CE-412

Water Supply & Wastewater Disposal Systems

Supplementary Information I
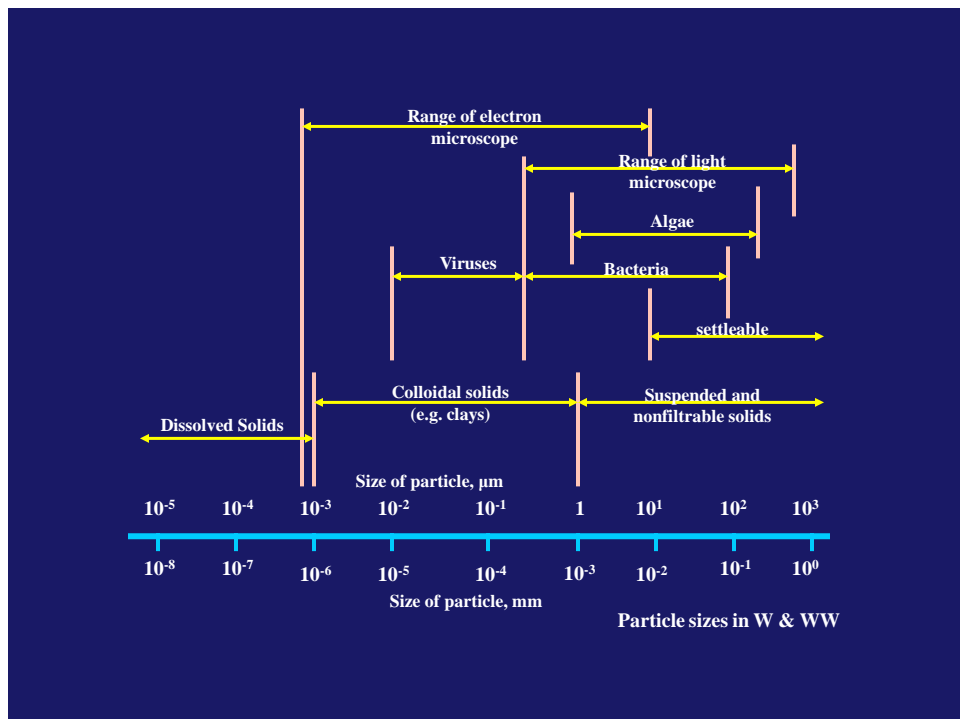
By

Dr Vinod Tare
Professor
Department of Civil Engineering
Indian Institute of Technology Kanpur

Supplementary Information I | CE 412 Water Supply and Wastewater Disposal System | Dr Vinod Tare

Particle sizes in W & WW

Environmental Systems

- In a broader sense, for analysis purposes, could be considered to consist of Two Phases
  - Dispersion Phase (Medium, example liquid → water)
  - Dispersed Phase (Other than medium, example solids, gases or liquids other than water)

Types of Dispersions

Dispersed Phase	Dispersion Medium	Type of Dispersion
Solid	Solid	Solid Gel
Solid	Liquid	Solution or Suspension
Solid	Gas (Air)	Aerosol
Liquid	Solid	Gel
Liquid (Oil)	Liquid (Water)	Emulsion
Liquid	Gas (Air)	Mist

Supplementary Information I   **CE 412**
Water Supply and Wastewater Disposal System   **Dr Vinod Tare**

Aqueous Systems

Dispersed phase can be classified into three groups

Soluble or Dissolved (Solution or Molecular Dispersion)	Colloidal (Colloidal Suspension)	Coarse (Coarse Suspension)
• Size $< 10^{-9}$ m (1 nm) • Molecules or atoms • Optically non- resolvable • Stable Dispersed Phase	• Size: 1 –500 nm • Ultra microscopically resolvable ➢ Electron microscope size < 0.5 µm ➢ Microscopically resolvable Size: 0.5 – 20 µm • Stable Dispersed Phase	• Size > 20 µm • Can be seen • Can be easily separated/filtered • Unstable Dispersed Phase or Unstable Dispersion
Dispersed phase can't be separated from dispersion phase easily, say be settling, filtration, etc.		

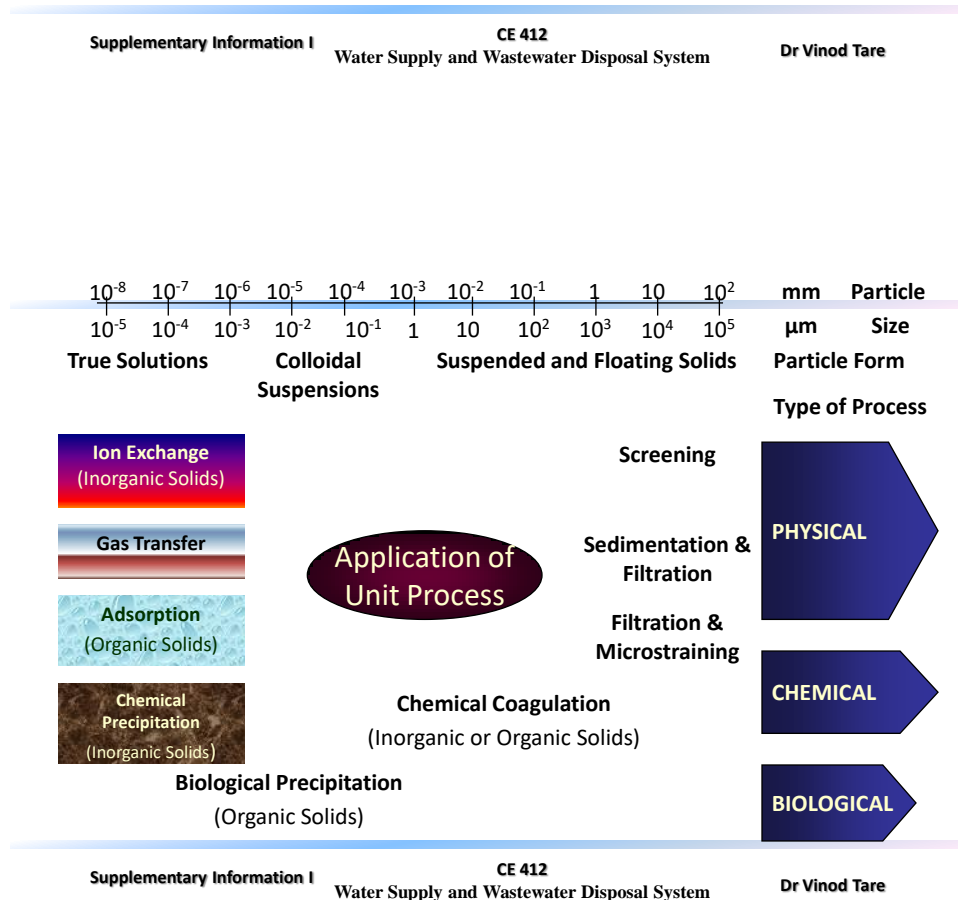**Supplementary Information I**   **CE 412**
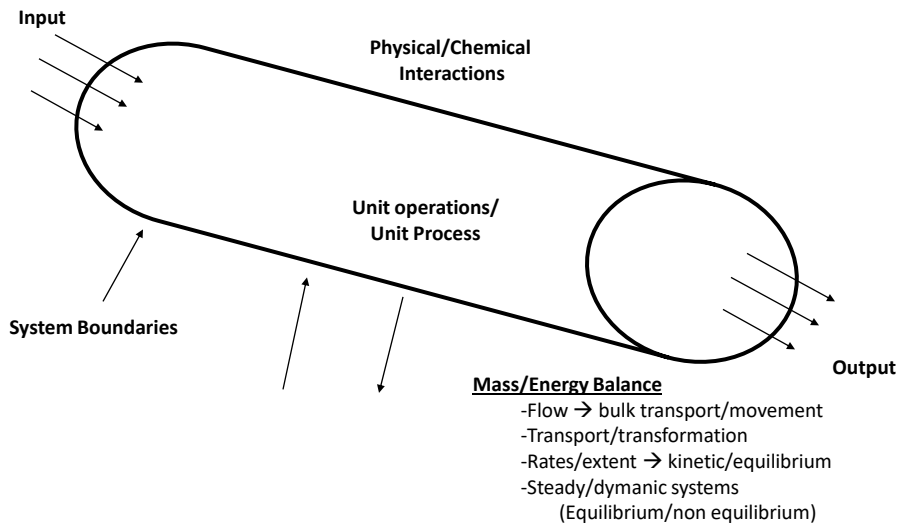**Water Supply and Wastewater Disposal System**   **Dr Vinod Tare**

Physical and Chemical Processes

- **Physical and Chemical Interactions due to:**
  - Body forces (attractive, e.g. gravitational forces)
  - Kinetic energy
  - Potential energy
  - Pressure differences
  - Thermal energy (kT)
  - Electrostatic: charge-charge
  - Etc.
- Processes Involving:
  - Only one phase
  - Two phases
  - All three phases

- **Examples:**
  - Settling/Floating
  - Coagulation/flocculation
  - Adsorption/Ion exchange
  - Absorption
  - Gas transfer
  - Filtration
  - Chemical: Precipitation, dissolution, oxidation-reduction, complexation, etc.
- Processes associated with input/release of energy
- Can be imagined to occur in a reactor

Rate and Extent of Changes are Important – Kinetic and Equilibrium Laws; Steady State (may or may not be in Equilibrium) V/S Dynamic Systems

Supplementary Information I
CE 412
Water Supply and Wastewater Disposal System
Dr Vinod Tare

10^{-8}	10^{-7}	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^2	**mm**	**Particle**
10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^2	10^3	10^4	10^5	**μm**	**Size**

True Solutions   **Colloidal Suspensions**   **Suspended and Floating Solids**   **Particle Form**

Type of Process

Ion Exchange (Inorganic Solids)

Gas Transfer

Adsorption (Organic Solids)

Chemical Precipitation (Inorganic Solids)

Biological Precipitation (Organic Solids)

Application of Unit Process

Screening

Sedimentation & Filtration

Filtration & Microstraining

Chemical Coagulation (Inorganic or Organic Solids)

PHYSICAL

CHEMICAL

BIOLOGICAL

Supplementary Information I
CE 412
Water Supply and Wastewater Disposal System
Dr Vinod Tare

System Analysis Approach

Input

Physical/Chemical Interactions

Unit operations/ Unit Process

System Boundaries

Output

Mass/Energy Balance
-Flow → bulk transport/movement
-Transport/transformation
-Rates/extent → kinetic/equilibrium
-Steady/dymanic systems
    (Equilibrium/non equilibrium)

Physical Processes: Settling/Floating

- **Settling or Sedimentation**
  - Solid liquid separation process in which a suspension is separated in two phases
  a) Clarified Supernatant → over flow
  b) Concentrated Portion or sludge → underflow

- **Sedimentation** is effective for separating:
  ➢ Coarse dispersed phase
  ➢ Coagulated and flocculated impurities,
  ➢ Precipitated impurities after chemical treatment,
  ➢ Microbial mass (biomass), etc.

Types of Settling or Sedimentation or Clarification

Particles settle from suspension in different ways, depending upon the concentrations of the solids and characteristics of solid particles. Accordingly four different types of settling based on the concentrations of the solids and flocculating characteristics of solid particles have been recognized.

1. **Discrete Particle Settling**
   Class I or Type I: Settling/Sedimentation/Clarification

   Particles settle down as separate entities having no interaction with other particles and hence no tendency to flocculate i.e. size and shape of the particles are unchanged resulting in constant terminal settling velocity.

2. **Settling of Dilute Suspensions of Flocculent Particles**
   Class II or Type II: Settling/Sedimentation/Clarification

   These particles coalesce or flocculate while settling. As such particle size and shape changes. As a result settling velocity also varies as the particles settle.

3. Zone Settling
Class III or Type III Settling/Sedimentation/Clarification

The particles settle en masse.

A distinct solid-liquid interface can be seen.

When the particles are sufficiently close, inter-particle forces (repulsive forces) are able to hold them in fixed relative positions. As a result, the particles subside as a large mass rather than as discrete particles.

$$(Conc^n \text{ of Solids})_{Type\ III} \gg (Conc^n \text{ of Solids})_{Type\ II} > \text{ or } \approx (Conc^n \text{ of Solids})_{Type\ I}.$$

4. Compression Settling
Class IV or Type IV Settling/Sedimentation/Clarification

- Occurs when the concentration of particles is high.

- Particles come in physical contact and get compressed.

- The compressed mass restricts further consolidation (expulsion of water).

Types of Settling/Sedimentation/Clarification
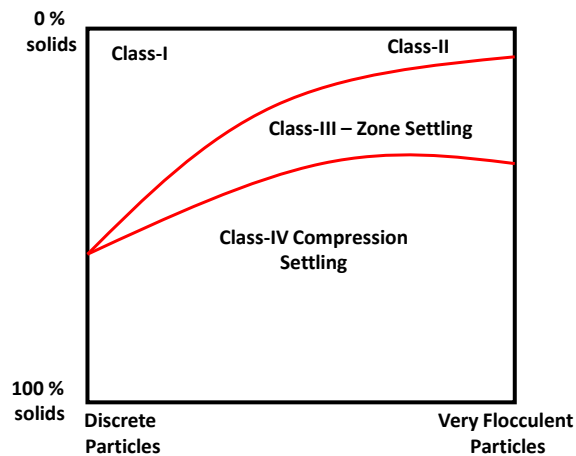
Class I or Type I Settling

- The settling of discrete, non-flocculating particles in a dilute suspension can be described by the equation of classical mechanics.

- Assumptions
  - ➢ There are no inter-particle forces
  - ➢ Particle does not alter its size, shape or weight

- Sedimentation (Settling) of such particles depends upon
  - ➢ Properties of fluid
  - ➢ Characteristics of particles

Class I or Type I Settling: Force Balance on Particle
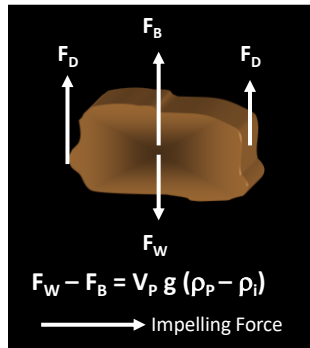
$F_w \rightarrow$ Force due to gravity;

$F_B \rightarrow$ Buoyant force;

$F_D \rightarrow$ Drag Force

The downward acceleration of the particle, or the time rate of change of its velocity, can be obtained from Newton's Second law:

$$F = mf \text{ or } m\frac{dv_s}{dt} = F_w - F_B - F_D$$

$$\text{or } F = V_P\gamma_s - V_P\gamma_l - F_D$$

$$\text{or } F = V_P g(\rho_s - \rho_l) - F_D$$

$v_s \rightarrow$ linear settling velocity; m $\rightarrow$ mass of the particle; t $\rightarrow$ time; $V_P \rightarrow$ volume of the particle; γ_P and $\gamma_l \rightarrow$ density of particle and liquid respectively; ρ_P and $\rho_l \rightarrow$ specific gravity of particle and liquid respectively; g $\rightarrow$ acceleration due to gravity.

Class I or Type I Settling: Force Balance on Particle

• In falling freely through a quiescent fluid, particle accelerates until the fractional resistance or drag of liquid equals the impelling force acting upon the particle. Therefore the particle settles at a constant or uniform (terminal) velocity, which is an important hydraulic attribute or characteristic of the particle.

• Thus when the particle achieves *Terminal Settling Velocity:*

$$m\frac{dv_s}{dt} = 0 = F_W - F_B - F_D \text{ or } F_W - F_B = F_D$$

$$\text{i.e. Impelling Force } (F_I) = \text{Drag Force } (F_D)$$

$$\text{or } V_P g(\rho_s - \rho_l) = F_D \rightarrow f(v_s, \underline{d_P}, \rho_l, \mu)$$

$$d_P \rightarrow \text{Characteristic Diameter}$$

Class I or Type I Settling: Force Balance on Particle

To be fully representative, this diameter must reflect (i) the orientation of the particle relative to its direction of motion, represented for example, by its cross-sectional area or projected area at right angles to motion, and (ii) the relative frictional surface of the particle in contact with the fluid, represented for example, by its surface area in relation to its volume.

$$F_D = [v_s^x d_P^y \rho_l^p \mu^q] \text{ or } [MLT^{-2}]$$

$$= [\{L^x T^{-x}\}\{L^y\}\{M^p L^{-3p}\}\{M^q L^{-q} T^{-q}\}]$$

$$= [\{M^{p+q}\}\{L^{x+y-3p-q}\}\{T^{-x-q}\}]$$

$$= [\{v_s^{2-q}\}\{d^{2-q}\}\{\rho_l^{1-q}\}\{\mu^q\}]$$

$$= v_s^2 d^2 \rho_l [\frac{\mu^q}{v_s^q d^q \rho_l^q}] = v_s^2 d^2 \rho_l f(R_e)$$

$$p+q=1; x+y-3p-q=1; -x-q=-2$$
$$\therefore x=2-q; p=1-q; y=2-q$$

This dimensionally derived relationship for the fractional drag has been verified experimentally.

Class I or Type I Settling: Force Balance on Particle

By substituting the cross-sectional area or projected area, A_P at right angles to the direction of settling for d^2, the dynamic pressure $\rho_l v_s^2/2$ for $\rho_l v_s^2$ and Newtons Drag Coefficient C_D for $f(R_e)$, we get

$$F_D = C_D A_P \rho_l \frac{v_s^2}{2}; \text{Equating } F_D = F_I;$$

$$V_P g(\rho_s - \rho_l) = C_D A_P \rho_l v_s^2/2$$

$$\text{or } v_s^2 = \frac{2g}{C_D} \frac{\rho_s - \rho_l}{\rho_l} \frac{V_P}{A_P}$$

$$\text{or } v_s = [\frac{2g}{C_D} \frac{\rho_s - \rho_l}{\rho_l} \frac{V_P}{A_P}]^{\frac{1}{2}}$$

Class I or Type I Settling: Force Balance on Particle

$$v_s = [\frac{2g}{C_D}\frac{\rho_s - \rho_l}{\rho_l}\frac{V_P}{A_P}]^{\frac{1}{2}}$$

For spherical particles →

$$\frac{V_P}{A_P} = \frac{\frac{\Pi}{6}d_P^3}{\frac{\Pi}{4}d_P^2} = \frac{2}{3}d \ or$$

$$v_s = [\frac{4}{3}\frac{g}{C_D}\frac{\rho_s - \rho_l}{\rho_l}d]^{\frac{1}{2}}$$

For low Re i.e.
Laminar Flow (Re < 0.5)
$$\Rightarrow C_D = \frac{24}{R_e}$$

$$v_s = [\frac{4}{3}\frac{g}{\frac{24}{R_e}}\frac{\rho_s - \rho_l}{\rho_l}d_P]^{\frac{1}{2}}$$

$$= [\frac{g}{18}R_e\frac{\rho_s - \rho_l}{\rho_l}d_P]^{\frac{1}{2}}$$

$$= [\frac{g}{18}\frac{v_s d_P \rho_l}{\mu}\frac{\rho_s - \rho_l}{\rho_l}d_P]^{\frac{1}{2}} \ or$$

$$v_s^2 = \frac{g}{18}\frac{v_s d_P \rho_l}{\mu}\frac{\rho_s - \rho_l}{\rho_l}d_P \ or$$

$$v_s = \frac{g}{18}\frac{\rho_s - \rho_l}{\mu}d_P^2 = \frac{g}{18}\frac{S_s - 1}{\nu}d_P^2$$

STOKES LAW

Class I or Type I Settling: Force Balance on Particle

$$v_s = [\frac{2g}{C_D}\frac{\rho_s - \rho_l}{\rho_l}\frac{V_P}{A_P}]^{\frac{1}{2}}$$

For high Re i.e.
Turbulent Flow (Re > 10^4)
$$\Rightarrow C_D = 0.4$$

$$v_s = [\frac{4}{3}\frac{g}{0.4}\frac{\rho_s - \rho_l}{\rho_l}d]^{\frac{1}{2}}$$

$$= [3.3g(S_s - 1)d_P]^{\frac{1}{2}}$$

For spherical particles →
For $0.5 < Re < 10^4$
(Laminar & Turbulent Flow)
$$\Rightarrow C_D = \frac{24}{R_e} + \frac{3}{\sqrt{R_e}} + 0.34$$

Solve by trial and error

Effect of shape of particle

→ rod like → settling velocity is 78 % of sphere of equal volume

→ Disk like → Settling velocity is 73 % of sphere of equal volume

Shape Factor = A/V = 6/Ψd = S/d

Ψ→ Sphericity of the particle;

S → Shape factor;

Replace $1/d_P$ by S/d_P in Stokes Equation, etc.

Newton's coefficient of drag for varying magnitudes of Reynolds Number
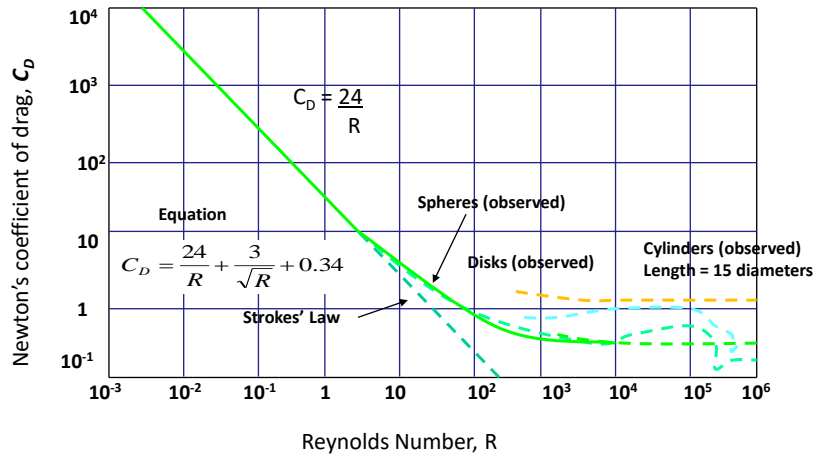
$$C_D = \frac{24}{R}$$

Equation

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

Strokes' Law

Spheres (observed)

Disks (observed)

Cylinders (observed)
Length = 15 diameters

Settling and Rising velocities of discrete spherical particles in quiescent water at 10C. For other temperatures, multiply the Strokes values by $\nu/(1.31 \times 10^{-2})$, where ν is the kinematic viscosity at the stated temperature.
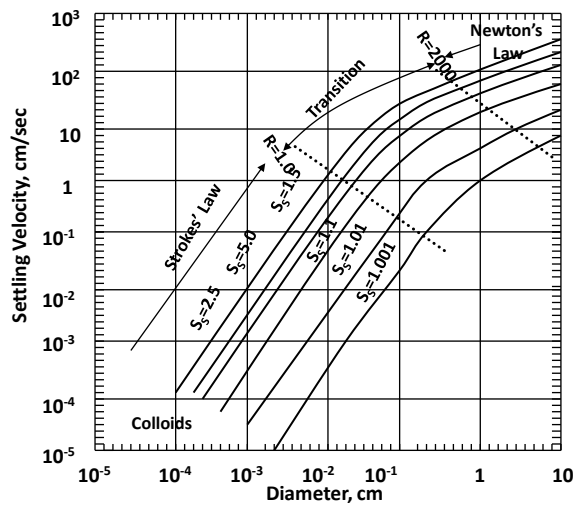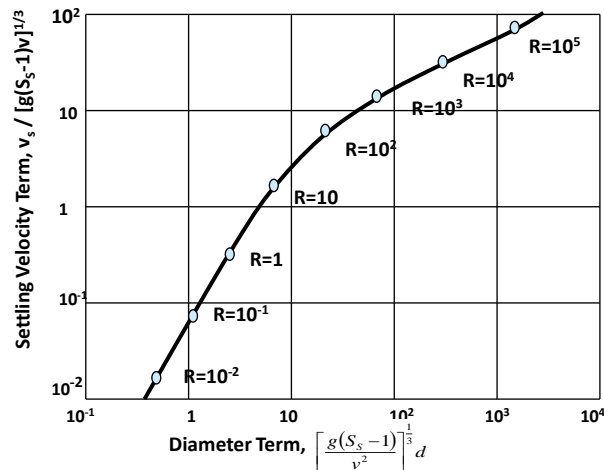
Settling and rising velocities of discrete spherical particles in a quiescent fluid in terms of the specific gravity of the particle (as related to the fluid), the kinematic viscosity of the fluid, and the gravity constant

Analysis of Settling Basins

A knowledge of settling velocity is fundamental requirement in calculating the performance of the sedimentation basin.
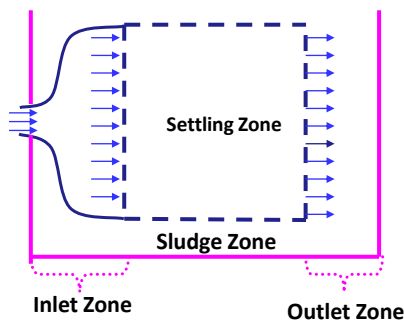
- **Let us consider an ideal sedimentation basin.**
  - <u>Inlet Zone</u>: A region in which it is assumed that the incoming flow is uniformly distributed over the cross section of the basin in such a manner that flow through settling zone follows horizontal path.
  - <u>Settling Zone</u>: Settling occurs under quiescent conditions.
  - <u>Outlet Zone</u>: Clarified effluent is collected and discharged.
  - <u>Sludge zone</u>: Below the settling zone. It is assumed that particles reaching the sludge zone are effectively removed from the suspension.

Analysis of Settling Basins

Settling Zone
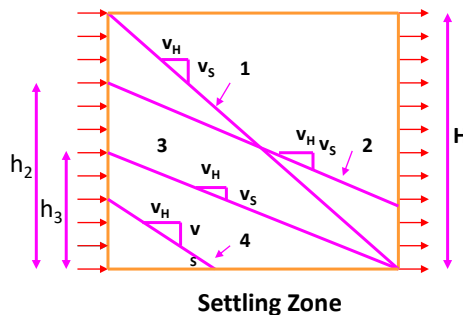
- Consider a particle with settling velocity "v_s" at height – h. The path of the particle is given by the vector sum of horizontal velocity "v_h" and vertical settling velocity "v_s" of the particle. Thus trajectory of the particle can be traced.

➤ This particle is just removed by the time it traverses "L" (H & v_s → 1)

➤ Particles with settling velocity of this particle or less and entering at height "h_2" or greater will not be removed and reach the outlet zone (h_2 & v_s → 2)

➤ Particles with settling velocity of this particle or more and entering at height "h_3" or less will also be completely removed.

Analysis of Settling Basins

Settling Zone
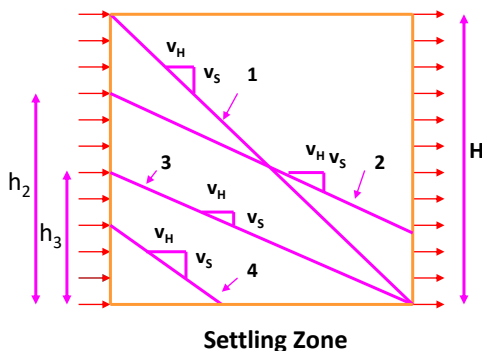
Critical minimum velocity for clarification = $v_o = H/t_o$

- Particles entering at height "H" (equal to depth of the tank) can be removed only if settling velocity $v_s > v_o$ (critical minimum velocity for clarification of discrete particles)

- Some particles with settling velocity < v_o and entering at height less than H are also removed.

Settling Velocity and Surface Over Flow Rate

$$v_s = \frac{H}{t_o} \rightarrow \text{velocity of particle falling through full depth}$$

of the settling zone in the detention time " t_o "

$$t_o = \frac{V}{Q} \rightarrow \text{Volume of tank/flow rate; } A = \text{surface area} = V/H$$

$$v_s = \frac{H}{t_o} = \frac{H}{\left(\frac{V}{Q}\right)} = \frac{HQ}{V} = \frac{H}{AH}Q = \frac{Q}{A}$$

= surface loading or over flow velocity of the basin,

i. e. critical minimum settling velocity

= surface overflow rate "SOR" = v_o

Settling Zone Analysis

- From the geometry of the trajectory (v_h & v_s being constant) it can be said that the area of the triangle having height " H " and base " L " represents 100 % removal of the particles with settling velocity $v_s < v_o$ is given by the area of triangle with height (h_3 = h) and base " L"

- Thus → removal of particles with $v_s \geq \frac{1}{2}HL$

- And removal of particles with $v_s < v_o = \frac{1}{2}hL$

$$\text{Re } moval\ Ratio = \frac{\frac{1}{2}hL}{\frac{1}{2}HL} = \frac{h}{H}$$

Settling Zone

$$\frac{h}{H} = \frac{v_s t_o}{v_o t_o} = \frac{v_s}{v_o} \rightarrow \text{i.e. equal to the ratio of settling velocities}$$
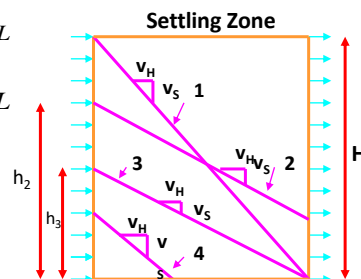
Efficiency of Sedimentation Basin

- Let the SOR be fixed at " v_o "
- Particles with settling velocity $\geq v_o$ are 100 % removed.
- Let x_o is the fraction of particles with settling velocity $< v_o$
- So (1- x_0) fraction is removed completely while some fraction removed for with settling velocity v_s

$$v_s = \frac{v_s}{v_o} dx$$

- Fraction removed for (x_o) → $x_0 = \int_o^{x_o} \frac{v_s}{v_o} dx$

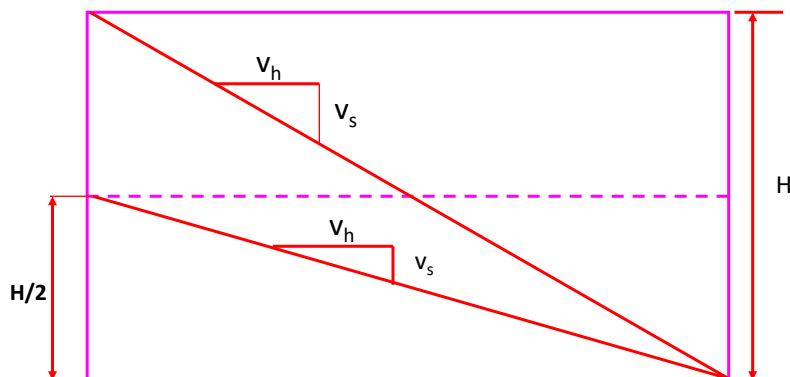- Overall removal → $(1 - x_0) + \frac{1}{v} \int_0^{x_0} v_s dx$

Settling Zone Analysis
Importance of Depth of Sedimentation Basin

Importance of Depth of Sedimentation Basin

$$\text{Removal Ratio} = \frac{v_s}{v_o} = \frac{h}{H} \text{ for some Q \& V}$$

Now if we introduce a tray at H/2; Q, V and other dimensions remain same. Settling velocities also remain same.

$$\text{Removal Ratio} = \frac{h}{H/2} = \frac{2h}{H} = 2 \times \text{that with hieght "H"}$$

The maximum depth through which the particles must settle is reduced to half, but the effective floor area of the tank is doubled. It can be demonstrated that this increased removal is not a function of depth change but only of the change in floor area.

Importance of Depth of Sedimentation Basin

- Consider now a basin of depth H/2 with a flow Q. For this condition, $v_H = 2 v_H$ for depth H or $t_o = t_o / 2$ but removal ratio = v_s/v_o

- This indicates that the removal ratio in an ideal sedimentation basin is independent of basin depth. Thus the basin depth can be varied with no effect on removal efficiency. Ideal Depth is ZERO.

  ➢ Small depths are economically desirable. Other governing factors are space requirements for sludge removal equipment, control of the horizontal flow velocity to avoid scouring of deposited sludge, etc. → Tube Settlers or high rate settlers

Class II or Type II Settling: Flocculent Settling

Suspended solids in natural waters, and domestic and industrial wastewater usually can not be described as discrete particles of known specific gravity. These solids comprise of broad spectrum of different sizes, shapes and surface characteristics.

Class II or Type II Settling: Flocculent Settling

- The settling properties of dilute suspensions of flocculating particles differ from those of non flocculating particles in that the flocculating properties of the suspension must be considered along with settling characteristics of the particles .

- In this case, heavier particles having large settling velocities overtake and coalesce with smaller, lighter particles to form still larger particles with increased rates of subsidence.

- The opportunity for particle contact increases as the depth of settling basins increases. As a result, removal of suspended matter depends not only on clarification rate but on depth as well. This is the important difference between Type I and Type II.

- Examples: Organic particles, flocs formed by chemical coagulants, zooglear growth. Normally these settle more rapidly and removed more readily than the constituent particles or flocs. Flocculent particle can join when they colloid with each other in the liquid.

Class II or Type II Settling: Flocculent Settling

Density of Flocculated Material

- Flocculated aggregates contain mostly water and are thereby enlarged in volume but reduced in density.

- The clustering of any number of particles of specific gravity S_s, for example, will, on entraining P % water (by weight) of specific gravity S lower the specific gravity S_a of the aggregate to

$$S_a = \frac{100}{\left[\frac{100-P}{S_s}+\frac{P}{S}\right]} = \frac{100\,S_s.S}{(100 - P)S + PS_s} = \frac{100\,S_s.S}{P(S_s - S) + 100\,S}$$

- And replace the aggregate volume $\sum V$ for the particles by

$$V_a = \left[\frac{100\,S_s\,S}{(100-P)S_a}\right]\sum V$$

For e.g., if S_s= 2.65, P = 90 → S_a= 1.066

V_a = 24.86 $\sum V \cong$ 25 $\sum V$; And if P = 95 → S_a= 1.032

V_a = 51.356 $\sum V \cong$ 52 $\sum V$

Supplementary Information I — CE 412 Water Supply and Wastewater Disposal System — Dr Vinod Tare

Class II or Type II Settling: Flocculent Settling

Empirical Relation for Floc Density

$\rho_s - \rho = k\,d^{-0.7}$

$\rho_s \rightarrow$ Density of floc;

$\rho \rightarrow$ Density of water

$d \rightarrow$ Diameter of the particle or the diameter of a sphere of equivalent surface area

$k \rightarrow$ Coefficient dependent upon the characteristics of the water and chemicals involved

"Unfortunately there is no adequate mathematical relationship to determine the effect of flocculation on sedimentation. Settling Column. Analysis is required to evaluate this effect"
→ Experimental

Supplementary Information I — CE 412 Water Supply and Wastewater Disposal System — Dr Vinod Tare

Class II or Type II Settling: Flocculent Settling

Laboratory Experiment: Test suspension is placed in a column (minimum diameter = 300 mm) with sampling ports at various depths, and allowed to settle in a quiescent manner. Samples are withdrawn at various time intervals and concentration is measured.
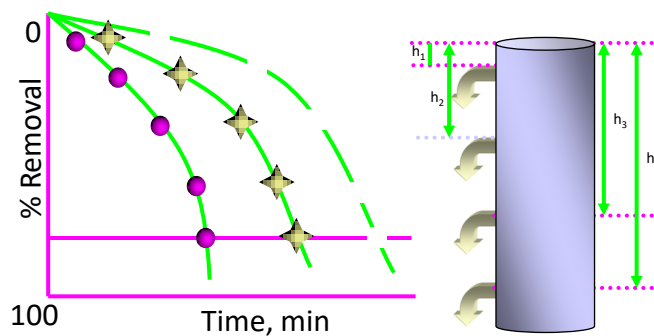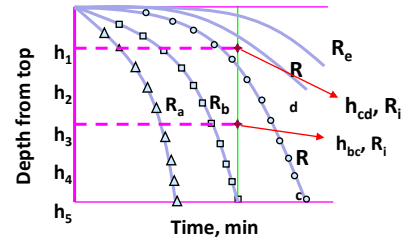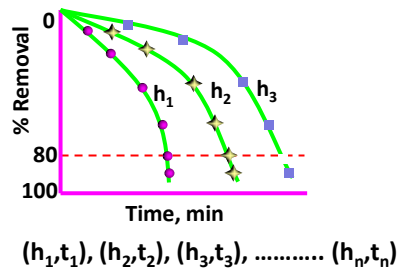
Class II or Type II Settling: Flocculent Settling

Laboratory Experiment: Test suspension is placed in a column (minimum diameter = 300 mm) with sampling ports at various depths, and allowed to settle in a quiescent manner. Samples are withdrawn at various time intervals and concentration is measured.

Class II or Type II Settling: Flocculent Settling

$(h_1,t_1), (h_2,t_2), (h_3,t_3), ... (h_n,t_n)$

R_a, R_b, R_c, R_d, R_e ....constant % removals

$R_e > R_d > R_c > R_b > R_a$

Class II Settling: Computation of SOR and Solids Removal Efficiency

For Re*tention Time* t_o *and Height* h_5

$$SOR = v_o = \frac{h_5}{t_o} = \frac{Depth}{t_o}$$

Particles with settling velocity $v_s \geq v_o$ are removed 100% $= R_b$

Particles with settling velocity $v_s \prec v_o$ are removed in proportion to

$$\frac{v_s}{v_o} = \frac{h_i / t_o}{h_5 / t_o} = \frac{h_i}{h_5}; \text{ and the Removal} = R_i \frac{h_i}{h_5}$$

Class II Settling: Computation of SOR and Solids Removal Efficiency

For example,

If particles enter at height h_{bc} than % removal is $\dfrac{(R_c - R_b)}{h_5} h_{bc}$

If particles enter at height h_{cd} then % removal is $\dfrac{(R_d - R_c)h_{cd}}{h_5}$

If particles enter at height h_{de} then % removal is $\dfrac{(R_e - R_d)h_{cd}}{h_5}$

The total removal

$$= R_b + \frac{h_{bc}}{h_5}(R_c - R_b) + \frac{h_{cd}}{h_5}(R_d - R_c) + \frac{h_{de}}{h_5}(R_e - R_d) + \frac{h_e}{h_5}(100 - R_e)$$

The approximation can be refined by adding more terms and decreasing the interval between iso-concentration lines

Class III Settling: Zone Settling

Zone Settling occurs when particles aggregate, forming a mass which settle as a blanket. There is a clear interface between dispersed phase and dispersion phase

Example: Settling of Biomass (Activated Sludge) in SST or SC, coagulated and flocculated suspension (Sweep Floc formation → metal-hydroxide precipitate)
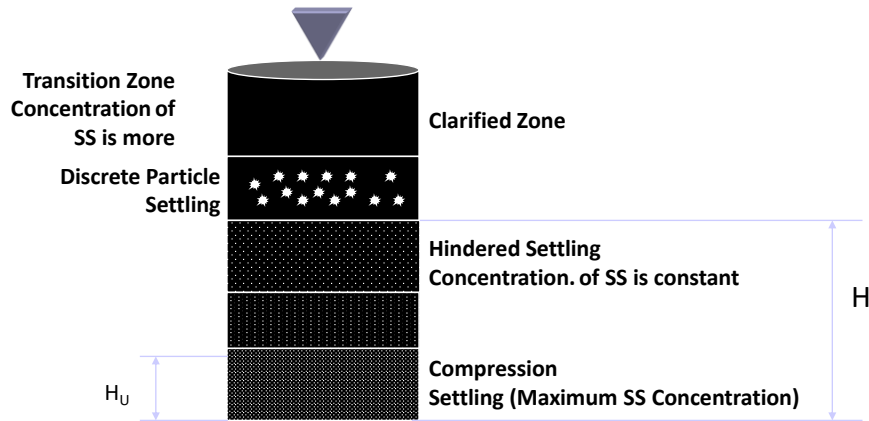
• Initially the column contains a suspension of uniform concentration. After sometime, an interface is formed at some depth below the surface and a zone of clear liquid develops above the interface.

• Below the interface a constant uniform suspension having some specific settling velocity remains. The settling velocity is of mass of large number of particles which is influenced by inter-particle attraction and other forces. In dilute suspensions → no inter-particle forces, particle settle independently with constant terminal settling velocity until it reaches the sludge zone. Since the settling velocity in this class of clarification is other than terminal settling velocity, it is called as "Hindered Settling".

Class III Settling: Zone Settling

| Label	Zone
Transition Zone Concentration of SS is more	Clarified Zone
Discrete Particle Settling	
	Hindered Settling Concentration. of SS is constant
H_U	
	Compression Settling (Maximum SS Concentration)

H

Class III Settling: Zone Settling

- Settling of zone (interface) is a function of
  - ➤ terminal settling velocity
  - ➤ forces of attraction/repulsion between the particles

- The initial rate at which interface subsidence takes place permit an estimation of clarification capacity of the system i.e. the rate at which the clarified effluent is formed.

- If we know v_s i.e. the settling velocity in hindered settling (obtained by finding the slope of the curve in the hindered settling zone) and Q, the flow-rate; area A can be calculated as $A = Q/v_s$

Class III Settling: Zone Settling

Class III Settling: Zone Settling

2/7/2020
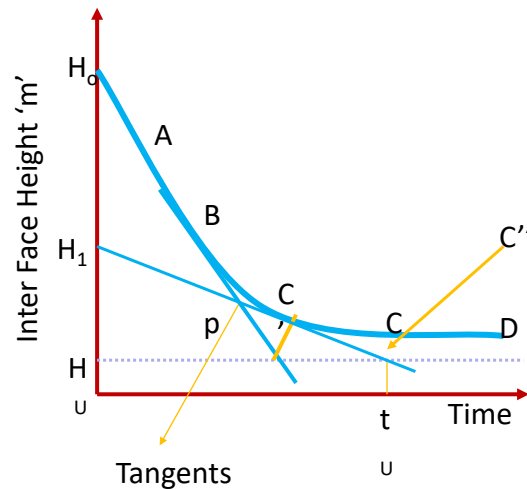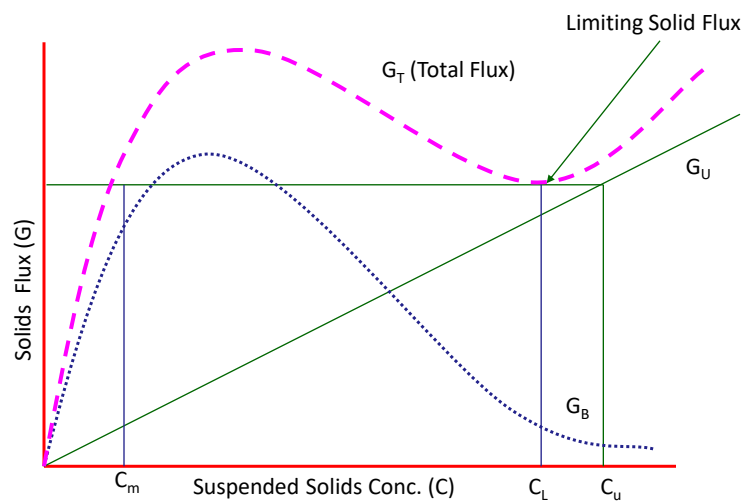
Class III Settling: Zone Settling
Area of thickening

- Graphical Method
- Solids Flux Theory
  - Solids Flux: Amount of solids passing an unit area in unit time

Total Solids Flux = Batch Solids Flux

   + Flux due to Underflow

$G_T = G_B + G_U = U.C + V.C$

$U \rightarrow$ Zone Settling Velocity; $V \rightarrow$ Underflow Velocity

$U = g\, C^{-h}$; $G_T = g\, C^{-h} . C + V.C$

$$\frac{\partial GT}{\partial C} = g(1-h)\,c^{-h} + V$$

$$= g(1-h)c^{-h} + \frac{Q_s}{A}$$

$$= o\,, \text{ for limiting flux}$$

$$C_L = \left[\frac{g(h-1)A}{Q_s}\right]^{1/h}$$

Class III Settling: Zone Settling
Area of thickening

- Check if this corresponds to minimum solids flux

$$\frac{\partial G_T}{\partial C^2} = \frac{gh(h-1)}{c^{1+h}} \text{ is + ve if } g \geq 0 \,\&\, h \geq 1 \,(\text{which is usually th e case})$$

$$G_L = \left[g(h-1)\right]^{1/h} \frac{h}{h-1}\left(\frac{Q_s}{A}\right)^{(h-1)/h} \text{ limiting solid flux}$$

- Assuming 100 % solids capture

$$Q\, C_o = G_L\, A = Q_s C_u$$

Class III Settling: Zone Settling
Area of Thickening

- So in case of Class III clarification zone settling, two things are happening
  1) Clarification of fluid (overflow) → area obtained by Q/V$_s$ (zone settling velocity) &
  2) thickening of sludge → based on desired under flow solids concentration (use solids flux theory)

- The clarification area and thickening area should be compared and larger value should be adopted for design such that max clarification and thickening occur simultaneously (maximum HRT in SC ?)

Class IV Settling: Compression Settling

- The zone of compression occurs when the subsiding particles accumulate at the bottom of sedimentation basin. <u>The weight of particle is supported mechanically by the structure of compacting mass: consolidation mass.</u> Consolidation of sediment at the bottom is extremely time consuming process because the fluid which is displaced must flow upward decreasing pore size (pore volume) between the particles.

Class IV Settling: Compression Settling
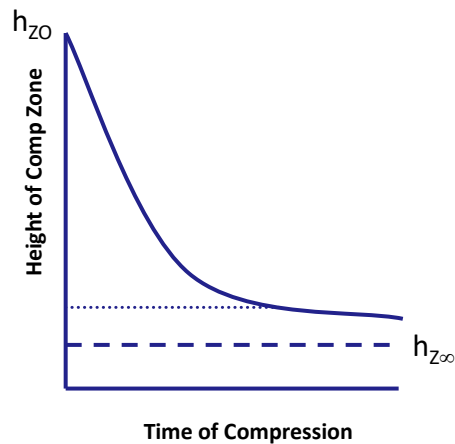
- The consolidation rate is approximated by first order equation as shown in the figure.

$$\frac{-dh_z}{dt} = k(h_z - h_{z\infty})$$

$$\int_{h_{z0}}^{h_z} \frac{dh_z}{dh_{z\infty}} = -k \int_0^t dt$$

Class IV Settling: Compression Settling

$$\ln\left(\frac{h_z - h_{z\infty}}{h_{z0} - h_{z\infty}}\right) = kt \text{ or } h_{z0} - h_z = (h_0 - h_{z\infty})(1 - e^{-kt})$$

$$y = L(1 - e^{-kt}) \rightarrow \text{BOD exertion equation}$$

$h_z \rightarrow$ *hieght of the sludge zone at time* t

$h_{z\infty} \rightarrow$ *Ultimate hieght when* $t \rightarrow \infty$

k $\rightarrow$ *First order rate constant*

$h_{z0} \rightarrow$ *Initial hieght i.e. at* $t = 0$

Scour of Bottom Deposits

- Fine, light and flocculent solids settling from coagulated water, biologically treated waste waters, and the like may be lifted from the sludge zone when

$$v_s = \left(\frac{\tau}{\rho}\right)^{1/2}$$

- $\tau \rightarrow$ is the shear stress at the liquid sludge interface
- $\rho \rightarrow$ is the density of the supernatant water

This $\quad \frac{\tau}{\rho} = grs = g.r\frac{h_f}{l} = g.\frac{d}{4}.\frac{fv^2}{2gd} = \frac{fv^2}{8}$

$$v_s = \left(\frac{\tau}{\rho}\right)^{1/2} = \left(\frac{f}{8}v_H{}^2\right)^{1/2} \; or \; v_H = \left(\frac{8}{f}\right)^{1/2}v_s$$

Scour of Bottom Deposits

- This follows that, as the matter of safety
  - v_h should be kept well below 18 v_s for f = 2.5 x 10^{-2}
  - Or v_h = 10 v_s ; accordingly, the ratio of length, depth in rectangular basin or of the surface area A to cross sectional area a must be below

$$\frac{A}{a} = \frac{L}{H} = \frac{v_h t_d}{v_0 t_0} = \frac{\left(\frac{8}{f}\right)^{1/2}v_0 t_d}{v_0 t_0} = \left(\frac{8}{f}\right)^{1/2}\left(\frac{t_d}{t_0}\right) \approx 10\frac{t_d}{t_0}$$

Flotation

- Particles heaving density less than that of water can not settle. On the other hand such particles have tendency to rise to the surface
- Flotation is the process of converting suspended substances, and some colloidal emulsified and dissolved substances to floating matter
- In current practice flotation is essentially a unit operation in wastewater treatment

Natural Flotation

- In natural flotation oil, grease or other substances lighter than water tend to rise naturally to the surface of basins in which wastewater is brought to rest. The resulting surface scum is then skimmed off in ways analogous to the removal of sludge from the settling basins

$$v_s = -v_r = \frac{g}{18}(S_s - 1)\frac{1}{v}d\rho^2$$

$S_s < 1 \text{ or } v_s \rightarrow -ve$

$v_r \text{ (rising velocity)}$

Air Flotation

- Suspensions which contain small and difficult to settle particles (with density ≈1or with small size such that they take very long time to settle) can be flocculated and brought to the liquid surface by the lifting power of many minute air (gas) bubbles which attach themselves to the suspended particles. Floated, agglomerated sludge, can be readily and continuously removed from the liquid surface by skimming

  ➢ Thus flotation is facilitated by introducing a gas phase in the solid - Liquid phase in the system
  ➢ The rising bubble either

- Adheres to the solids particle or
- Gets entrapped in the particle structure, there by imparting buoyancy to the particle
- Thus particles having density greater than liquid can also be removed by flotation
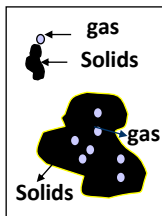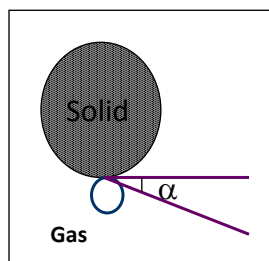
Nature of Gas Particle Contact

- Gas may be trapped in the particle structure of flocculent suspension. Bond between bubble and particle is physical (physical capture only)

- Adhesion: Results because of inter molecular attraction that are exerted at the interface between the two phases (interfacial attraction result in adhesion)

- The angle formed between S-L interface and G-L interface at the point where the three phases make contact is called the angle of contact and the adhesion depends upon the angle of contact. The equilibrium existing between interfacial tension at the point of contact can be given by fore diagram.
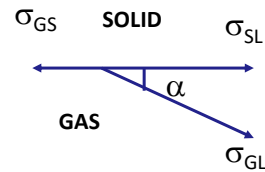
Nature of Gas Particle Contact

$$\sigma_{GS} = \sigma_{SL} + \sigma_{GL}\cos\alpha$$
$$= \sigma_{SL} + \sigma_{GL} \quad (\text{where } \alpha = 0)$$

$$If \quad \sigma_{GS} \leq \sigma_{SL} + \sigma_{GL}$$

Then the particle can't be lifted by gas in liquid film prohibits the contact between solid and gas and hence gas can't lift the solid

σ_{GS} SOLID σ_{SL}

α

GAS

σ_{GL}

$\sigma_{GS}\rightarrow$ interfacial tension between gas and **liquid***** phase
$\sigma_{SL}\rightarrow$ interfacial tension between solid and liquid phase
$\sigma_{GL} \rightarrow$ interfacial tension between gas and liquid phase

Nature of Gas Particle Contact

At equilibrium → $\sigma_{GS} = \sigma_{SL} + \sigma_{GL}\cos\alpha$

For particle rise → $\sigma_{GS} > \sigma_{SL} + \sigma_{GL}\cos\alpha$

We can separately find out σ_{GS}, σ_{SL}, σ_{GL}

α = 90, $\sigma_{GS} > \sigma_{SL}$ → minimum value of (σ_{SL} + σ_{GL} cosα) manipulate angle and σ_{GS}, σ_{SL} & σ_{GL}

Choose chemical or substances which can achieve this

Coagulation & Flocculation

- A large portion of Suspended Solids (SS) in water and wastewater is sufficiently small that their separation due to settling is impossible at reasonable SORs and Retention Time and hence their aggregation is required before separation.

- Small SS → Colloids → There are two different sizes of colloids:
   (i) Ultra-microscopically resolvable (1-500 nm)
   (ii) Microscopically Resolvable (500 nm – 20 µm).

- Colloids → General Properties: (i) So small that their Surface Area in relation to mass is very large – the major difference between colloids and coarse particle (single cubical particle of 1 cm^3 has surface area of 6 cm^2 and several cubical particles 1 nm size having total volume of 1 cm^3 have surface area of 600 m^2; (ii) Electrically charged.
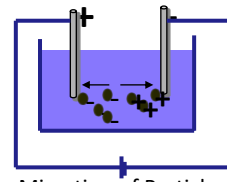
Migration of Particles →
Electrophoretic Mobility →
µm/sec/volt

Coagulation & Flocculation: Properties of Colloids

- Constant motion because of bombardment by molecules of dispersion medium → Earlier this was thought to be only for living matter → Robert Brown, 1827 →Brownian Motion → Can be seen through high power microscope.

- Tyndall Effect

- Adsorption → Colloids have lot of active surface for adsorption → Adsorption is preferential → Stability mainly due to preferential adsorption of ions.

- Lyophobic (solvent hating;) and Lyophilic (solvent loving) colloids.

- Hydrophobic and Hydrophilic colloids.

- Thermodynamically Stable or reversible (e.g. soap, detergents, proteins, starches, etc.) and Thermodynamically Unstable or irreversible (e.g. clays, metal oxides, microorganisms, etc.) colloids.

Coagulation & Flocculation: Properties of Colloids

- Some thermodynamically unstable colloids aggregate slowly and are termed as *Diuturnal*; other colloids aggregate rapidly and are termed as *Caducous*

- Loosely, Stable colloids are referred as *Diuturnal* and unstable colloids as *Caducous*

- Coagulation is primarily concerned with the aggregation of thermodynamically unstable (irreversible) colloids.

- Coagulation processes are used to increase the rate of aggregation of colloides i.e. these processes transform a *Diuturnal* colloids to *Caducous* colloids.

Thermodynamically Unstable Colloids
(*Irreversible & Diuturnal*)

- Let us assume that a colloidal particle is placed in water. Colloidal particle has high surface area. There are many surface groups on the surface of colloids and ions from water, particularly OH^- ions, are adsorbed on the surface. OH^- ions fit better in the crystal lattice of structure of colloids and hence preferentially adsorbed. The extent of primary charge is a function of

  ➢ ionic strength, and
  ➢ pH. Thus the particle charge depends upon whether +ve or –ve ions are adsorbed.

- However, colloidal dispersion (solid & liquid phase together do not have a net electric charge)

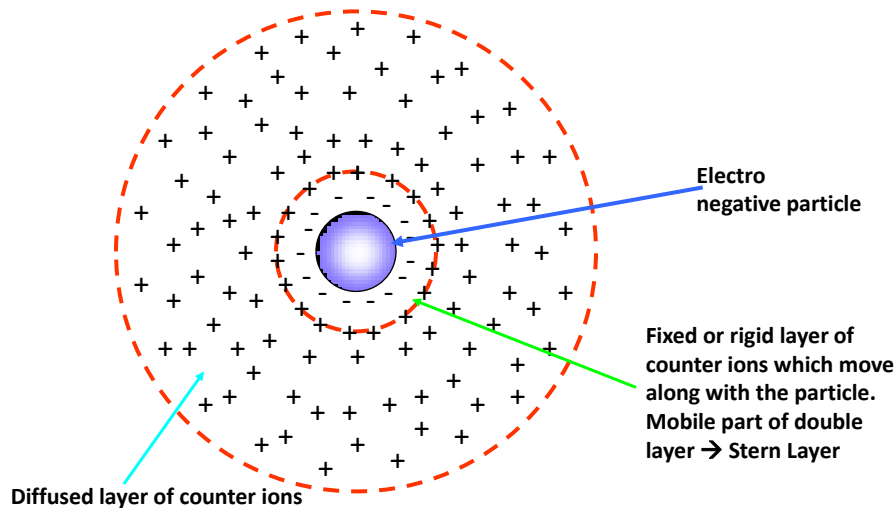## Thermodynamically Unstable Colloids
(*Irreversible & Diuturnal*)

- <u>For Example</u>: Clays are silicates of Na, K, Ca, Mg, Fe, Al, etc. When clays come in contact with water Na, K, silicates, etc. ionize and Na^+, K^+ being highly mobile diffuse into water. Once some + ve charges are lost from the system the clay particles become negatively charged (loss of + ve charge due to desorption of +ve ions from clay surface)

- Thus the primary charge depends upon the composition of water and colloids.
  - Preferential adsorption of OH^- → depends on pH of water.
  - Ionization at the surface and migration of highly mobile ions
  - In proteins & microorganisms → the primary charge is aquired through the ionization of carboxyl and amino groups (COOH & NH_2)

Double Layer Around a Colloidal Particle in Water

The negative surface of colloid attracts a layer of +ve ions, which originate from the bulk of the surrounding liquid. The oppositely charged ions or counter ions are drawn to the colloid surface by *Electrostatic Attraction.* If the –ve charge of the colloid is large; some counter ions are so strongly adsorbed to the surface that they stick to the colloid as <u>compact layer</u> (known as <u>Stern Layer</u>). The Stern Layer partially neutralizes the charge on the colloid and other counter ions are kept in the vicinity of colloids but away from the colloid. <u>These remaining counter ions form a layer called diffused part of the double layer</u>. Following the double layer is bulk liquid.

Colloidal Particles in Water

Electro negative particle

Fixed or rigid layer of counter ions which move along with the particle. Mobile part of double layer → Stern Layer

Diffused layer of counter ions
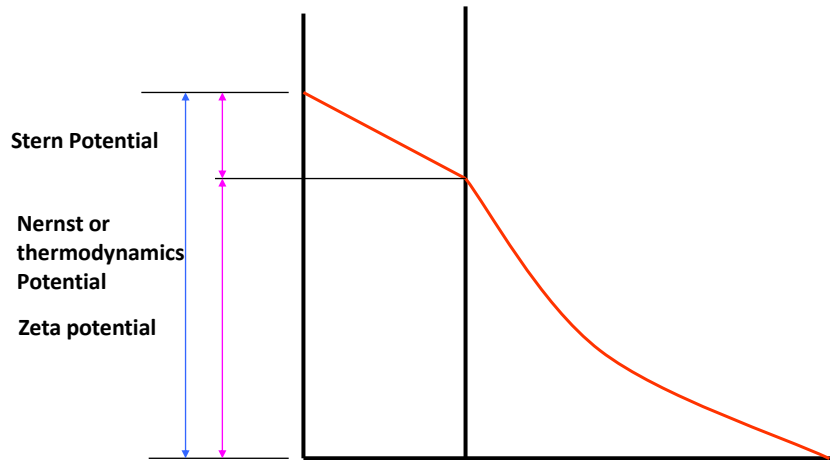
Colloidal Particle in Water

- When a colloid particle is suspended in water, two competing processes start
  - Movement of counter ions towards the surface of colloids due to electrostatic attraction, and
  - Movement of counter ions away from the colloid surface due to diffusion because of concentration gradient established.
- Ultimately dynamic equilibrium is achieved at which time
  - Rate of migration of ions towards the surface of colloid = Rate of diffusion of ions away from the colloid surface.
- And at this stage potential gradient and counter ion concentration gradient exists which is a function of ionic strength, charge on the particle, type of counter ion, etc.

Modified Gouy - Chapman Model of Electric Double Layer

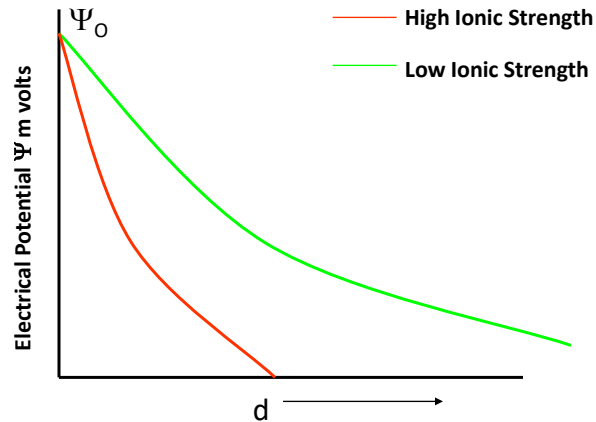## Double Layer Around a Colloidal Particle in Water

Modified Gouy-Chapman Model

- The potential at any layer or point is defined as the amount of work done in bringing a +ve charge from infinity i.e. the bulk solution to the surface.
  - → The potential between the surface of colloid and plane of shear (as shown in figure, earlier) is called stern potential.
  - → Zeta potential is the potential at the surface that separates the immobile part of Double Layer from diffused part.

- Nernst potential = Stern potential + Zeta potential;

Electrical Potential Ψ m volts

Ψ_O

High Ionic Strength

Low Ionic Strength

d

Interaction Between Two Similar Colloids

q_1 q_2

d
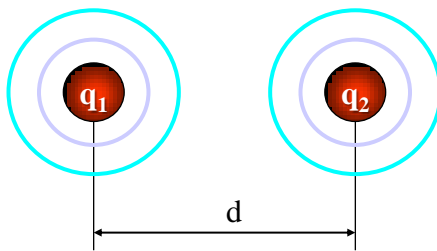
- When two similar colloidal particles approach each other their diffuse layer begin to interact . The nature of interaction is repulsion because they are of similar charge.

- **Electrostatic Forces:**

  The magnitude of repulsive forces is given by—
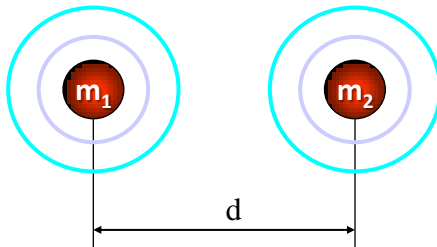
  $$V_R^{\circ} = q_1 q_2/d^2 \text{ or } V_R^{\circ} \propto 1/d^2$$

- The magnitude of repulsive force increases as the distance decreases (inverse square law).

Interaction Between Two Similar Colloids

- <u>Vander Wall Forces</u> (Attractive): These forces are responsible for aggregation of colloids. The magnitude of attractive forces decrease with increasing distance and vice versa
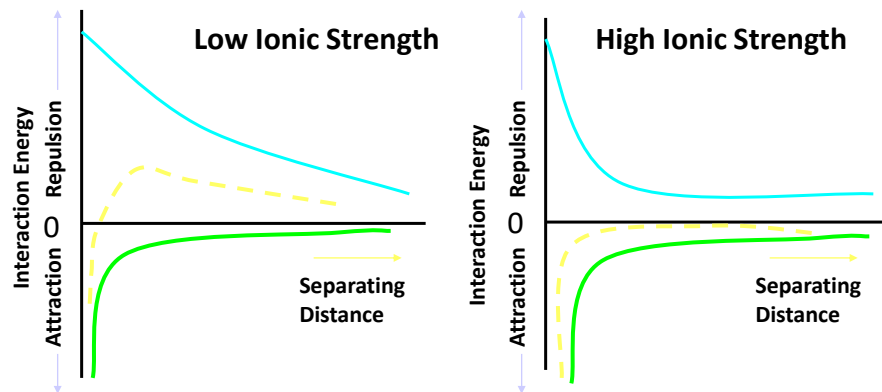
$$V_A° = m_1 m_2/d^6 \text{ or } V_A° \propto 1/d^6$$

- The net effect of these two opposing forces acting on the particle can be determined by summing $(V_R° - V_A°)$ and can be drawn as a function of distance

Interaction Between Two Similar Colloids

- Net Repulsive Force, which may be considered as <u>energy barrier</u>, should be overcome before aggregation occurs. The magnitude of energy barrier depends upon (1) the charge on the particle, (2) ionic composition of water.

- Further the particles (colloids) are under constant motion (Brownian Motion) and posses certain amount of kinetic energy. If the kinetic energy of colloid particle is large enough to overcome the energy barrier, the aggregation occurs.
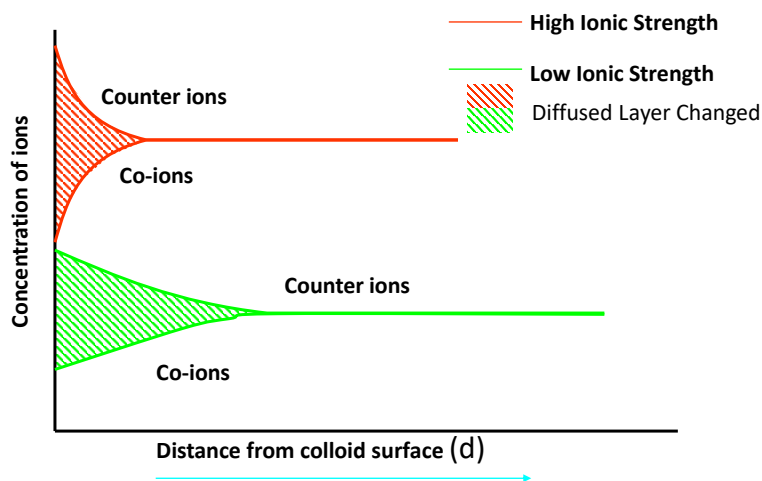
Interaction Between Two Similar Colloids

Low Ionic Strength

High Ionic Strength

Interaction Energy — Attraction 0 Repulsion

Separating Distance

Interaction Between Two Similar Colloids

High Ionic Strength

Low Ionic Strength

Diffused Layer Changed

Counter ions

Co-ions

Counter ions

Co-ions

Concentration of ions

Distance from colloid surface (d)

2/7/2020

Interaction Between Two Similar Colloids

- Kinetic energy = kT; k→Boltzman's constant & T→ Temperature.
- If the <u>zeta potential</u> is such that repulsive forces > Vanderwall's forces → Particles will not coalesce →Perfectly stable suspension, and if
- Repulsive forces < Vanderwall's forces + K.E.→ Particles will aggregate.
- <u>How to make stable suspension to unstable one</u>?
  → Challenge of Coagulation Process

Supplementary Information I   **CE 412**
Water Supply and Wastewater Disposal System   **Dr Vinod Tare**

How to Achieve Agglomeration of Particles?

- **Promoting particle contacts**
  - Change characteristics of colloid particles → Adsorption to provide charge neutralization → Compression of double layer;
  - Increase KE →Flocculation

- **Physical trapping of particles**

- **Providing bridges between particles**
  - Adsorption to permit inter particle bridging
  - Increase KE →Flocculation

Supplementary Information I   **CE 412**
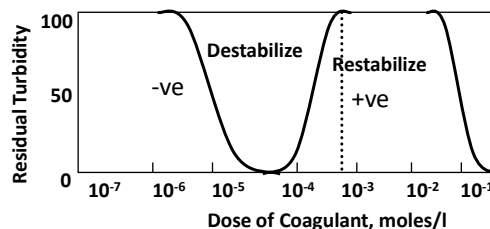**Water Supply and Wastewater Disposal System**   **Dr Vinod Tare**

**Effect of Addition of Coagulants Destabilization/Restabilization of Colloids →
Depends on Concentration of Counter Ions and the Type of Counter Ions to be
Added**

1.   **Destabilization of particles (double layer compression):**

Schulze → 1:20:350
Freundlich → 1:7: 531   } **Ratio of movement : Divalent :
Picton and Lihder → 1:20:1500   Trivalent Counter Ions**
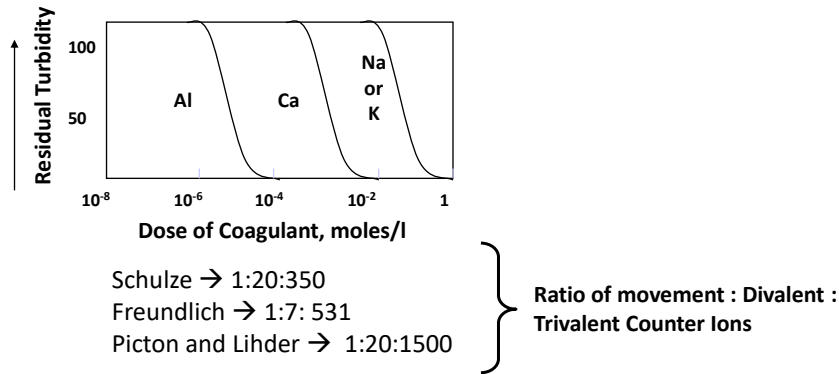
Approximately Na^+: Ca^{++}: Al^{+++}:: $1: 10^{-2}: 10^{-3}$; This is called as Schulze - Hardy Rule. Only
from double layer compaction theory, but in water and wasterwater we have many other
reactions. The electrolytes are not "in different"

Effect of Addition of Coagulants
**Destabilization/Restabilization of Colloids → Depends on Concentration of Counter Ions
and the Type of Counter Ions to be Added**

2. Restabilization of Colloids:

Adsorption of counter ions on colloid surface results in charge neutralization i.e. destabilization.
The ability of coagulant to destabilize the colloidal particles depends on the interaction between
colloid-coagulant, coagulant-solvent, solvent-colloid interaction. The coagulant or its species
produced in the above interaction are adsorbed on negatively charged colloids, thus neutralizing
the charge on colloids. If the chemical is added in excess, then excessive adsorption of
counter ions (than required for charge neutralization) may take place. This may change colloid
charge from -ve to +ve. This results in restabilization of colloid with opposite charge i.e. +ve
colloid. If coulombic interactions were the only driving force for destabilization, such an
adsorption of excess of counter ions to produce charge reversal and restabilization would
not be possible.

Effect of Addition of Coagulants

- Enmeshment in a Precipitate: $Al_2(So_4)_3$ or $FeCl_3$ or metal oxider or hydroxide in case of lime [CaO or $Ca(OH)_2$] is used as a coagulant in concentration sufficiently high to cause rapid precipitation of metal hydroxide, e.g [$Al(OH)_3$ S, $Fe(OH)_3$ S , $Mg(OH)_2$ S) or metal carbonates (e.g . $CaCo_3$). Colloidal particles can be enmashed in these precipitates as they are formed .
- Rate of precipitation depends on the extent of oversaturation

$$[Fe^{+3}][\overline{OH}]^3 = K_{SP} = 10^{-38} \quad [Al^{+3}][OH^-]^3 = K_{SP} = 10^{-32}$$

$$Fe \rightarrow \frac{[Fe^{+3}][OH]^3}{10^{-38}} \rightarrow \quad Al \rightarrow \frac{[Al^{+3}][OH^-]^3}{10^{-32}} > 100 \text{ For rapid Precipitation}$$

- Charge on the precipitate depends on pH $\rightarrow$ In neutral or acidic range precipitate are positively charged.

Effect of Addition of Coagulants

Enmeshment in a Precipitate

- Rate of precipitation is enhanced by presence of anions, So_4^{-2} ions are particularly effective
- Colloids can also increase rate of precipitation $\rightarrow$ Colloids can serve as nuclei
- Rate of precipitation increases with increase in colloid concentration $\rightarrow$ This can result in inverse relationship between the optimum coagulant dose and concentration of material to be removed

Effect of Addition of Flocculants or Coagulant Aids
### Adsorption and Inter-particle Bridging

→ Use of synthetic organic polymers as destabilizing agents in treatment of water and wastewater is quite common. Effective treatment occurs by anionic polymers even though colloid particles in water and wastewater are negatively charged.

→ Can not be explained by simple electrostatic model. To be effective in destabilization, a polymer molecule must contain chemical groups which can interact with the sites on the surface of the colloids.

Supplementary Information I   **CE 412**
Water Supply and Wastewater Disposal System   Dr Vinod Tare

Particle - Polymer Interaction
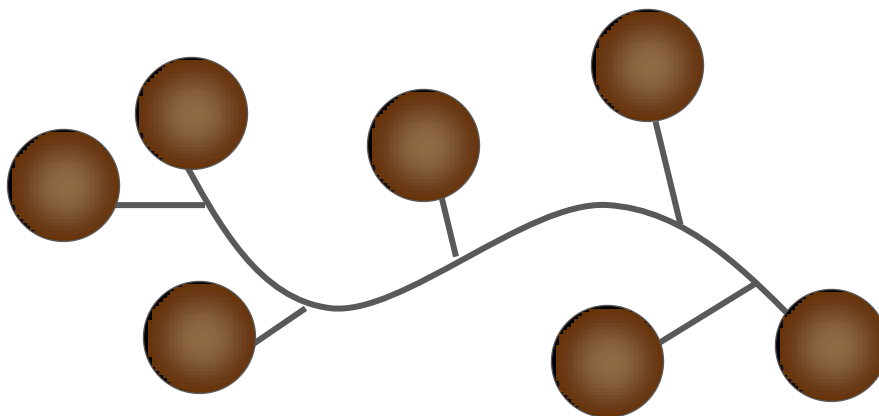
Supplementary Information I   **CE 412**
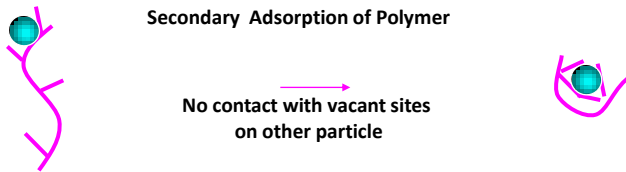Water Supply and Wastewater Disposal System   Dr Vinod Tare

Reaction 1
Initial Adsorption at the Optimum Polymer Dosage

Polymer + Particle → Destabilized Particle
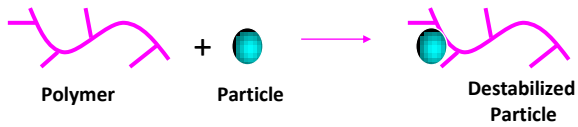
Reaction 2
Floc Formation

Flocculation
(Perkinetic or orthokinetic)

Destabilized Particles → Floc Particle
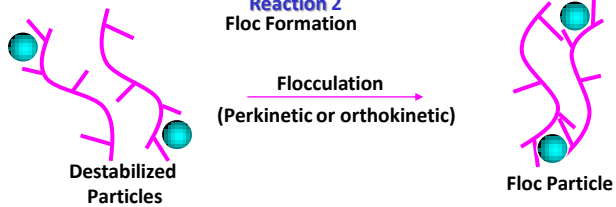
Reaction 3
Secondary Adsorption of Polymer

No contact with vacant sites
on other particle

Reaction 4
Initial Adsorption at the Excess Polymer Dosage

Excess Polymers + Particle → Stable Particle no vacant sites
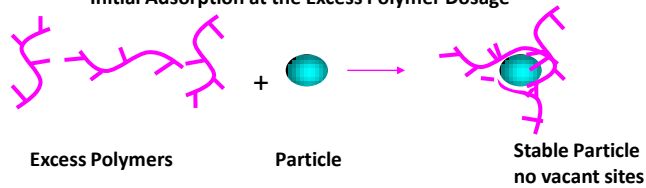
Reaction 5
Rapture of Floc

Intense or
Prolonged Agitation

Floc Particle → Floc Fragments
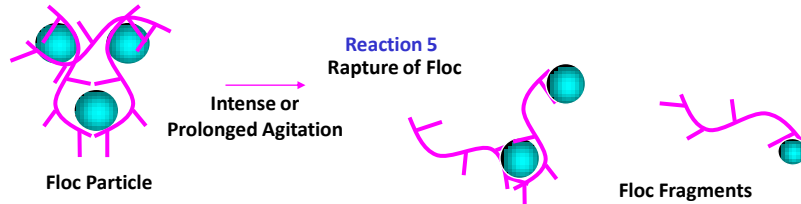
Reaction 6

Secondary Adsorption of Polymer
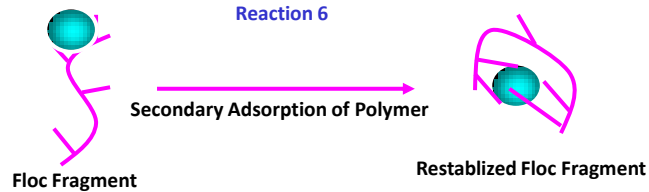
Floc Fragment → Restablized Floc Fragment

Destabilization of Colloidal Suspensions

Hydrolysis of metals, solubility diagram, pH, alkalinity, colloid concentration

- Destabilisation is probably accomplished either by
  - (1) Adsorption of coagulant species formed - sorbable species are usually polymers, _added directly_ are synthetic organic polymers, activated silica, etc.
  - (2) Enmeshment within hydroxide or carbonate precipitates (e.g. lime → precipitate of $CaCo_3$; at high pH → $Mg(OH)_2$; aluminum and iron coagulants or more complex).
- Precipitates or polymers may be _added directly_ or formed from salts added [e.g. Al (III) or Fe (III)] or they may be produced directly within the system from substances present in water or wastewater e.g. Extra-cellular polymers
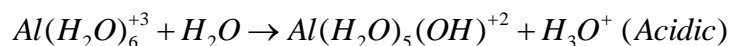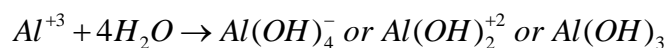
Destabilization of Colloidal Suspensions

Hydrolysis of metals, solubility diagram, pH, alkalinity, colloid concentration

- All metal cations are hydrated in water. Simple species such as Fe^{+3}, Al^{+3}, Ca^{+2} and H^+ do not exist. These are present as aqua complexes such as $Fe(H_2O)_6^{+3}$, $Al(H_2O)_6^{+3}$, $Ca(H_2O)_6^{+2}$; $H(H_2O)^+$, $H(H_2O)_4^+$, etc. These aqua metal ions are acidic. The other hydroxy complexes such as follows are also formed.

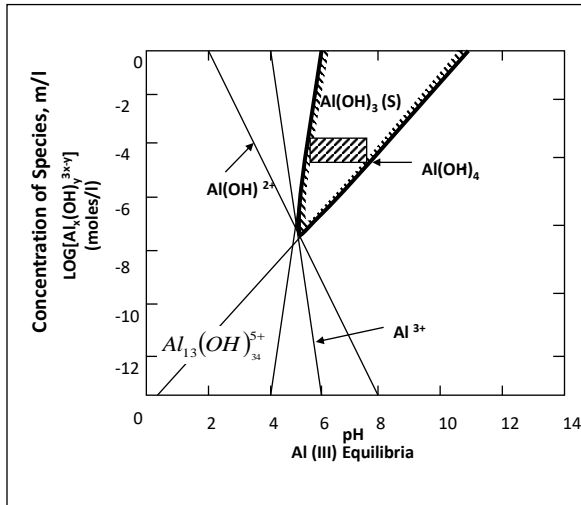$$Al^{+3} + 4H_2O \rightarrow Al(OH)_4^- \ or \ Al(OH)_2^{+2} \ or \ Al(OH)_3$$
$$Al(H_2O)_6^{+3} + H_2O \rightarrow Al(H_2O)_5(OH)^{+2} + H_3O^+ \ (Acidic)$$

- Reaction such as these are called hydrolytic reaction .

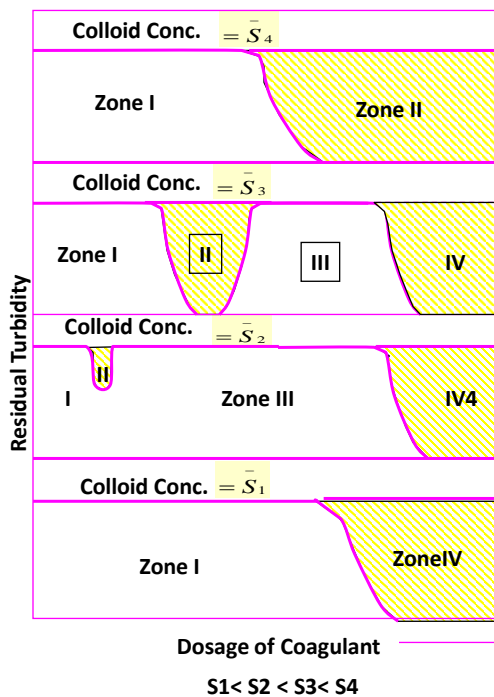# Solubility Diagram of Aluminium

Al (III) Equilibria

Dose used are usually sufficient to exceed the solubility of metal hydroxide, thus destabilisation is brought about by Al^{3+} & Fe^{3+} polymers which are kinetic intermediates in eventual precipitation of metal hydroxides.

The amount of polymer adsorbed and consequently the dose of Fe (III) or Al (III) coagulant necessary to bring about the destabilization of a colloid which are present can be expressed as a function of concentration of surface i.e. surface area per unit volume.
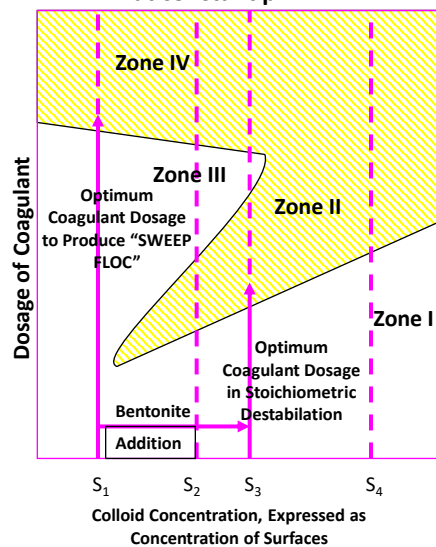
Colloid Conc. $= \bar{S}_4$

Zone I   Zone II

Colloid Conc. $= \bar{S}_3$

Zone I   II   III   IV

Colloid Conc. $= \bar{S}_2$

II   I   Zone III   IV4

Colloid Conc. $= \bar{S}_1$

Zone I   ZoneIV

Residual Turbidity
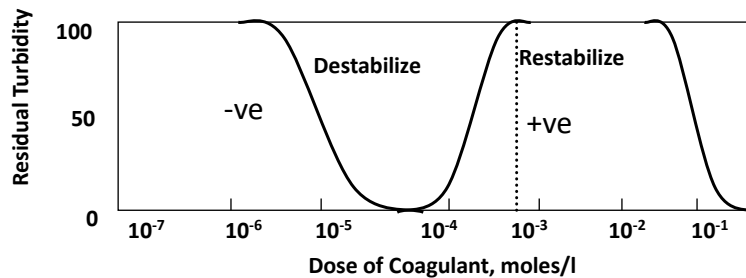
Dosage of Coagulant ⟶

S1< S2 < S3< S4

Schematic representation of Coagulation observed in jar test using aluminum-(III) or iron (III) salts at constant pH

Dosage of Coagulant

Zone IV

Optimum Coagulant Dosage to Produce "SWEEP FLOC"

Zone III

Zone II

Zone I

Optimum Coagulant Dosage in Stoichiometric Destabilation

Bentonite Addition

S_1 S_2 S_3 S_4

Colloid Concentration, Expressed as Concentration of Surfaces

Coagulant Dose V/S Residual Turbidity

- **Zone I:** Insufficient coagulant, low doses insufficient contact .
- **Zone II:** Increasing coagulant, destabilization aggregation .
- **Zone III:** Increasing coagulant, restabilization.
- **Zone IV:** Rapid precipitation of metal hydroxides en mashing the colloids →Sweep floc.

Effective of Colloid Concentration and Alkalinity on Coagulation

- **High Colloid Concentration and Low Alkalinity** → Easiest system, only one chemical parameter to be determined i.e. optimum dose. Destabilization is achieved by adsorption and/or double layer compaction of/due to positively charged hydroxyl metal complexes/ polymers. These are produced at acidic pH values i.e. pH 4-6 depending upon the coagulant.
- **High Colloid Concentration and High Alkalinity** → Destabilization is achieved by adsorption and charged neutralization at neutral and acidic pH. High dose required due to high alkalinity → pH remains neutral where the metal complexes are not +vely charged.
- **Low Colloid Concentration and High Alkalinity** →High coagulant dose for enmeshment of colloid particles in a "sweep floc" or increase turbidity to make to type II (Zone II).
- **Low Colloid Concentration and Low Alkalinity** →Coagulation is most difficult. pH gets depressed to from sweep floc; Rate of inter-particle contact is to slow and hence destabilization by charge neutralization is not effective. Add additional alkalinity and/or additional colloid particles. (e.g. Ganga water in summer → add alum and lime)

Coagulation and Flocculation

- **Coagulation**
  - Two steps: Transport and Attachment → Two different aspects: (i) Particle/Colloid Destabilization through Charge Neutralization, and (ii) Flocculation
- **Flocculation**
  - Destabilization of suspension through particle-polymer-particle bridges
  - Promotion of particle transport through mixing or induced velocity gradients.

Flocculation

Due to three mechanisms

(i) collision resulting from thermal motion → Kinetic energy → often termed as Brownian Motion or Brownian Diffusion →Perikinetic Flocculation;

(ii) collision resulting from bulk fluid motion →for example transport induced by stirring → Orthokinetic Flocculation; and

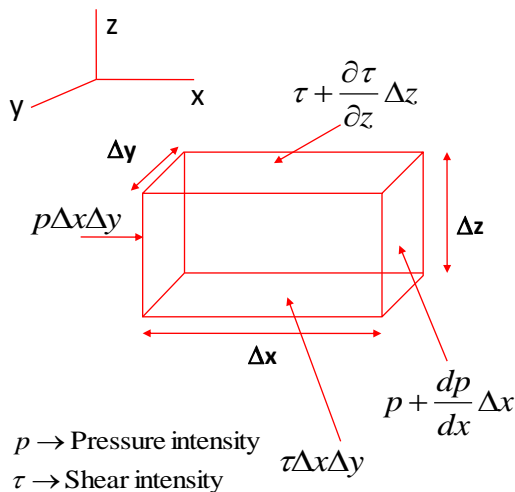(iii) collisions resulting from differential settling → heavier particle overtaking the lighter particle.
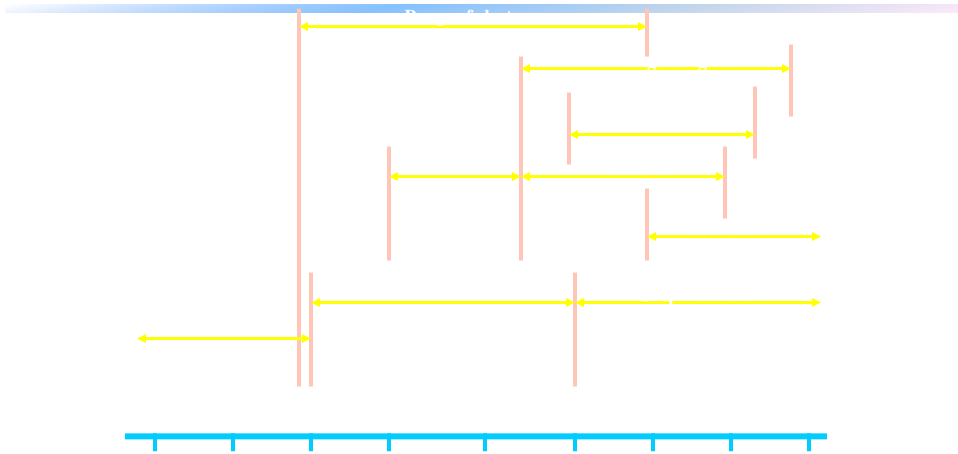
Relation of Power Dissipation to Velocity Gradient

$$\tau + \frac{\partial \tau}{\partial z}\Delta z$$

$$p\Delta x\Delta y$$

$$p + \frac{dp}{dx}\Delta x$$

$$\tau \Delta x \Delta y$$

$p \rightarrow$ Pressure intensity
$\tau \rightarrow$ Shear intensity

- Consider an elemental volume of water
- Because of velocity gradient we will have varying shear stress along z direction

$$p\Delta y\Delta z + \left(\tau + \frac{\delta \tau}{\delta z}\Delta z \right)\Delta x\Delta y$$

$$= \tau \Delta x\Delta y + \left(p + \frac{dp}{dx}\Delta x \right)\Delta y\Delta z$$

$$\Rightarrow \frac{d\tau}{dz} = \frac{dp}{dx}$$

Relation of Power Dissipation to Velocity Gradient

- The power expanded, or the rate at which work is done by the couple ($\tau\Delta x.\Delta y$), equals the torque ($\tau\Delta x.\Delta y$) Δz times the angular velocity dv/dz
- Hence, the power consumption (P) = ($\tau.\Delta x.\Delta y$) Δz . dv/dz
- And the power consumption per unit volume = P/V = [($\tau.\Delta x.\Delta y$) Δz . dv/dz]/ $\Delta x.\Delta y.\Delta z$ = τ.dv/dz

$Also,$

$$\tau = \mu \frac{dv}{dz} \; and \; G = \frac{dv}{dz} \rightarrow \frac{P}{V} = \tau \frac{dv}{dz} = \mu \left(\frac{dv}{dz}\right)^2 = \mu G^2$$

$$or,$$

$$G = \sqrt{P/\mu v} \rightarrow Camp's \; Equation$$

Relation of Power Dissipation to Velocity Gradient

The power dissipation function P/V = μ G2 is an important unifying concept in modern water and waste water treatment operations or processes. If G is combined with detention/displacement time,

$$t = V/Q \Rightarrow Gt = \frac{V}{Q}\sqrt{\frac{P}{\mu V}} = \frac{\sqrt{PV/\mu}}{Q}$$

Where, Gt is in a sense, a ratio of power induced rate of flow to displacement included rate of flow. For a given value of Gt, for instance the loading of flocculation unit is

$$\frac{Q}{V} = 1/t = \frac{\sqrt{P/\mu v}}{Gt}$$

Implying that hydraulic loading of flocculation unit is not merely a function of their relative capacity or detention time, but more significantly; a function also of power input and viscosity. Power input thereby becomes a design variable.
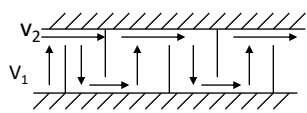
Mixing and Stirring Devices

- Gravitational $\quad Power\,Dissipiated = Q\rho gh = P$

- Baffled Channel $\quad Permissible\ Channel\ Loading$

$$\frac{Q}{V} = \sqrt{\frac{Q\rho gh}{\mu V}} \Big/ Gt \rightarrow \sqrt{\frac{Qgh}{W}} \Big/ Gt$$

Limitations: G can not be varied, G is at times very high at 180° turns and may break the floc, and is too low in the straight portion. Channel velocity 0.1 to 3 m/sec. G is proportional to Q and can not be controlled → not an operational variable

- Hydraulic Jump (Mixing Unit)

Mixing and Stirring Devices

- Pneumatic Mixing or Stirring: Amount of work done is directly proportional to amount of air. Size of air bubble is important
- Mechanical Mixing
  - Rotary paddles

$$F_D = \frac{C_D A \rho_i v_r^2}{2} \qquad\qquad G = \left(\frac{\left(C_D A \rho_i v_r^3\right)}{2\mu v} \right)^{\frac{1}{2}}$$

$v_r \rightarrow relative\ velocity$

$A \rightarrow Area\ of\ paddle$

  - Reciprocating Blades → Simple Harmonic Motion

- Particle Concentration → Turbidity v/s number/litre
→ Particle Counter
→ Coulter counter

Commonly Used Coagulants in Water and Wastewater Treatment

| S No	Common Chemical Name	Active Product	Coagulant Aids
1	Sodium Aluminate ($Na_2Al_2O_4$)	$Al(OH)_3$	Poly-electrolytes. Can be used as Primary Coagulants also. 1. Nirmali seed 2.Clay 3.Return Sludge
2	Sodium Aluminate + Ferric Chloride	$Al(OH)_3 + Fe(OH)_3$	
3	Alum-Aluminum Sulphate + Slaked Lime or Caustic Soda or Sodium Carbonate	$Al(OH)_3$	
4	Ferric Sulphate + Slaked Lime	$Fe(OH)_3$	
5	Ferrous Sulphate	$Fe(OH)_2 \rightarrow Fe(OH)_3$	
6	Activated Silica (Sodium Silicate & H_2SO_4) aeration	Complex silicates	

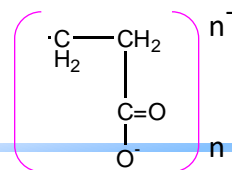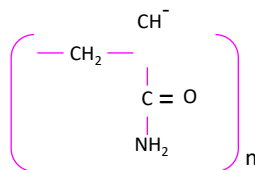Supplementary Information I — **CE 412** Water Supply and Wastewater Disposal System — Dr Vinod Tare

Synthetic Organic Polymers

1. Nonionic Polymers

(i) Polyethylene oxide
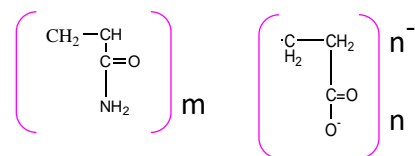
$$(- CH_2 - CH_2 - O)_n$$
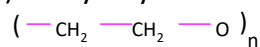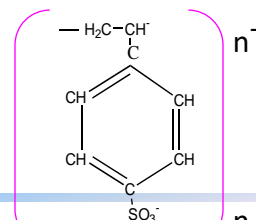
(ii) Polyacrylamide (PAM)

2. Anionic Polyelectrolytes

(i) Polyacrylic Acid (PAA)

(ii) Hydrolyzed Polyacrylamide (HPAM)
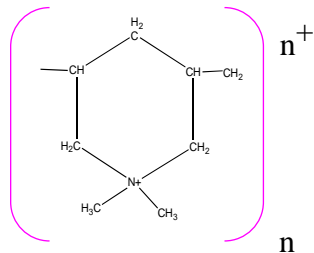

(iii) Polystyrene Sulfonate (PSS)

Supplementary Information I — CE 412 Water Supply and Wastewater Disposal System — Dr Vinod Tare

51

Synthetic Organic Polymers

1. Cationic Polymers

n^+

n

Bioflocculation

Polymers (biopolymers) excreted or exposed at the cell surface from/by microorganisms form bridges between tiny organisms (microorganisms, mostly bacteria)

Selection of Coagulants/Coagulant Aid Doses

Jar Test: Variables → pH, coagulant dose, alkalinity, dose of coagulant aids such as polyelectrolytes, colloid surface i.e. additional turbidity, etc.

Filtration

• Settling (Primary Sedimentation), and coagulation-flocculation followed by settling (Secondary Sedimentation) are not fully effective in separating suspended solids (causing turbidity) including fine colloids (microorganisms; mostly bacteria). Hence, filtration is very important unit operation in separation of suspended solids including colloids, bacteria, etc. for producing clear and sparkling water in natural as well as anthropogenic systems.

• Basically there are two types of filters:

  – Surface Filters: Suspended solids are trapped at the surface and depth of the filter is not an important consideration in separation of particles, e.g. as in screens, strainers, microstrainers, cloth filters, vacuum filters, etc. → Separation efficiency for fine solids is low or very high pressure drop/head loss

  – Depth or Gravity Filters: Suspended solid penetrate deep into the filter bed and get distributed; separation is predominantly due to mechanisms other than simple straining; e.g. natural filtration by flow of suspended solids containing water while flowing through porous media such as soils, sand, etc.
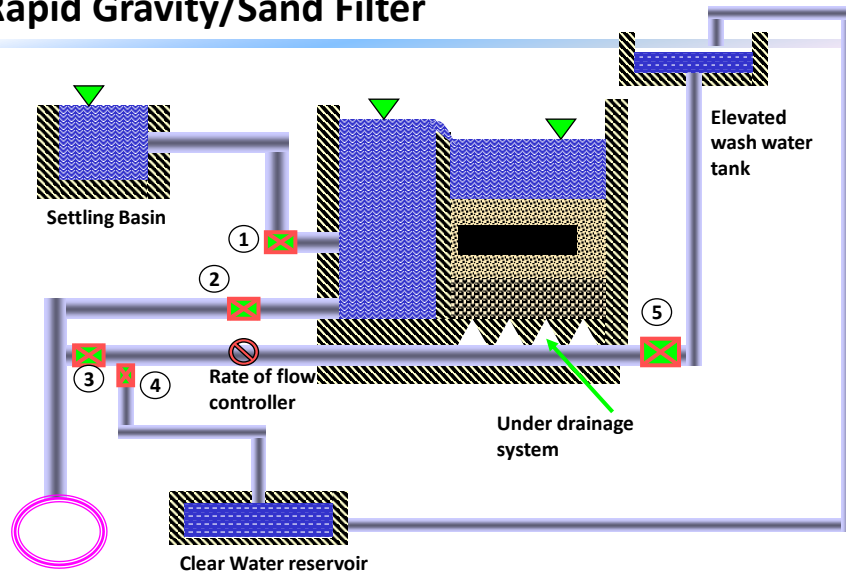
Surface Waters V/S Ground Waters

- Ground waters naturally filtered, but may have more dissolved solids.

- Surface waters need to be filtered if clear/ sparkling water is required → Various types of filters are used → Gravity filters of the following types are commonly used:

  – Slow Sand Filters (SSF): Earliest and simplest filters without any mechanical equipment → Developed first in England around 1829. The sand size = 0.23 to 0.35 mm; Uniformity coefficient, d_{60}/d_{10} = 2-3. Because of use of fine sand, the pore size is small and mechanism of separation of SS is *Simple Straining* in the filter media in the initial stages. However, as the filtration progresses, formation of biological mat (layer) called *Schmutzdecke* (dirty layer) takes place which plays an important role in separation of SS, particularly bacteria, and bacterial removal in this is more compared to Rapid Sand Filters. Mainly the removal occurs in top 5 cm of sand and hence often these type of filters are also called as Surface Filters. The main disadvantage of these types of filters is very low rate of filtration – 130 – 150 l/h/m^2 (0.05 gpm/sq ft).

Gravity Filters

- Rapid Gravity/Sand Filters: Most common in water treatment. Coarser (0.4 – 0.6 mm or higher), uniform (Uniformity Coefficient = 1.3-1.7) media. High rate of filtration → 4000 – 8000 l/h/m2 (2-4 gpm/sq ft → 0.136-0.272 cm/s). Removal is with depth. These filters are backwashed when the head loss is about 1.2-2.5 m).

- Dual and Multimedia Filters: Coal-Sand-Anthracite → Rate of filtration can be increased →Penetration of SS to higher depths.

- Activated Carbon Filters: For refractory (non-biodegradable organics) materials → Adsorption

- Pressure Filters: Closed pressure systems; More head loss permitted; Used for ground water purification to remove Fe and Mn: For small installations → Swimming pools, etc.

- Cake or Pre-coat Filtration: Diatomaceous earth filters → mobile units for water purifications in fields; Filtering media is a layer of diatomaceous earth built-up on a porous septum; Home/Candle filters

Rapid Gravity/Sand Filter

Settling Basin

① ②

③ ④

Rate of flow controller

Under drainage system

Elevated wash water tank

⑤

Clear Water reservoir

Filter backwash to drain or to thickener

Filtration Removal Efficiency & Head

Loss/Pressure Drop

- **Depends on →**
  - 1. Characteristics of media, 2. Characteristics of suspension, 3. Filtering aids – coagulants or coagulant aids such as polyelectrolytes, 4. Operating variables – rate of filtration.
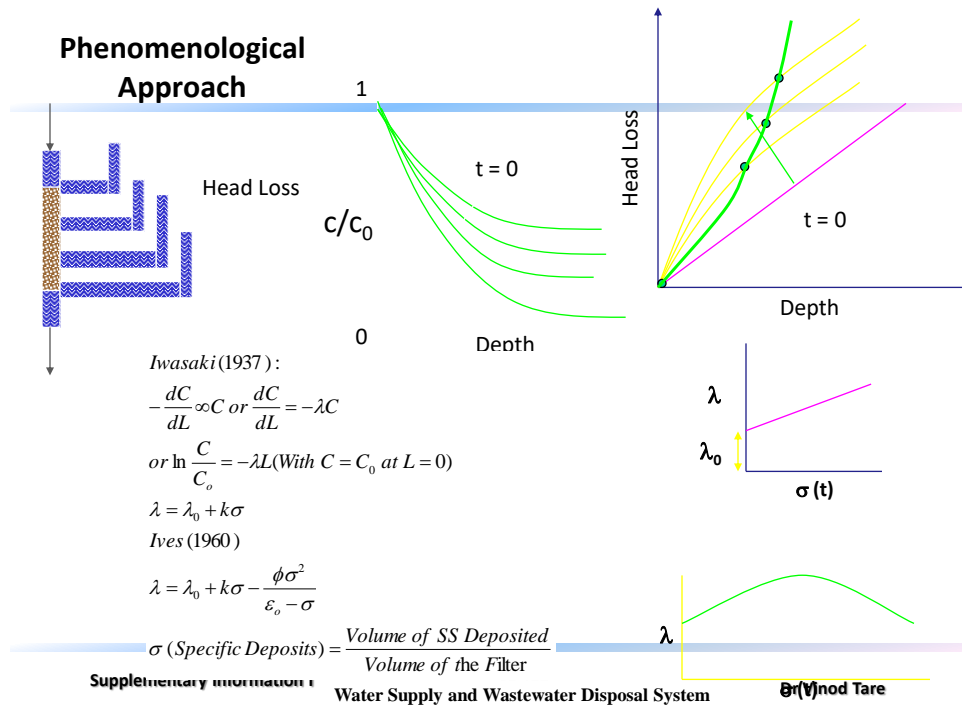
- **Analysis Approach:**
  - Phenomenological → Based on field/gross observation → Mostly empirical
  - Theoretical → Rational but complicated. Yet not fully developed because of complications and large number of variables and unknowns involved. Nevertheless gives a basic understanding to the process of filtration.

Phenomenological Approach

Head Loss

c/c_0

1

t = 0

0

Depth

Head Loss

Depth

t = 0

$Iwasaki\,(1937):$

$$-\frac{dC}{dL} \infty C \; or \; \frac{dC}{dL} = -\lambda C$$

$$or \; \ln \frac{C}{C_o} = -\lambda L (With \; C = C_0 \; at \; L = 0)$$

$$\lambda = \lambda_0 + k\sigma$$

$Ives\,(1960)$

$$\lambda = \lambda_0 + k\sigma - \frac{\phi\sigma^2}{\varepsilon_o - \sigma}$$

$$\sigma \; (Specific \; Deposits) = \frac{Volume \; of \; SS \; Deposited}{Volume \; of \; the \; Filter}$$

λ

λ_0

$\sigma\,(t)$

λ

$\sigma\,(t)$

Theoretical Approach

- Coagulation and Filtration are Similar
- Separation of SS from Water Involves Two Steps
  - Transport
  - Attachment
- Filter Consists of Collectors → Single Collector Removal Efficiency, η_r → Rate at which particles are deposited on the collector/Rate at which particles move towards the collector
- η_r is a function of transport or collision efficiency and attachment efficiency = $\alpha\,\eta_c$
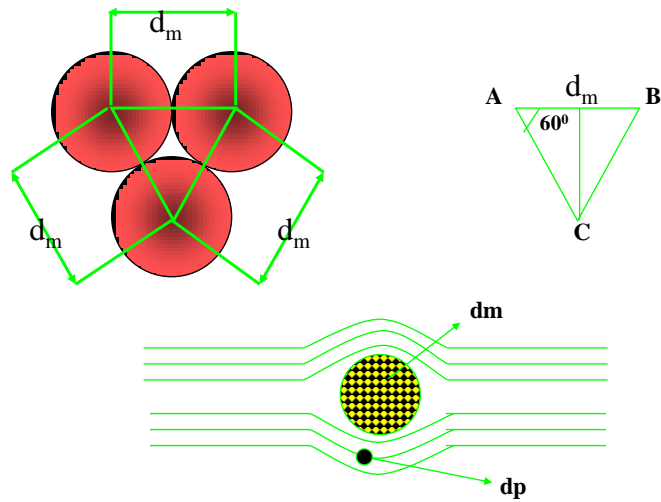
Transport Mechanisms

- Mechanical Straining
- Gravitational Settling
- Flocculation
- Interception
- Impaction
- Diffusion (Brownian)
- Electrokinetic → Due to electrical field developed
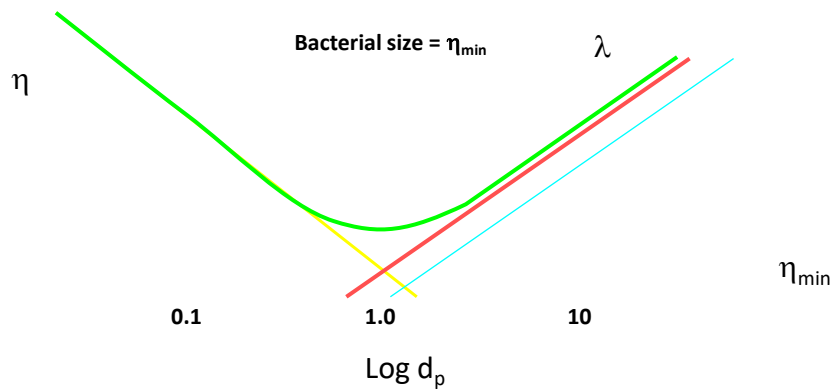 → Streaming Potential

Transport Mechanisms

- Mechanical Straining
- Gravitational Settling
- Flocculation
- Interception
- Impaction
- Diffusion (Brownian)
- Electrokinetic → Due to electrical field developed
  → Streaming Potential

Transport Mechanisms

CE 412
Water Supply and Wastewater Disposal System

Dr Vinod Tare

Removal Efficiency

CE 412
Water Supply and Wastewater Disposal System

Dr Vinod Tare

Hydraulics of Filtration Flow Through Porous Media

For the velocities commonly employed in ground water flow/filters, flow is normally laminar and obeys Darcy's Law

$$v_o = Ks = K\frac{h_f}{L}$$

$v_o = $ Approach or Face Velocity Above the Sand Level

$K = $ Darcy's Coefficient of Permeability

$= f(\rho, \mu, \varepsilon_o, \varphi, d_c)$

Kozeny's Equation :

$$\frac{h_f}{L} = \frac{K}{g}\frac{\mu}{\rho}v_0\frac{(1-\varepsilon)^2}{\varepsilon^3}(\frac{A}{V})^2$$

$K \rightarrow Kozeny's\ Coefficient \rightarrow Dimension\ Less \rightarrow Close\ to\ 5$

$$v = \frac{v_0}{\varepsilon}\ \&\ \frac{A}{V} = \frac{\pi d^2}{\frac{\pi}{6}d^3} = \frac{6}{\varphi d}$$

Hydraulics of Filtration Flow Through Porous Media

$$\frac{h_f}{L} = \frac{K}{g}\frac{\mu}{\rho}v_0\frac{(1-\varepsilon)^2}{\varepsilon^3}(\frac{6}{\varphi d})^2$$

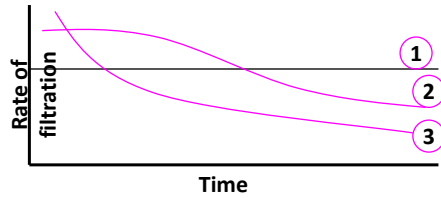$$\frac{h_f}{L} = \frac{K}{g}\frac{\mu}{\rho}v_0\frac{(1-\varepsilon)^2}{\varepsilon^3}(\frac{6}{\varphi})^2\sum_{i=1}^{m}\frac{P_i}{d_i^2}\quad(1)$$

$$\frac{h_f}{L} = \frac{K}{g}\frac{\mu}{\rho}v_0\frac{(1-\varepsilon)^2}{\varepsilon^3}(\frac{6}{\varphi}\sum_{i=1}^{m}\frac{P_i}{d_i})^2\quad(2)$$
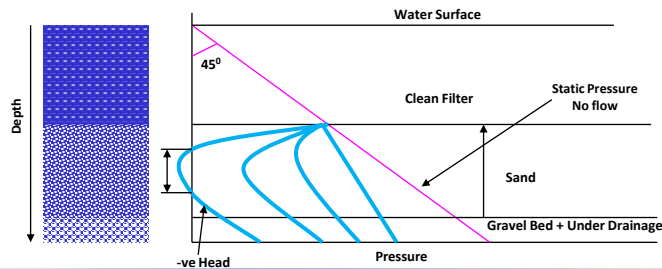
1. Stratified Bed (RSF);   **2. Un-stratified Bed (SSF)**

Filter Operations

1. Constant Rate Filtration
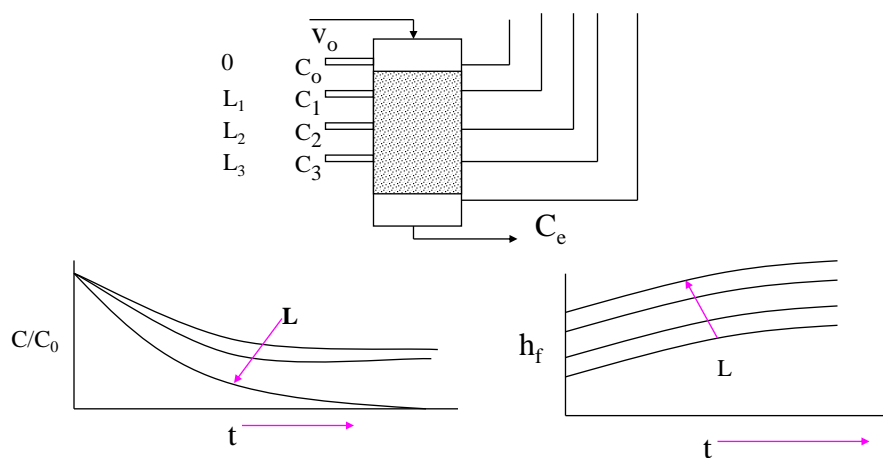2. Variable/Declining Rate Filtration
3. Constant Pressure Filtration

Laboratory Techniques