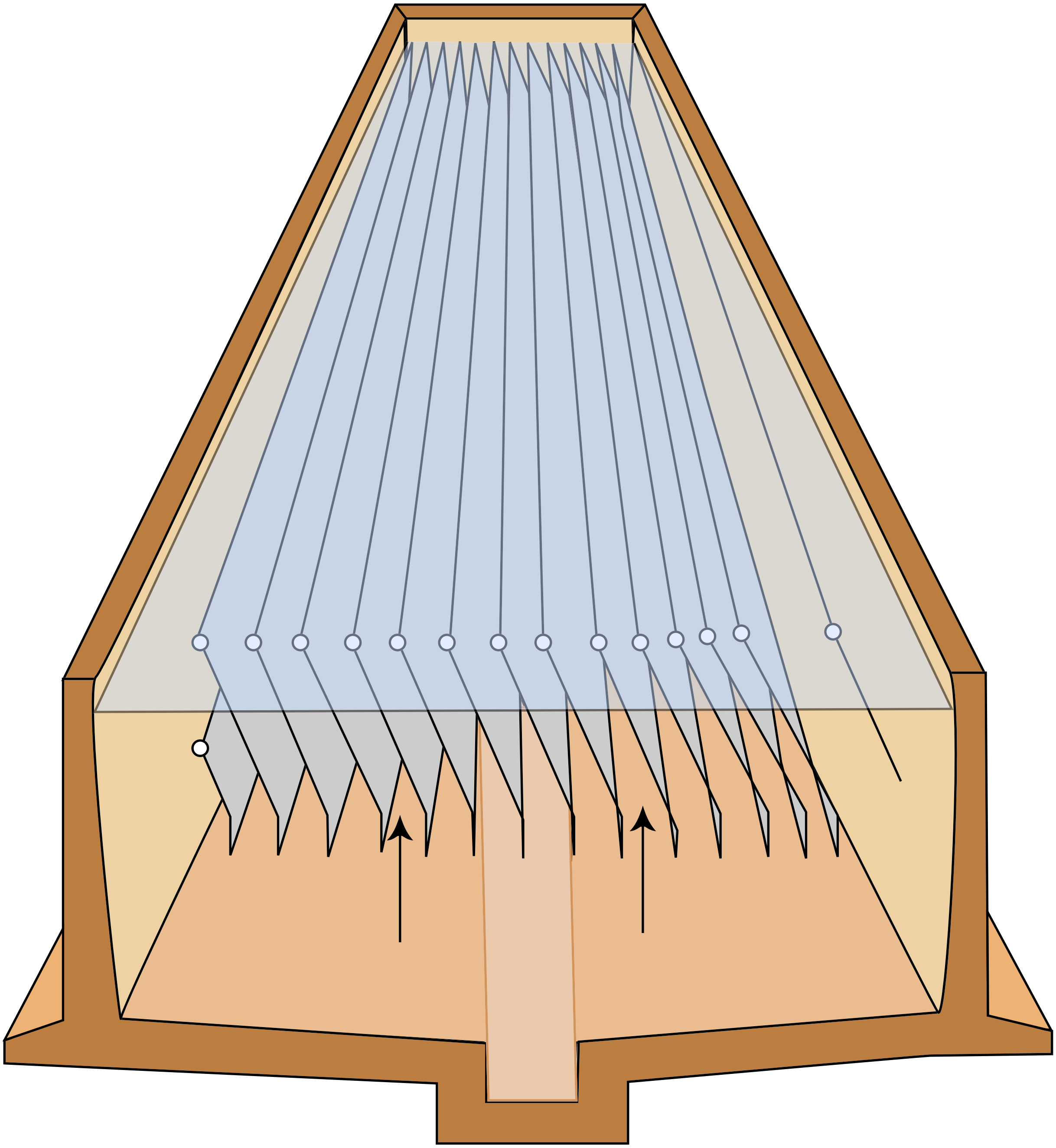


Figure by MIT OCW.

Adapted from: Binnie, C., M. Kimber, and G. Smethurst. *Basic Water Treatment*. 3rd ed. Cambridge, UK: Royal Society of Chemistry, 2002.

Mixing

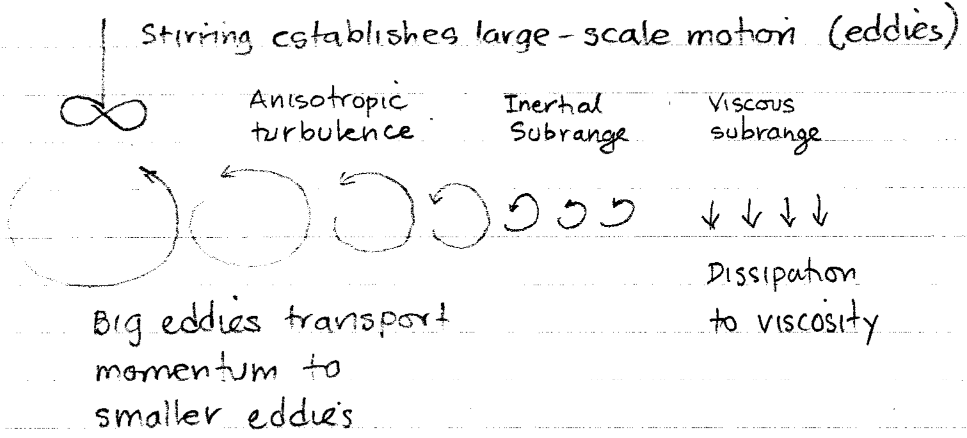
Mixing causes particles to collide so they can stick together (coagulate) and form and grow flocs

Mixing for coagulation is vigorous → causes lots of collisions to get particles to coalesce

Mixing for flocculation is gentle: Strong enough to cause collisions but not so strong to break up large flocs

Mixing in water + wastewater treatment is turbulent

Turbulence goes through turbulence cascade:

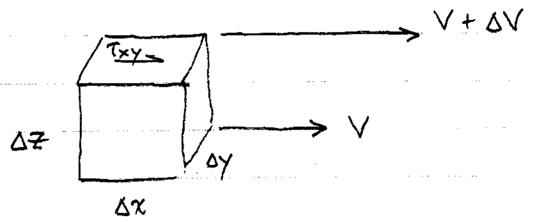


Summary by L.F. Richardson

"Big whorls have little whorls
Which feed on their velocity
Little whorls have smaller whorls
And so on to viscosity"

Rate of energy dissipation dictates velocity gradient $\left(\frac{dV}{dz} = G \right)$
In turn, number of collisions is proportional to velocity gradient

Consider fluid element subject to shear force τ_{xy} which causes velocity gradient



$$\text{Force} = \underset{\substack{\uparrow \\ \text{force per unit area}}}{\tau_{xy}} \Delta x \, \Delta y = \underbrace{\mu \frac{dV}{dz}}_{\text{by definition of Newtonian fluid}} \Delta x \, \Delta y$$

μ = dynamic viscosity of water $\left[\frac{N \cdot s}{m^2}\right]$

Power = Force × Velocity

Power per unit volume is

$$\frac{P}{\forall} = \frac{P}{\Delta x \, \Delta y \, \Delta z} = \frac{\overset{\text{Force}}{\left[\mu \frac{dV}{dz} \Delta x \, \Delta y\right]} \overset{\text{Velocity}}{\left[\frac{dV}{dz} \Delta z\right]}}{\Delta x \, \Delta y \, \Delta z}$$

$$= \mu \left(\frac{dV}{dz}\right)^2 = \mu G^2$$

$$\therefore \quad G = \sqrt{\frac{P}{\mu \forall}} \qquad \text{Camp-Stein}$$

G = Root-mean-square velocity gradient caused by mixing $[1/s]$

P = Power of mixing input to reactor $\left[\frac{N\text{-}m}{s}\right]$

$\forall$ = Volume of vessel $[m^3]$

Number of particle collisions is proportional to GT_R

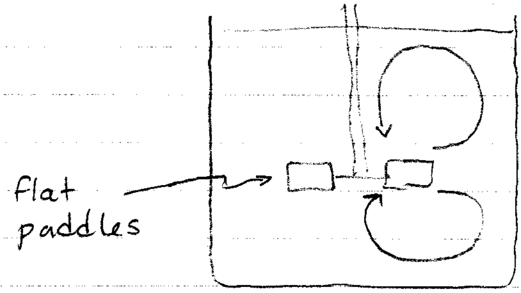
T_R = hydraulic residence time

→ Design parameters for mixing: G and T_R

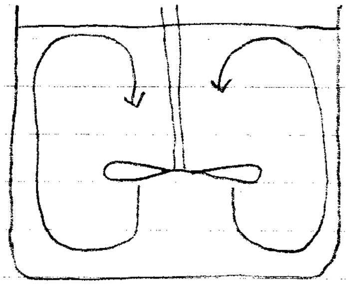
Jar tests determine optimum G and T_R for specific coagulants in specific water or wastewater

Different types of mixers impart energy in different ways, power is captured by different empirical or semi-empirical formulas. (see text)

Radial-flow mixers:



Axial-flow mixers



Some impellers cause vortices which can break up floc

Baffles are sometimes added to tanks to reduce vortices and rotational flow

Example of power equation:

Paddle flocculators (pg. 34)

$$P = \frac{C_D A_P \rho V_R^3}{2}$$

C_D drag coeff for paddle
A_P area of paddle projected in direction of movement
ρ density of water
V_R velocity of paddle relative to water
~ 70 to 80% of paddle speed

C_D = 1.2 to 1.9 for length : width of 1 to 20

Other mixing devices

Chemical injection into center of flowing pipe
(pumped flash mixing)

Static mixers (in-line vanes in pipe to cause mixing)

Baffling in tank

Pneumatic agitators (bubblers)