Lecture 5   Sedimentation and flocculation - Part 1

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:

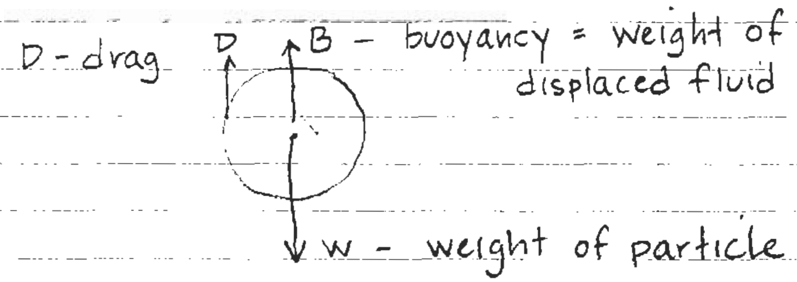
Particles are a pollutant in and of themselves with adverse impacts to aquatic life (damage fish gills, smother coral reefs)

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 much volume (i.e. 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

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

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

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

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

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

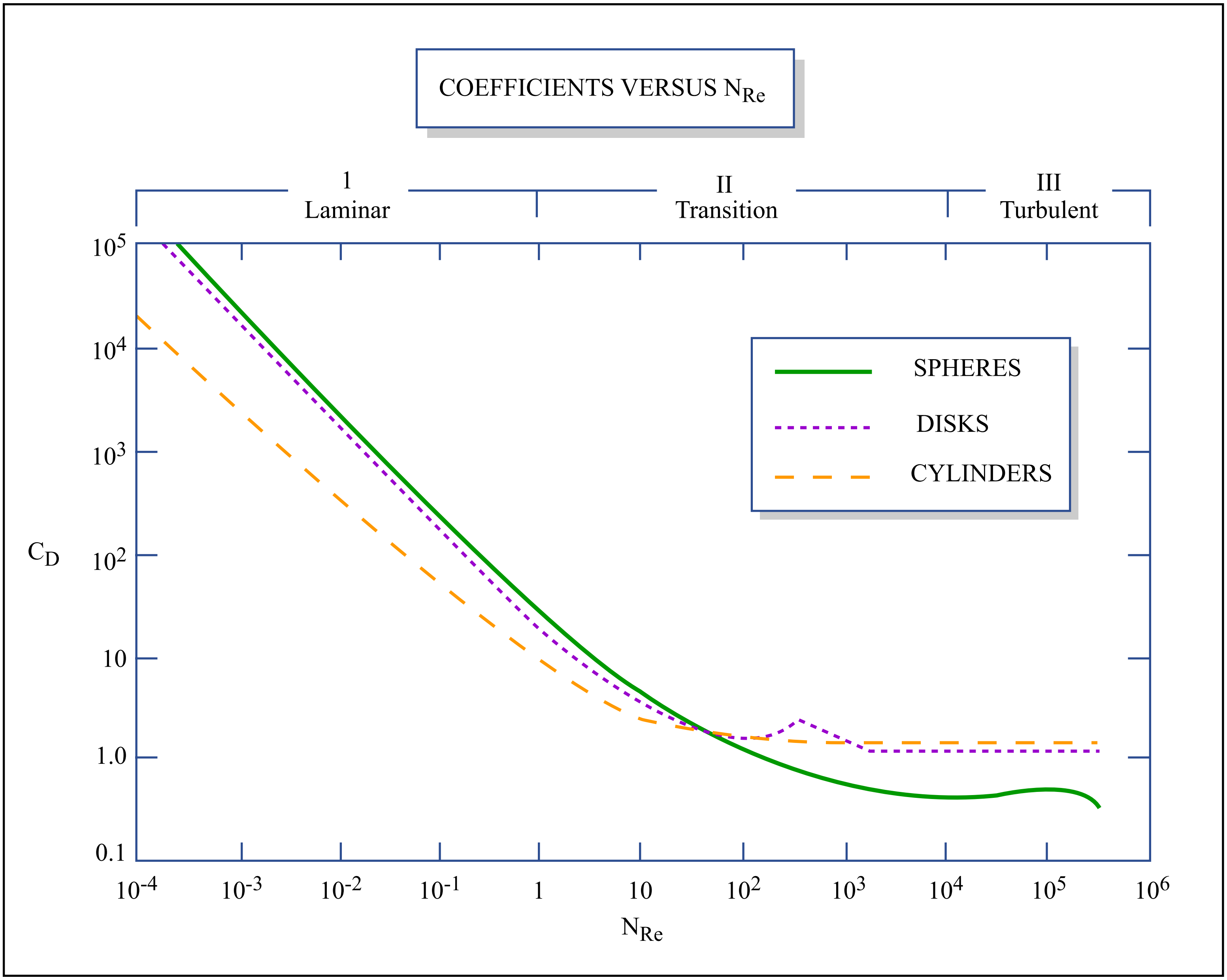


Figure by MIT OCW.

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 $\mathrm{Re} < 1$ viscous force >> inertial force

$C_D = 24/\mathrm{Re}$ 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 μm 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 Re: $\mathrm{Re} = 9 \times 10^{-4} \ll 1$ ✓)

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 $1 < \mathrm{Re} < 10^4$ viscous ≈ inertial force

$$C_D = \frac{24}{\mathrm{Re}} + \frac{3}{\sqrt{\mathrm{Re}}} + 0.34$$

Can only solve for V_s by iteration:
Guess C_D, compute V_s, compute Re, compute C_D

Keep iterating until V_s converges

For typical sand grain ($d = 1$ mm, $\rho_1 = 2.6$ g/cm³)
iteration yields:

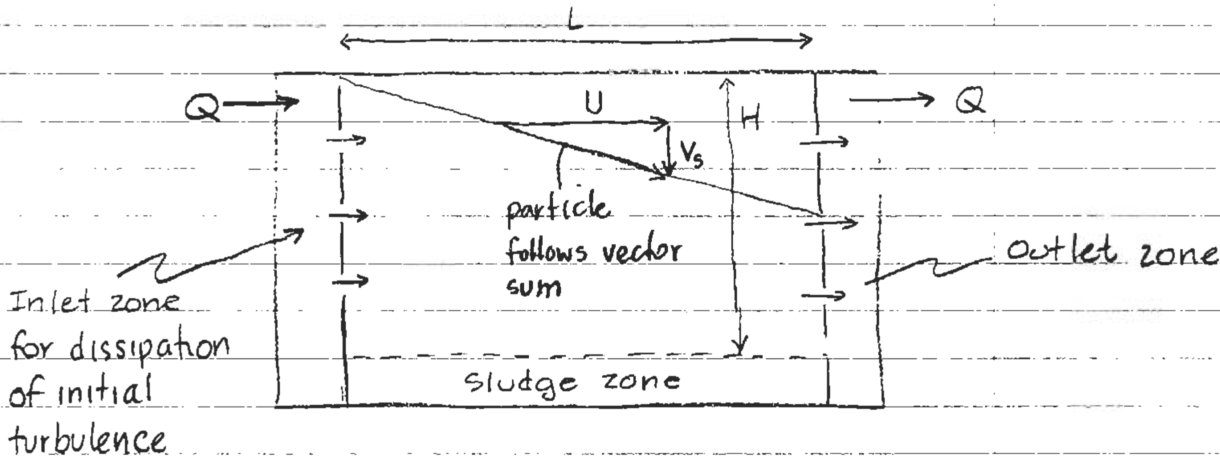
$$C_D = 0.71, \quad \mathrm{Re} = 170, \quad V_s = 0.17 \ \frac{m}{s}$$

III Turbulent flow $\quad \mathrm{Re} > 10^{+4}$

$$C_D = 0.4$$

How does this work in a reactor?

Consider rectangular settling basin:



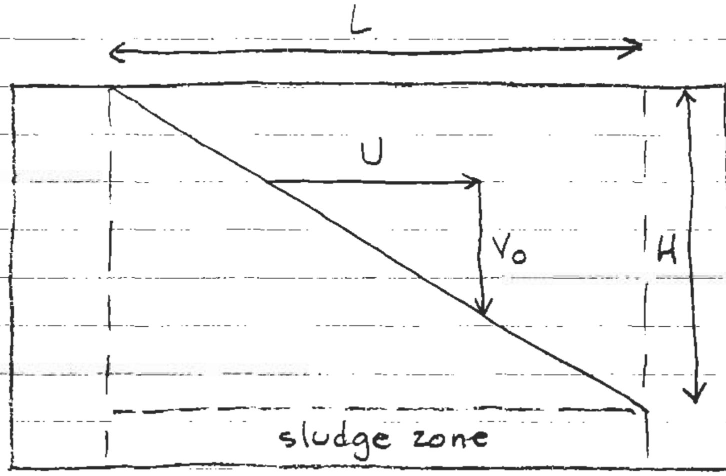
$$\text{settling time} = t_s = \frac{H}{V_s}$$

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

$$U = \frac{Q}{HW} \qquad W = \text{width of tank}$$

To get desired settling with most efficient tank size want

$$t_R = t_s \qquad \text{occurs when } V_s = V_o$$



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

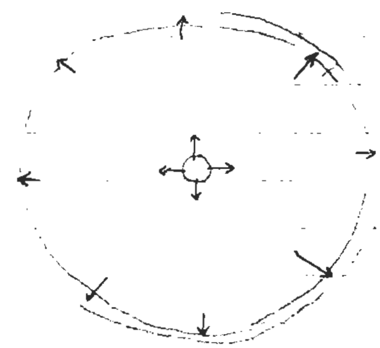
Camp, T.R., 1953 Studies of sedimentation basin design. Sewage and Industrial Wastes. Vol 25, No. 1, pp. 1-12.

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

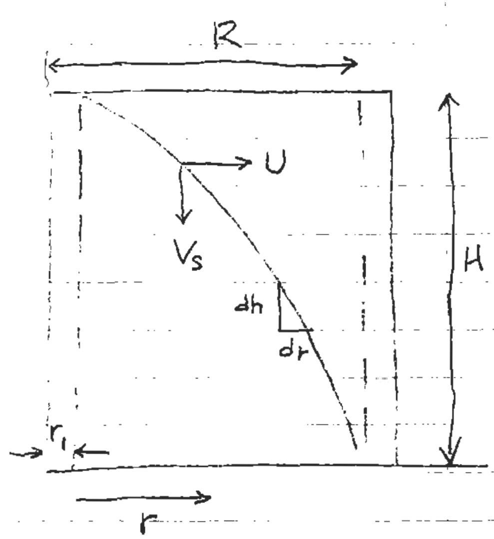
Often sedimentation tanks are circular with inflow at center and outflow along outer edge:

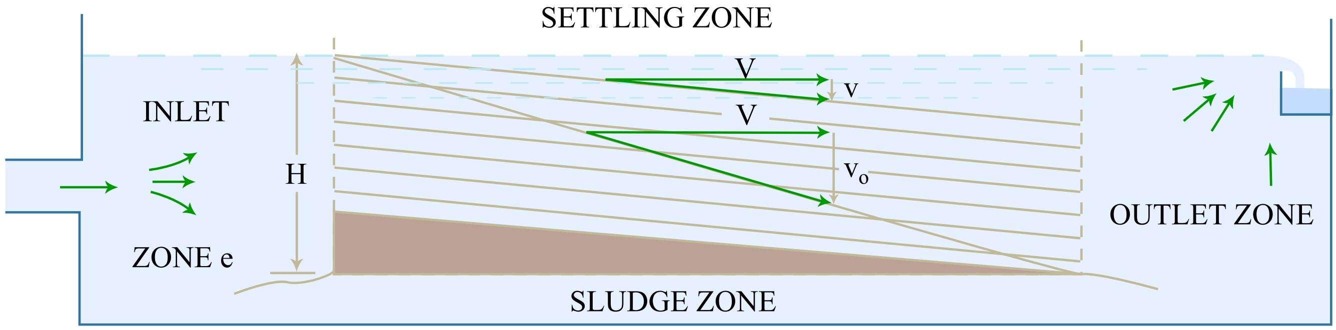


At radius r

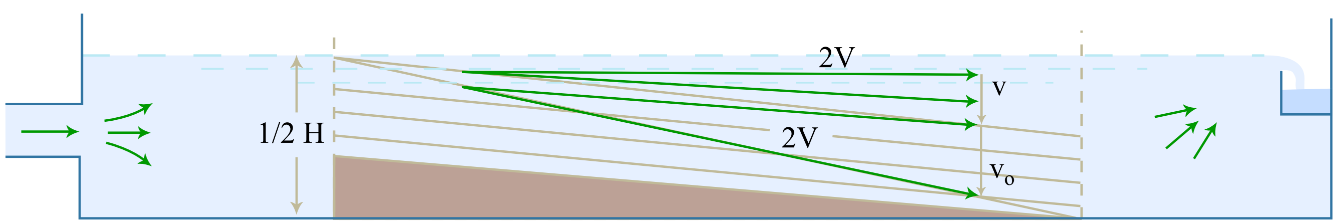
$$U = Q / 2\pi r H$$

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

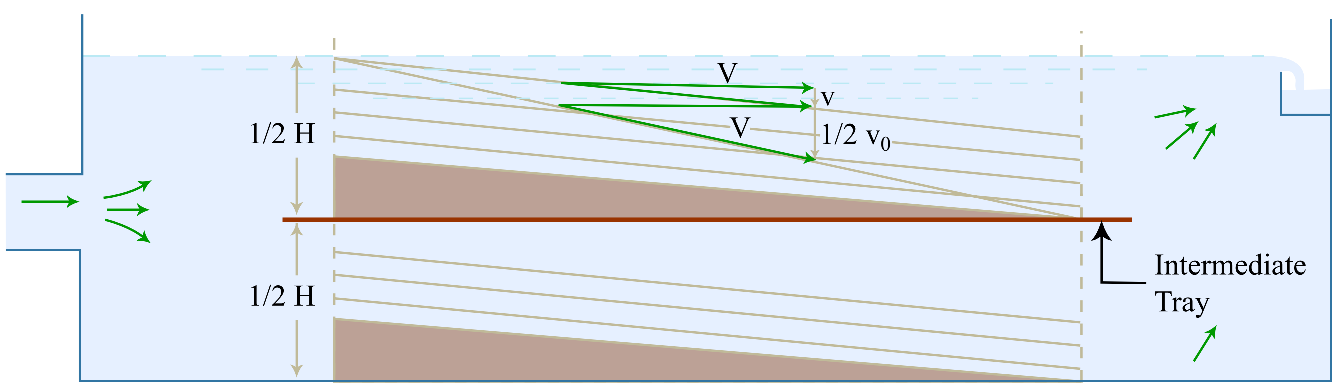




Zones of a rectangular, horizontal, continuous-flow sedimentation basin.



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.

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

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

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

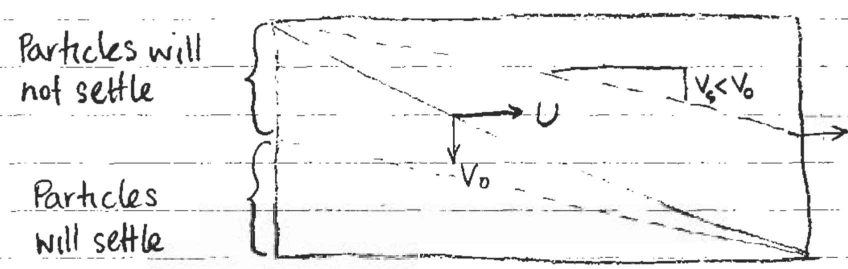
$$= \frac{HV_o}{Q} A_p$$

$\longrightarrow$ $V_o = \dfrac{Q}{A_p}$ overflow rate same as for rectangular tank

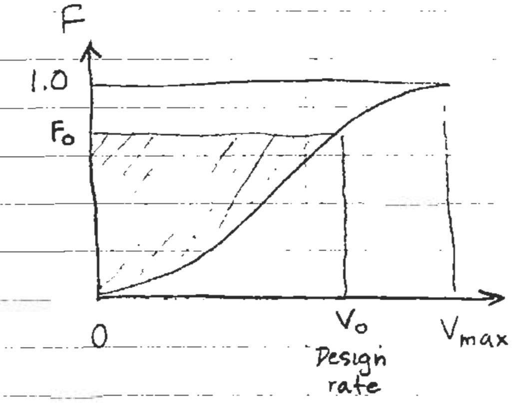
Depth of tank $H = V_o t_R$

Calculations assume uniform settling velocity, which never happens.

Particles smaller than assumed will have $V_s < V_o$ 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_o is:

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

$(1-F_o)$: all particles that settle faster than V_o

$\int_0^{F_o} \frac{V}{V_o}\, dF$: fraction of particles slower than V_o 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 14 shows pictures of typical flocs

Coagulation

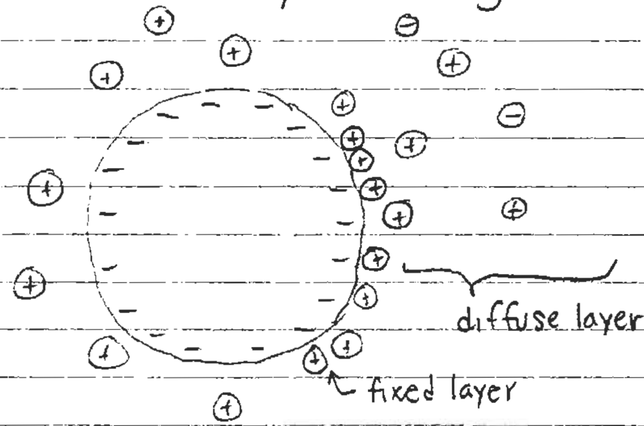
Colloids persist as small particles because they carry negative surface charge and therefore repel each other

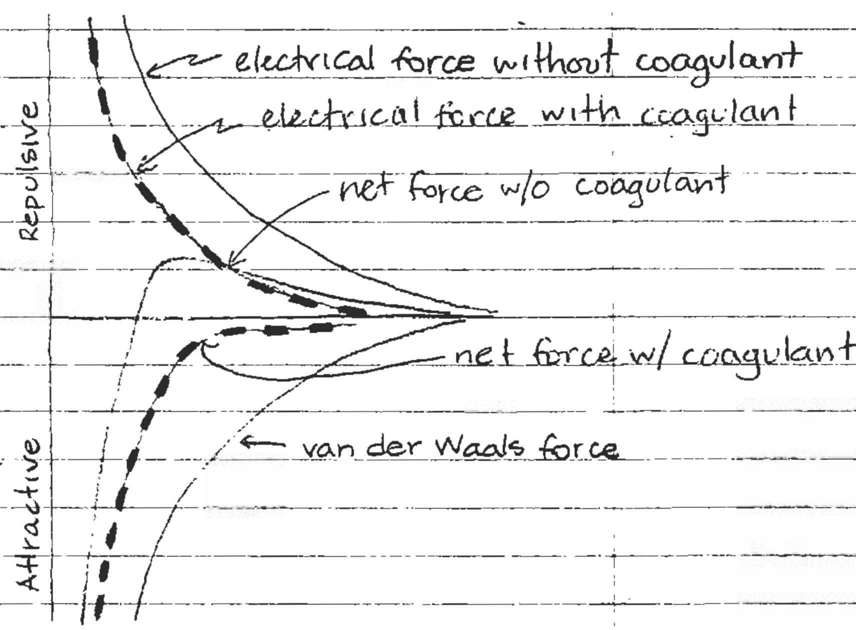
Colloids, by definition, do not settle and colloid removal requires that they be agglomerated into larger particles - this requires surface charge to be destabilized by one of these methods

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.

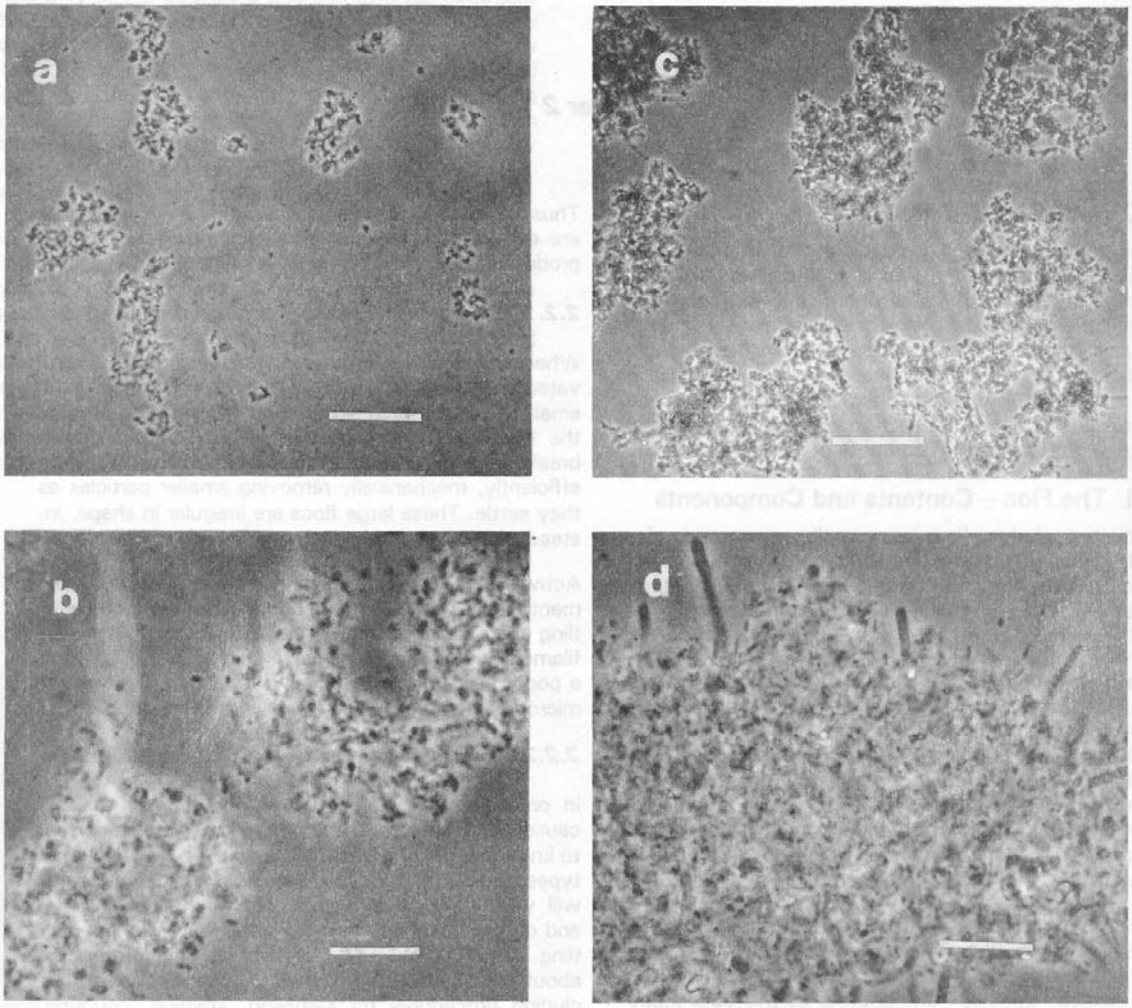
Diffuse double layer created by cations attaching to negatively charged particle (fixed layer) and cations and anions loosely attaching in outer diffuse layer:





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

Figure 1. Microscopic appearance of activated sludge flocs: *a.* small, weak flocs (pin-floc) (100 × phase contrast); *b.* small, weak flocs (100 × phase contrast); *c.* flocs containing microorganisms (100 × phase contrast); *d.* floc containing filamentous microorganisms "network" or "backbone" (1000 × phase contrast) (*a* and *c* bar = 100μm; *b* and *d* bar = 10μm).



From: Bartell, T., 1987. Summary Report: The Causes and Control of Activated Sludge Bulking and Foaming. Report Number EPA-625-8-87-012. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. July 1987.