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:

\[
D \text{- drag} \quad \uparrow B \text{- buoyancy} = \text{weight of displaced fluid} \\
\downarrow w \text{- weight of particle}
\]
$W = \text{gravitational force on particle (i.e. weight)}$

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

$\rho_1 = \text{density of sphere (}\frac{M}{L^3})$
$d = \text{diameter of sphere (L)}$
$r = \text{radius of sphere (L)}$
$g = \text{gravitational acceleration (L/T^2)}$

$B = \text{buoyancy force on sphere due to displaced fluid}$

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

$\rho = \text{density of water}$

$D = \text{drag on (moving) sphere}$

$= \frac{1}{2} \rho C_D \left( \frac{\pi}{4} d^2 \right) V_s^2$

$\frac{1}{\text{frontal area of sphere}}$

$C_D = \text{drag coefficient (dimensionless)}$

$V_s = \text{particle velocity}$

$\rho, \frac{\pi}{6} d^3 \frac{\partial V_s}{\partial t} = W + B + D$

\[ \text{Vertical momentum for sphere} \]

\[ \text{mass} \leftarrow \text{acceleration} \]
In practice, particle accelerates only a short while, so we can consider the "terminal" velocity when drag, weight, and buoyancy are in equilibrium.

\[ \frac{\partial V_s}{\partial t} = 0 \rightarrow W + B + D = 0 \]

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

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

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

\[ C_D = \text{function of Reynolds number} \]

\[ Re = \frac{\rho V_s d}{\eta} = \frac{V_s d}{\nu} \]

\[ \eta = \text{dynamic viscosity of water (often written as } \mu \text{)} \]

\[ \nu = \text{kinematic viscosity of water} = \frac{\eta}{\rho} \]

See chart of \( C_D \) vs. \( Re \) on page 4.

Figure by MIT OCW.
Three regions in graph:

I. Laminar flow \( \text{Re} < 1 \)  
viscous force >> inertial force

\[ C_D = \frac{24}{\text{Re}} \] 
for sphere  
This is exact relation since  
drag is due to viscous stress  
only - no form drag.

\[ V_s = \frac{g d^2 (\rho_i - \rho)}{18 \eta} \] 
Stoke's Law for 
creeping flow

Consider quartz particle with \( d = 10 \text{ mm} \), \( \rho_i = 2.6 \text{ g/cm}^3 \)  
(30 mm is smallest particle visible to the eye)

\[ \nu = 10^{-6} \text{ m}^2/\text{s} \quad \rho = 1 \text{ g/cm}^3 = 1000 \text{ kg/m}^2 \]
\[ \eta = 2 \nu \rho = 10^{-3} \text{ kg/m/s} \]
\[ \Rightarrow V_s = 9 \times 10^{-5} \text{ m/s} = 1 \text{ m/day} \]

(Need to check assumption of laminar flow  
by computing \( \text{Re} : \text{Re} = 9 \times 10^{-4} \ll 1 \checkmark \))

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

II. Transition flow \( 1 < \text{Re} < 10^4 \)  
viscous = inertial force

\[ C_D = \frac{24}{\text{Re}} + \frac{3}{\sqrt{\text{Re}}} + 0.34 \]

Can only solve for \( V_s \) by iteration:

- Guess \( C_D \), compute \( V_s \), compute \( \text{Re} \), compute \( C_D \)
  - Keep iterating until \( V_s \) converges
For typical sand grain \((d = 1 \text{ mm}, \rho_1 = 2.6 \text{ g/cm}^3)\)
iteration yields:
\[ C_D = 0.71, \quad \text{Re} = 170, \quad V_s = 0.17 \frac{\text{m}}{\text{s}}. \]

III Turbulent flow \(\text{Re} > 10^4\)

\[ C_D = 0.4 \]

How does this work in a reactor?

Consider rectangular settling basin:

\[ \text{settling time} = t_s = \frac{H}{V_s} \]

\[ \text{Detention time} = t_R = \frac{L}{U} \]

\[ U = \frac{Q}{HW} \quad W = \text{width of tank} \]

To get desired settling with most efficient tank size want
\[ t_R = t_s \quad \text{occurs when} \ V_s = V_0 \]
\( V_0 \) is known as overflow rate

Note that

\[
\frac{V_0}{U} = \frac{H}{L}
\]

\[
V_0 = \frac{HU}{L} = H \left( \frac{Q}{HW} \right)
\]

\[
= \frac{Q}{LW} = \frac{Q}{Ap}
\]

\( Ap = \) plan area of tank

\( V_0 = \frac{Q}{Ap} \) = overflow rate of tank

Camp. Fig 1 shows removal ratio (fraction of influent particles removed) is equal to $\frac{V_0}{V_0}$.

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 $r$

$U = \frac{Q}{2\pi rH}$

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

$= \frac{V_0}{U}$
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.

\[
\frac{dh}{dr} = \frac{V_0}{U} = \frac{V_0}{A} \cdot 2\pi r H
\]

\[
\int_0^H dh = \frac{V_0}{A} \int_{r_1}^R r dr
\]

\[
H = \frac{V_0}{A} \cdot 2\pi \int_{r_1}^R \frac{r^2}{2} = \frac{HV_0}{A} \cdot 2\pi (R^2 - r_1^2)
\]

\[
= \frac{HV_0}{A} \cdot A_p
\]

\[
\Rightarrow V_0 = \frac{A}{A_p} \text{ overflow rate same as for rectangular tank}
\]

Depth of tank \( H = V_0 t_R \)

Calculations assume uniform settling velocity, which never happens.

Particles smaller than assumed will have \( V_s < V_0 \)
and will not all settle out in time. Some will settle out - if they enter the tank from a low enough height:

Particles will not settle

Particles will settle
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:

$$(1-F_0) + \int_{0}^{F_0} \frac{v}{V_o} \, dF = \text{Fraction removed}$$

all particles faster than $V_o$

fraction of particles slower than $V_o$

Flocculation

Discrete (Type I) 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.

\[\text{Diffuse layer}\]

\[\text{Fixed layer}\]

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 x phase contrast); b. small, weak flocs (100 x phase contrast); c. flocs containing microorganisms (100 x phase contrast); d. floc containing filamentous microorganisms "network" or "backbone" (1000 x phase contrast) (a and c bar = 100 μm; b and d bar = 10 μm).