Effluent Treatment Processes for Energy Industry (10626584)

Lecture 12:
Gravity Separation Theory and Sedimentation

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Spring 2019

Objectives

- By the end of this lecture, students will be able to define:
- Gravity separation theory

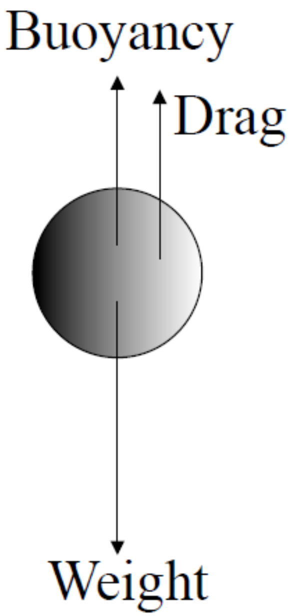
- Types of gravitational settling:
  - Discrete particles
  - Flocculent
  - Hindered, also called zone, settling
  - Compression

- Typical design parameters for flocculator and sedimentation tank
- Sedimentation tank performance

Gravity Separation Theory

Mechanics of particle motion:

- Three forces acting on a particle moving through a fluid:
  - The external force, gravitational or centrifugal
  - The buoyant force, which acts parallel with the external force but in the opposite direction;
  - The drag force, which appears whenever there is relative motion between the particle and the fluid



Equations for one-dimensional motion of particle through fluid:

- Consider a particle of mass m moving through a fluid under the action of gravity force F_G.
- Let the velocity of the particle relative to the fluid be v_p, let the buoyant force on the particle be F_b and let the drag be F_d, then:

Gravity Separation Theory

$$m\frac{dv}{dt} = F_G - F_b - F_d$$ ---------------- Eq(1)

$$F_G = mg$$

$$F_b = mg\rho_w / \rho_p$$

$$F_d = C_d v_p^2 g / \rho_p$$

F_G: gravitational force , (kg.m/s²)
ρ_p: density of particles, kg/m³
ρ_w: density of water, kg/m³
G: acceleration due to gravity (9.81 m/s²)
F_d: drag force , (kg.m/s²)
C_d: drag coefficient (unitless)
A_p: cross-sectional or projected area of particles in direction of flow (m²)
v_p: particle settling velocity (m/s)
$v_{p(t)}$: terminal particle velocity (m/s)
d_p: particle diameter, (m)
s_{gp}: Specific gravity of the particle

By substituting the forces into Eq(1), we have

$$\frac{dv}{dt} = g\frac{\rho_p - \rho_w}{\rho_p} - \frac{C_d v_p^2 A_p \rho_w}{2m}$$

The acceleration decreases with time and approaches zero. The particle quickly reaches a constant velocity which is the maximum attainable under the circumstances. This maximum settling velocity is called *terminal velocity*.

$$v_{p(t)} = \sqrt{\frac{4g}{3C_d}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p} \approx \sqrt{\frac{4g}{3C_d}(S_{gp} - 1)d_p}$$

Newton's law

Gravity Separation Theory: Particle shape

$$v_{p(t)} = \sqrt{\frac{4g}{3C_d\phi}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p} \approx \sqrt{\frac{4g}{3C_d\phi}(S_{gp} - 1)d_p}$$

- Where ϕ is a shape factor. The value of the shape factor is:
  - 1.0 for spheres
  - 2.0 for sand grains
  - 20+ for fractal floc
- For spherical particles

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34$$

- The shape factor must be accounted for in computing N_R.

Gravity Separation Theory: Settling in the Turbulent Region

- Inertial forces are predominant, and the effect of the first two terms in the drag coefficient equation is reduced.

$$C_d = 0.34$$

$$v_p = \sqrt{3.33 g \left(\frac{\rho_p - \rho_w}{\rho_w} \right) d_p} \approx \sqrt{3.33 g (S_{gp} - 1) d_p}$$

Gravity Separation Theory: Settling in the Laminar Region

- Assuming spherical particles

$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{v_p d_p}{v}$$

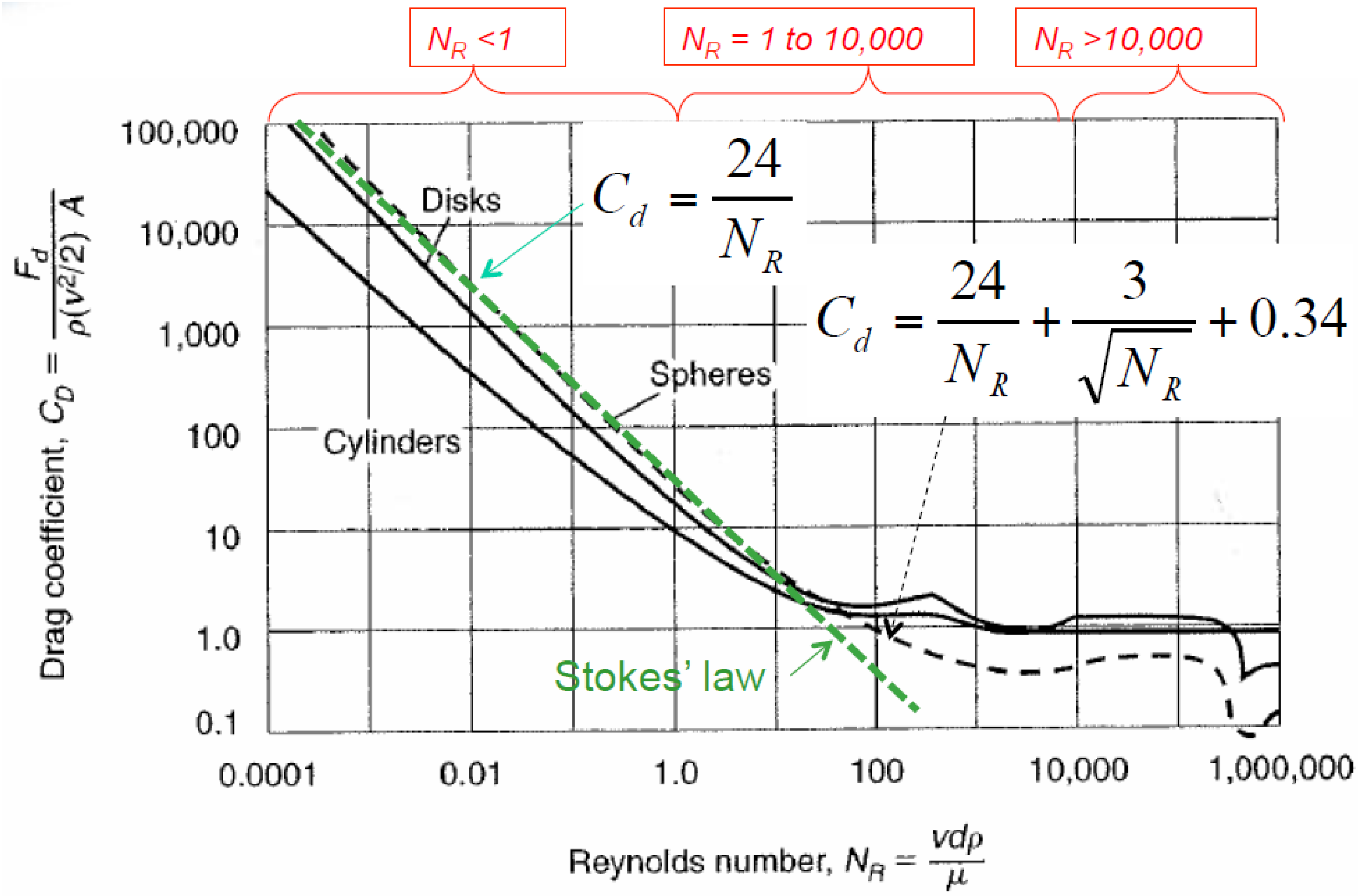
$$C_d = \frac{24}{N_R}$$

$$F_d = 3\pi\mu v_p d_p$$

$$v_p = \frac{g(\rho_p - \rho_w)d_p^2}{18\mu} \approx \frac{g(sg_p - 1)d_p^2}{18v}$$

Stokes' Law for spherical particles

Gravity Separation Theory: Drag coefficient (C_d)

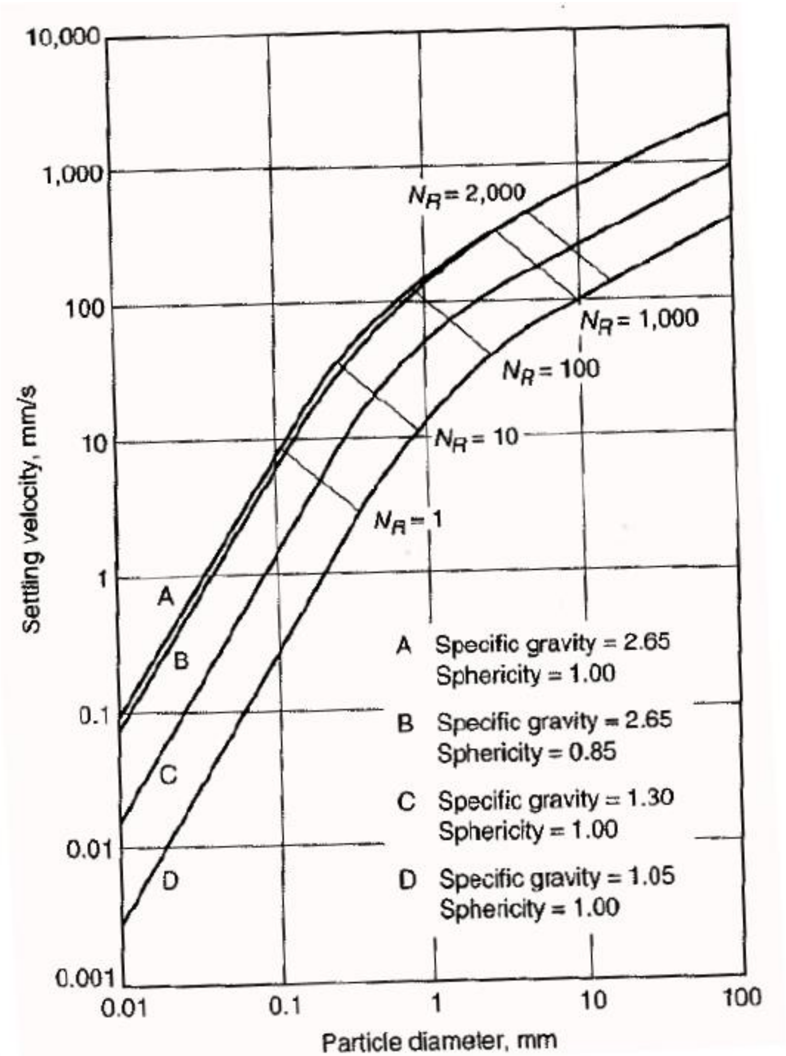


Gravity Separation Theory: Settling in the Transition Region

- Because of the nature of the drag equation finding the setting velocity is an iterative process

1) Assume an initial settling velocity
2) Find N_R
3) Find C_d using the general formula
4) Use the C_d in Newton's equation to find v_p
5) Check if v_p is equal to the assumed value
6) If not, assume the find v_p and repeat the steps from 2 to 5 until new v_p is equal to the assumed one

Gravity Separation Theory: Settling velocity (graphically)



Brownian Motion

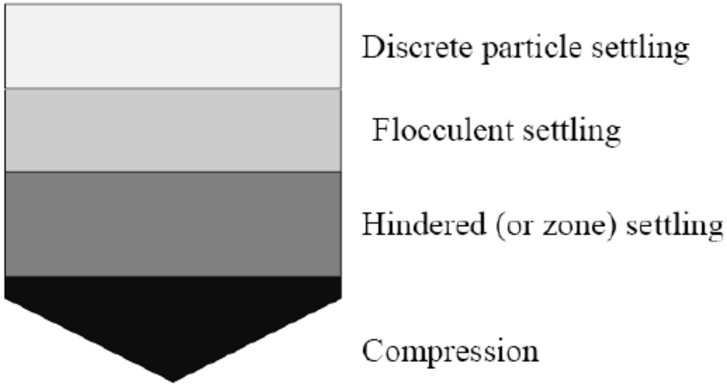
$$v_B = \frac{1}{\Delta x}\left(\frac{2kT}{3\pi\mu d_p}\right)$$

v_B: particle velocity in one direction due to Brownian motion, m/s
k: Boltzmann's constant, 1.38×10^{-23} N.m/K
T: absolute temperature, K (273 +°C)
Δx: net distance traveled in x-direction due to Brownian motion, m
μ: dynamic viscosity, N.S/m^2
d_p: particle diameter, m

- when $v_B > v_s$ (Stokes), particles will not settle out of solution.

Type of Settling

- Four types of settling:
  - Type 1 - discrete settling
    - follows Stokes' Law
  - Type 2 - flocculent settling
    - particles collide, increase in size and settle faster
  - Type 3 - zone settling
    - particles interlock and settle as one unit
  - Type 4 – compression:
    - This occurs when the particle concentration is so high, so that particles at one level are mechanically influenced by particles on lower levels. The settling velocity then drastically reduces.



Discrete Particle Settling

Gravity Settling Tanks

- All sedimentation tanks are modeled as plug flow reactors.
- Rectangular or Circular design.
- Their design is determined by the v_c of the particle size to be removed, so that all the particles that have a terminal velocity $\geq v_c$ *will be removed*.
- $Q = Av_c$ *the rate at which clarified water is produced*

Q: the overflow rate or surface loading
A: surface area of the sedimentation tank

- Rearranging, $v_c = Q/A$
- A common basis of design for discrete particle settling recognizes that the flow capacity is independent of the depth.

Discrete Particle Settling

- For continuous-flow sedimentation, the length of the tank and the detention time should be such that all particles with the design velocity, v_c, will settle to the bottom of the tank.
- v_c = depth/detention time

- In practice, design factors must be adjusted to allow for the effects of:
  - Inlet and outlet turbulence
  - Short circuiting
  - Sludge storage
  - Velocity gradient

Sedimentation Tank: Critical Path

- Horizontal velocity

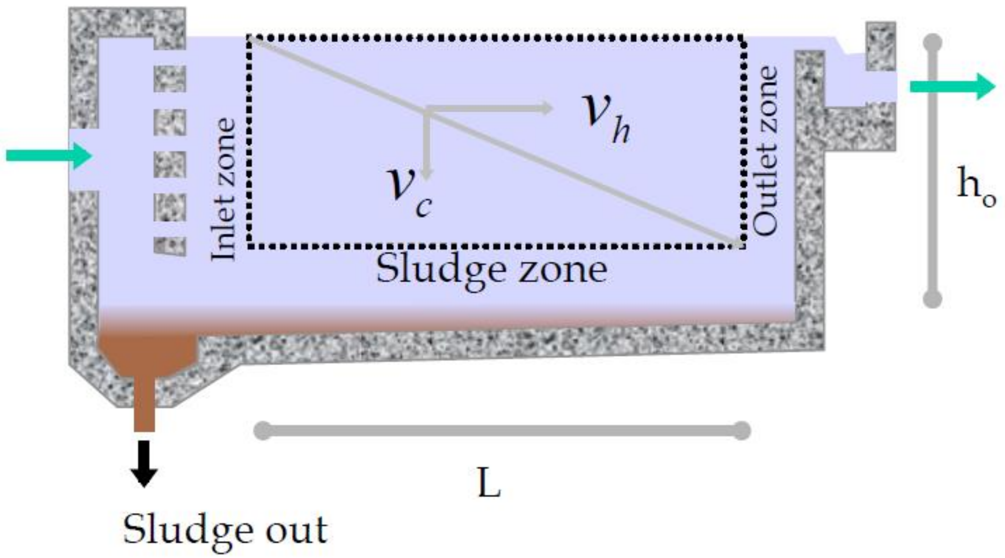
$$v_h = \frac{Q}{A}$$

Q → flow rate

A → $W \times h_o$

- Vertical velocity

$$v_c = \frac{h_o}{\tau}$$



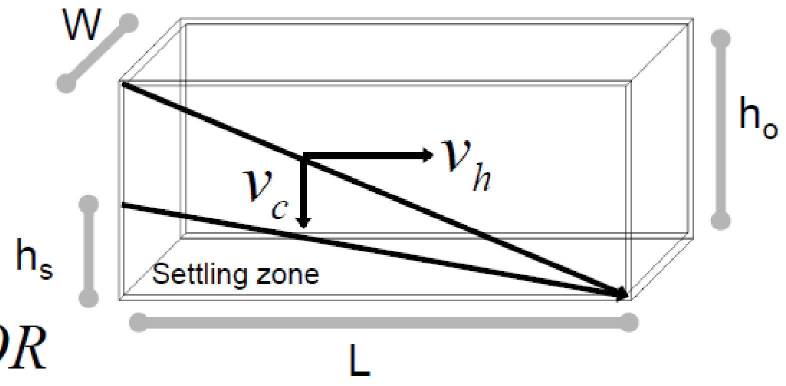
v_c = particle velocity that just barely gets captured

Sedimentation Tank: Importance of Tank Surface Area

$$\tau = \frac{V}{Q}$$ Time in tank

$$v_c = \frac{h_o}{\tau} = \frac{h_o Q}{V} = \frac{Q}{LW} = \frac{Q}{A_s} = OR$$

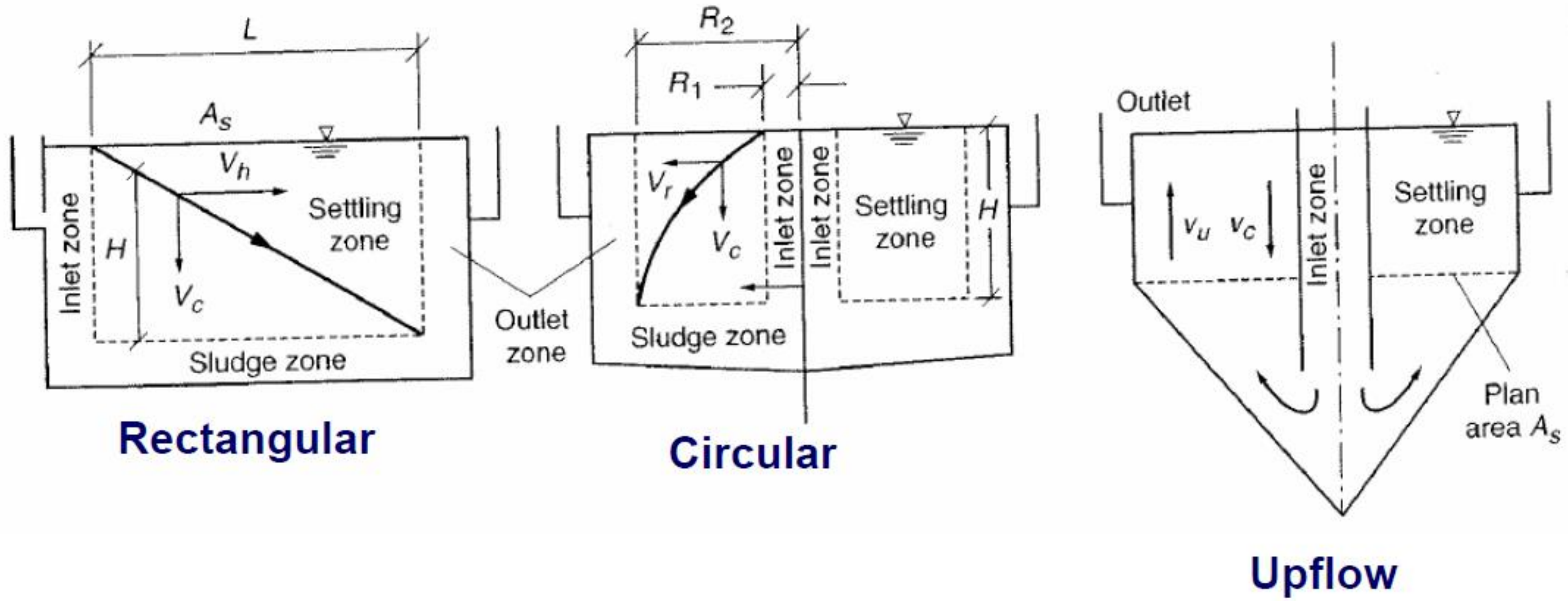
- v_c is a property of the sedimentation tank!
- OR: overflow rate, $m^3/m^2.h$ (equal to v_c)



τ: residence time
$V = Wh_oL$: volume of tank
A_s: top surface area of tank

Sedimentation: Discrete Particle Settling

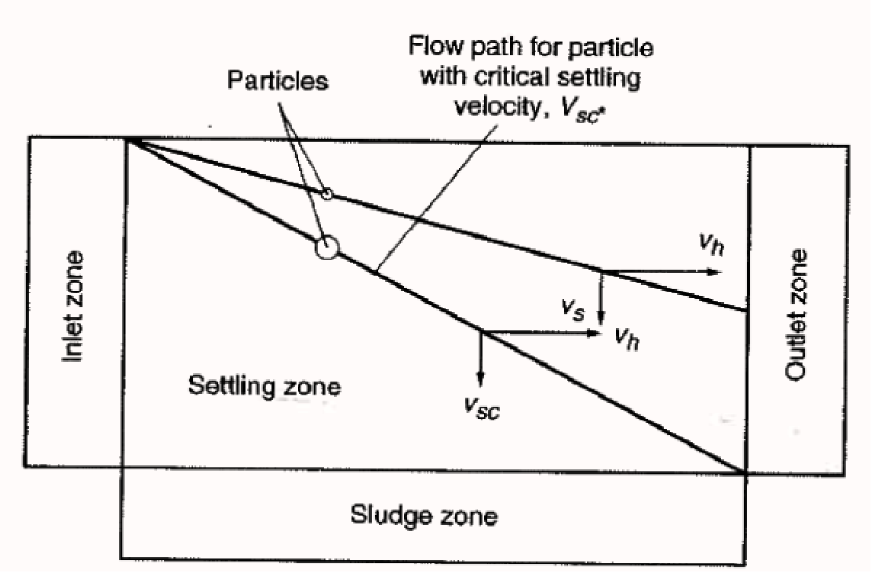
Ideal settling velocity of discrete particles in three different types of settling tank:



Discrete Particle Settling

- Particles with a settling velocity < v_c will <u>not all</u> be removed during the <u>time provided for settling</u>
- Assume that the particles of various sizes are uniformly distributed over the entire depth of the tank at the inlet
- Particles with a settling velocity < v_c will be removed in the ratio

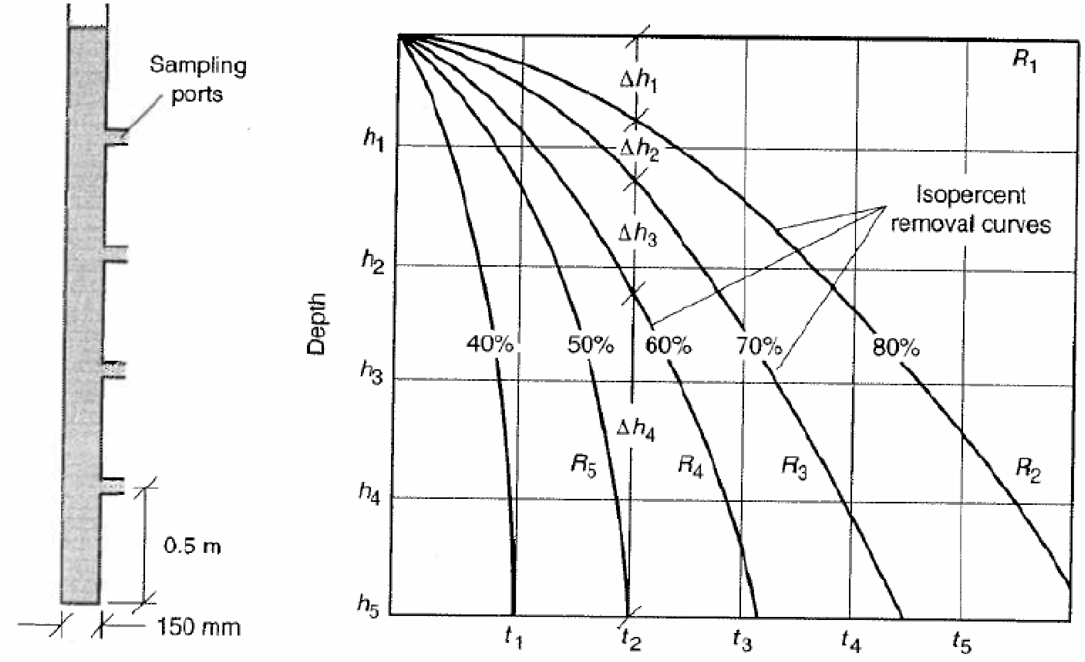
  $X_r = v_p/v_c$
- *where X_r is the fraction of the particles with settling velocity v_p that are removed.*



Discrete Particle Settling

- In most suspensions in wastewater treatment, a large graduation of particle sizes will be found
- To determine the efficiency of removal for a given settling time, it is necessary to consider the entire range of settling velocities present in the system.

Settling column test



Discrete Particle Settling

- The total fraction of particles removed for a continuous distribution:

$$Fraction\ removed = (1 - X_c) + \int_0^{x_c} \frac{v_p}{v_c}\,dx$$

where:

$(1\text{-}X_c)$ = fraction of particles with $v_p > v_c$

$\int_0^{x_c} \frac{v_p}{v_c}\,dx$ = fraction of particles removed with $v_p < v_c$

- The total fraction removed of discrete particles with a given velocity range:

$$Total\ \ fraction\ removal = \frac{\sum_{i=1}^{n} \frac{v_{ni}}{v_c}(n_i)}{\sum_{i=1}^{n} n_i}$$

where:

- v_n = average velocity of particles in the i^{th} velocity range
- n_i = number of particles in the i^{th} velocity range

Flocculent Particle Settling

Flocculent settling column test:

- The settling characteristics of a suspension of flocculent particles can be obtained using a setting column test. Such a column can be of any diameter but should be equal in height to the depth of the proposed tank.
- The solution introduced into the column should be in such a way that a uniform distribution of particle sizes occurs from top to bottom.
- Temperature should be maintained constant through out the experiment
- Settling should take place under quiescent conditions
- The duration of the test should be equivalent to the settling time in the proposed tank
- At the conclusion of the settling, the settled matter that has accumulated at the bottom is drawn off, the remaining liquid is mixed, and the TSS of liquid is measured.
- The TSS of the liquid is then compared to the sample TSS before settling to obtain the percent removal

Flocculent Particle Settling

Flocculent settling column test:

The overflow rate of various settling is determined by noting the value where the curve intersects the x axis.

$$v_c = \frac{H}{t_c}$$

H: Height of the settling column (m)

t_c: time required for a given degree of removal to be achieved.

The fraction of particles removed is given by:

$$R,\% = \sum_{h=1}^{n} \left(\frac{\Delta h_n}{H}\right)\left(\frac{R_n + R_{n+1}}{2}\right)$$

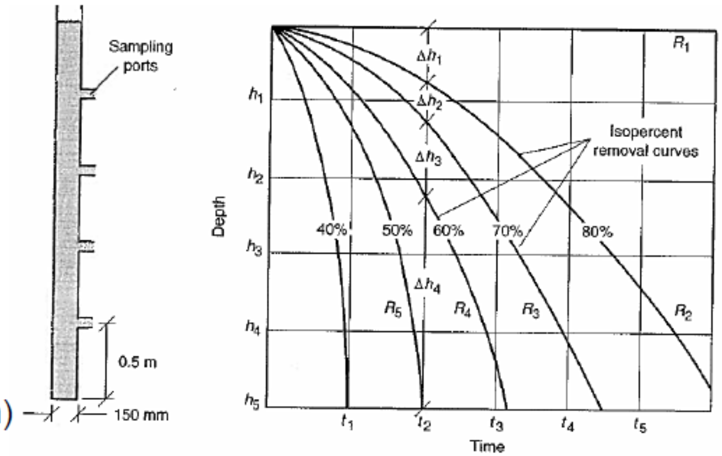
R, %: TSS removal, %

n: number of equal percent removal curve

Δh_n: distance between curves of equal percent removal (m)

R_n: equal percent removal curve number n

R_{n+1}: equal percent removal curve number n+1.



The advantage of the experiment is that it is possible to obtain removal data at various depths of settling.

Hindered (Zone) Settling

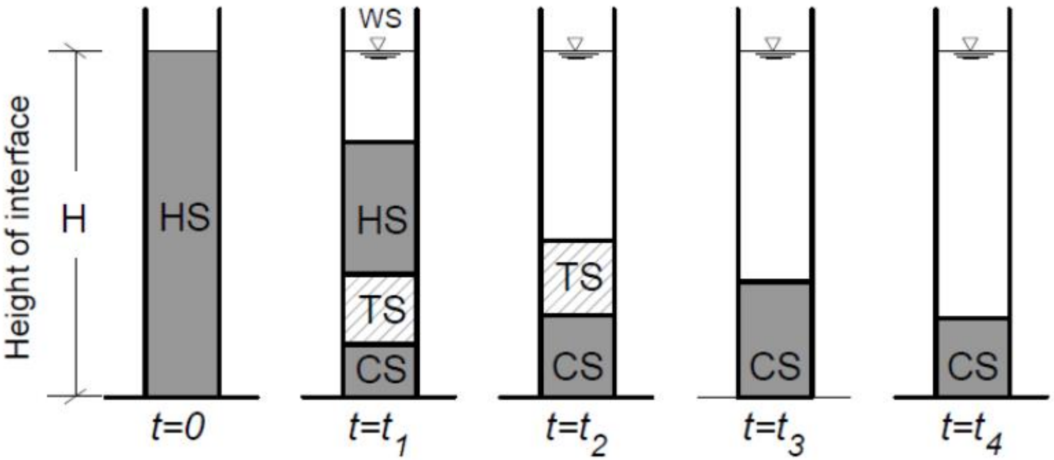
- As the concentration of particles in a suspension is increased, a point is reached where particles are so close together that they no longer settle independently of one another and the velocity fields of the fluid displaced by adjacent particles, overlap.

- There is also a net upward flow of liquid displaced by the settling particles. This results in a reduced particle-settling velocity and the effect is known as *hindered settling or zone settling*.

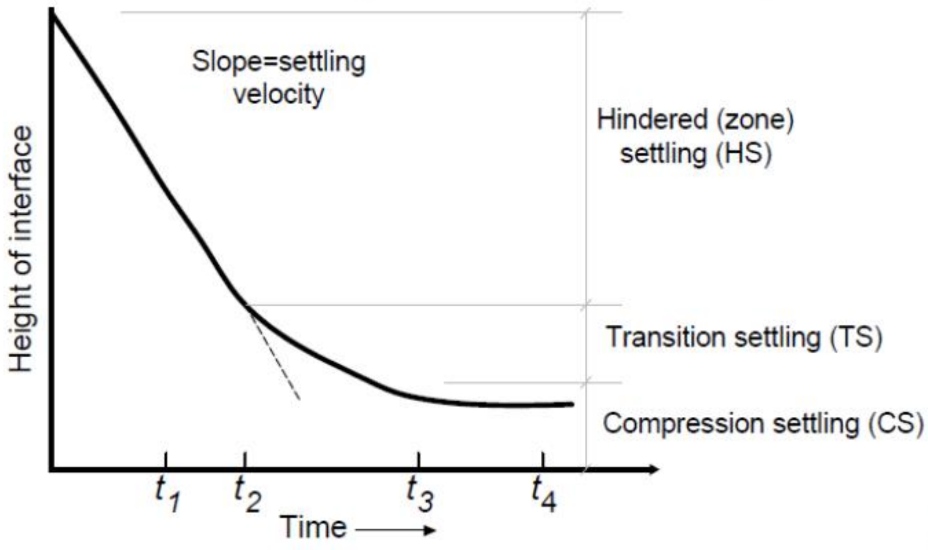
- The rate of settling in the hindered settling region is a function of the concentration of solids and their characteristics.

Hindered (Zone) Settling

- Settling column in which the suspension is transitioning through various phases of settling



- The corresponding interface settling curve



Hindered (Zone) Settling

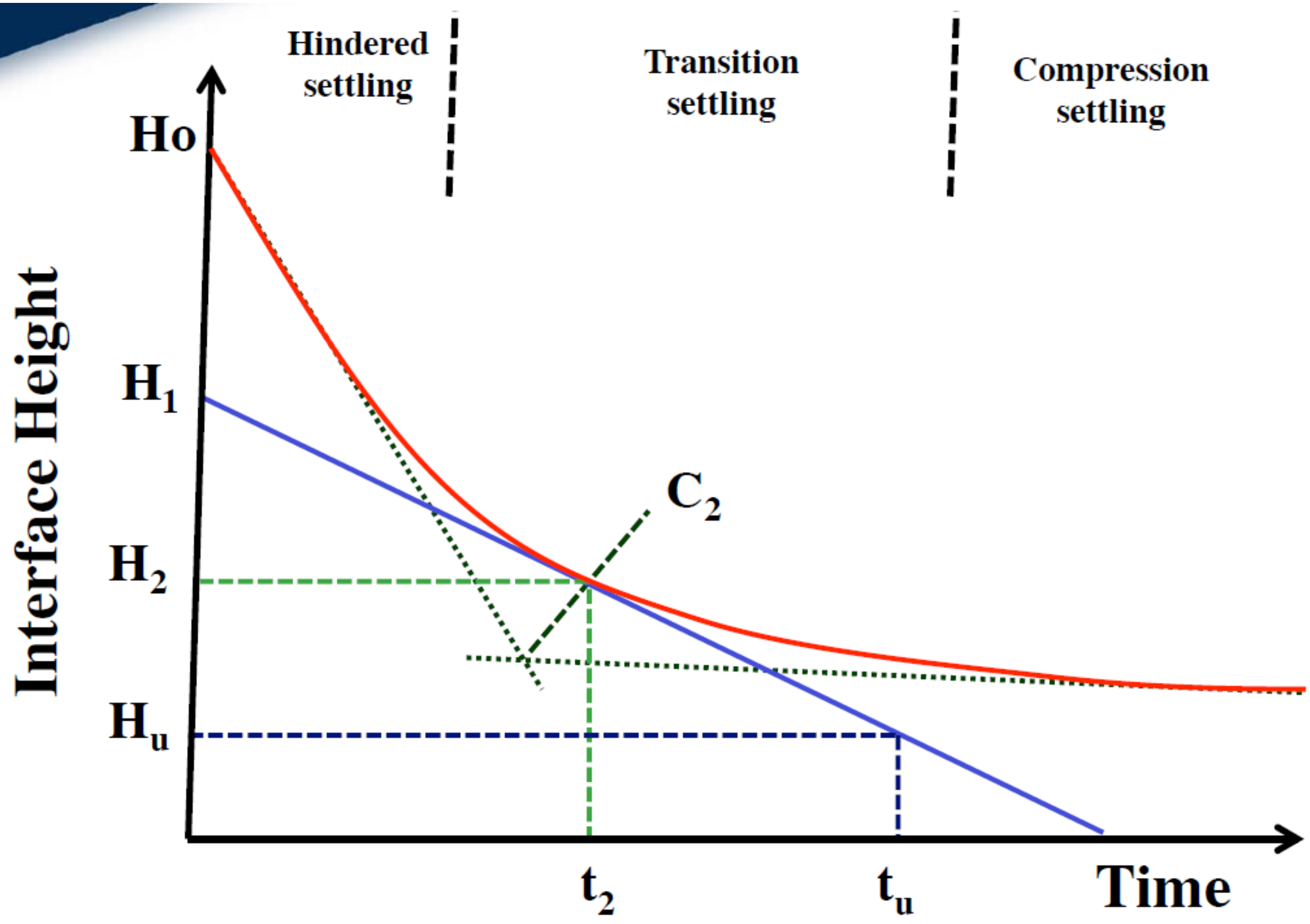
Design approach to obtain the required area for the settling/thickening facilities:

- The final overflow rate selected should be based on a consideration of the following:
  - The area needed for clarification
  - The area needed for thickening
  - The rate of sludge withdrawal

- Column test can be used to determine the area needed for the free settling region.

- The area required for thickening is usually greater than the area required for the settling, thus the rate of free settling rarely is the controlling factor.

Hindered (Zone) Settling



Hindered (Zone) Settling

Design Experiment

- **The area required for thickening is:**

$$A_t = \frac{Qt_u}{H_o}$$

A_t: area required for sludge thickening (m^2)
Q: flowrate into tank (m^3/s)
H_o: initial height of interface in column (m)
t_u: time to reach desired underflow concentration (s)

- **The time t_u can be determined as follows:**

1. Construct a horizontal line at the depth H_u that corresponds to the depth at which the solids are at the desired underflow concentration C_u. The value H_u is determined using the mass balance as follows:

$$H_u = \frac{C_o H_o}{C_u}$$

2. Construct a tangent to the settling curve at the point indicated by C_2.
3. Construct a vertical line from the point of intersection of the two lines drawn in steps 1 and 2 to the time axis to determine the value t_u.

Hindered (Zone) Settling

Design Experiment

- **The area required for clarifier is:**

$$A_c = \frac{Q_L}{v}$$

A_c: area required for clarifier (m^2)
Q_L: Clarification rate (m^3/s)
v: settling velocity (m/s) estimated from the slope.

- **Estimation of Clarification rate:**

The clarification rate is proportional to liquid volume above the sludge zone and thus can be estimated as follows:

$$Q_L = Q\left(\frac{H_o - H_u}{H_o}\right)$$

- **The controlling area:**

After estimating the values of A_t and A_c, check which one has the highest value and it will be considered the controlling area for design.

Compression Settling (Compaction)

- Very high particle concentrations can arise as the settling particles approach the floor of the sedimentation tanks and adjacent particles are actually in contact. Further settling can occur only by adjustments within the matrix, and so it takes place at a reducing rate. This is known as *compression settling, compaction* or *consolidation* and is illustrated by the lower region of the zone-settling diagram.

- Compression settling occurs as the settled solids are compressed under the weight of overlying solids, the void spaces are gradually diminished and water is squeezed out of the matrix.

- Compression settling is important in gravity thickening processes.

- It is also particularly important in activated-sludge final settling tanks, where the activated sludge must be thickened for recycling to the aeration tanks and for disposal of a fraction of the sludge.

Remember!

Purpose of Sedimentation

- Removal of particulate matters, chemical flocs, and precipitates from suspension through gravity settling

- The terms *sedimentation* and *settling* are used interchangeably

- Sedimentation basin may also be referred to as:
  - sedimentation tank
  - clarifier
  - settling basin, or setting tank

Types of Settlers/Clarifiers (Next Lecture)