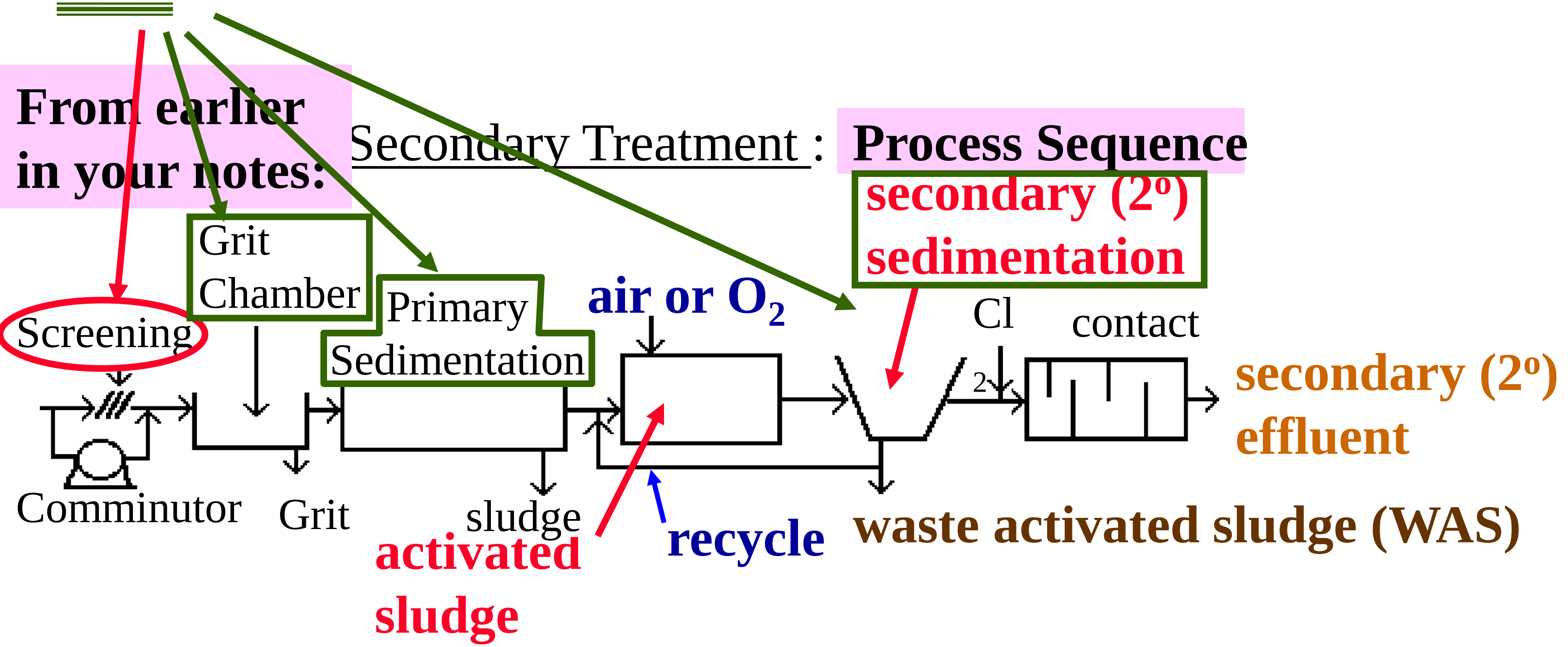
CONVENTIONAL 2^o WASTEWATER TREATMENT

We'll now go back to the front end of the treatment plant and examine the physical unit processes employed to achieve particle removal .



Green arrows & boxes indicate unit processes that employ gravity separation

PARTICLE REMOVAL

I. Gross Particle Removal: Accomplished by screening

Screening is usually the first process in the treatment of raw wastewater.

Screening is accomplished via a device with openings of a uniform size to remove coarse particles.

Devices employed can be parallel bars, rods or wires, gratings, mesh, perforated plates, etc.

Commonly used are vertical (perpendicular to flow) or slanted bars spaced with openings of 25 to 75 mm (bar racks).

Racks are either manually cleaned (periodic) or mechanically cleaned (periodic or continuous).

If the waste contains a lot of organic material which accumulates on the screen, it is often passed to a ___**comminutor**___ to grind it up. These materials are reintroduced to the flow and removed downstream.

Alternately, materials removed by screening may be disposed of by burial or incineration.

The channel in which a bar rack is installed is designed to insure a flow velocity high enough to prevent any sedimentation of grit (which is removed downstream).

i.e., sedimentation is NOT desirable in the channel for the bar rack.

II. Particle Removal by Gravity Forces

The process of removing particles by sedimentation is employed in both water and wastewater treatment. In the course of conventional secondary treatment 3 points can be identified where settling is used.

1. **Grit chambers**

2. **Primary sedimentation tank (1^o clarifier)**

3. **Secondary sedimentation tank (2^o clarifier)**

It is useful to look at sedimentation (a Unit Process) to see how it can be modeled or empirically described, and then to use such concepts in design.

Classes or Types of Sedimentation

Four types may be defined as a function of the solids concentration in suspension and the tendency of the solids to interact with one another as they settle.

Class I : **Discrete** Settling

Occurs in settling of dilute suspensions (<500 mg/L) of particles with little or no interaction. Each particle settles as an individual entity (No agglomeration or "flocculation" occurs which would change particle size and settling velocity).

No interaction between particles as they settle.

Discrete settling is the only sedimentation process which can be rigorously modeled. Ex. Sedimentation in a grit chamber may be considered to be discrete, but this is the only solid separation process where Class I sedimentation theory may be successfully applied.

Class II ___**Flocculent**_ Settling

Occurs in dilute suspensions (< 500 mg/L) of flocculent particles. Particles coalesce or flocculate during settling so that their mass ______**increases**_ and settling velocity ___**increases**__ as they fall.

Interaction between particles as they settle.

An example of flocculant settling is what happens in the primary sedimentation tank or in precipitation of chemical flocs (Ex, using lime to precipitate PO_4^{-3})

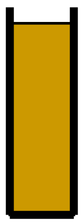
Class III. ___**Zone**___ or ___**hindered**___ Settling

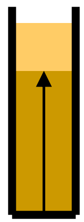
Occurs in suspensions of intermediate concentration (500 to 2000 mg/L). Inter-particle forces hinder settling of neighboring particles. Particles tend to remain in fixed positions (relatively) with respect to one another and the mass of particles settles as a unit. A distinct "solid-liquid interface" develops at the top of the settling mass with clarified liquid above and the particle mass below.

Particle interaction

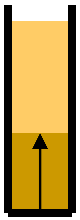
An example of this class of settling behavior is the sedimentation of activated sludge in the secondary sedimentation tank.

An experiment in Zone settling:



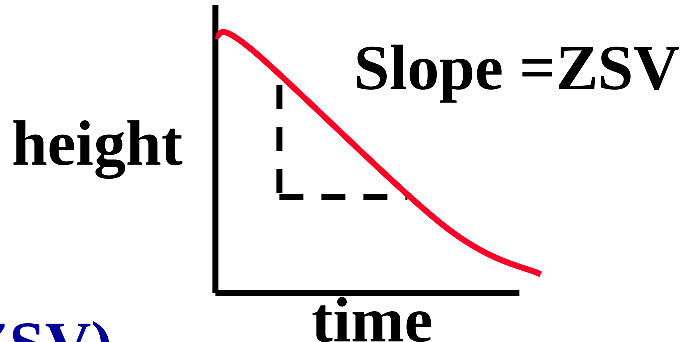


As time passes, the solids separate by settling and an interface is observed between the settling solids and the solids-free solution.



At time = 0 start with a homogeneous suspension

A plot of the height of the interface vs. time yields the Zone Settling Velocity (ZSV), which is what you'd use to do a design.



Class IV. **Compression** Settling

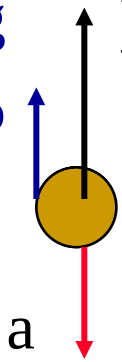
Particles are sufficiently concentrated that they form a "structure" and settling occurs by compression of the structure (water gets squeezed out) by the weight of additional solids settling from above.

gel-like

Ex., The solids (sludge) in the bottom layer of a secondary sedimentation tank.

Modeling of Sedimentation

1. **Discrete Settling** - this can be satisfactorily modeled based on fundamental principles



Requirements: - No particle interaction
- quiescent (laminar) flow

Under quiescent flow conditions, discrete particles reach a terminal settling velocity (**V_S**)

V_S = **f(particle size & density, fluid density & viscosity)**

The terminal settling velocity is attained when the downward force on the particle (**gravity**) is balanced by upward forces (**fluid drag**) and (**buoyant forces**).

At steady state (constant settling velocity):
$F_D + F_B = F_G$

$$\boxed{V_S = \left[\frac{4g(\rho_s - \rho_\ell)d_p}{3C_d(\rho_\ell)}\right]^{1/2}}$$

Do a force balance (assuming spherical particles) to get this.

A dimensionless number that is the ratio of inertial forces on the settling particle relative to viscous forces.

where: $\mathbf{d_p}$ = particle diameter

ρ_S = particle density

ρ_ℓ = fluid density

$\mathbf{g}$ = gravitational acceleration

$\mathbf{C_d}$ = drag coefficient, f $\boxed{\text{(Reynolds \#)}}$

For Laminar Flow $\quad C_d = \mathbf{24/Re}$

So, $Re = d_p \rho_\ell V_S / \mu$

$$\boxed{C_d = 24\mu / d_p \rho_\ell V_S}$$

where $\quad \mu$ = dynamic viscosity of water

Substitute into the equation on the previous page to get:

For spherical particles and laminar flow:

$$\boxed{V_S = \frac{g}{18\mu}\left(\rho_s - \rho_\ell\right) d_p^{\,2}}$$

← Stoke's Law

Design Considerations For Discrete Settling

Consider a simplified version of a clarifier.

Assume:

1. quiescent conditions in the settling zone **Laminar flow**

2. steady flow - no hydraulic fluctuations: Q = **constant**

3. uniform particle distribution at the clarifier inlet
(i.e., same concentration, top to bottom)

4. "hit and stick", particles which settle to the bottom (sludge zone) are removed. No particle scour.

Parameters:

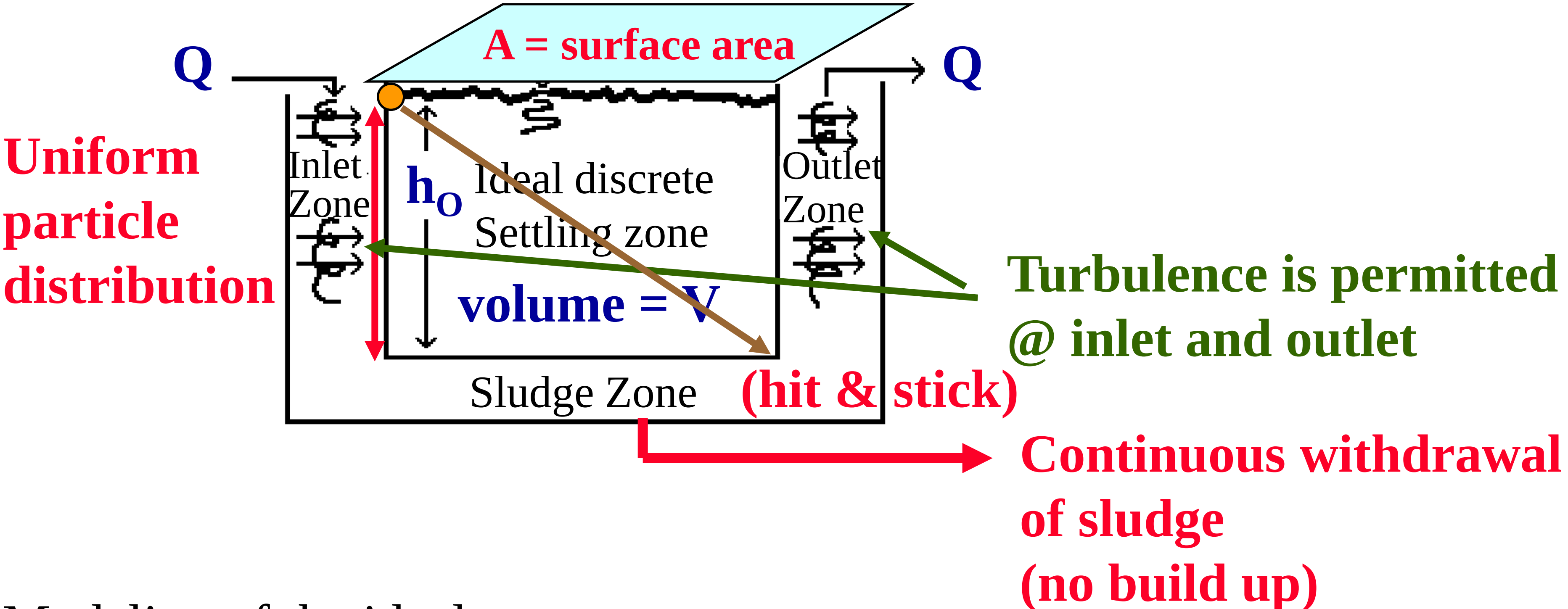
Q = volume flow rate

A = surface area of the ideal settling zone

$\mathbf{h_O}$ = depth of the ideal settling zone

V = volume of the ideal settling zone

Schematic of our ideal rectangular clarifier:



Modeling of the ideal zone:

Consider a particle which enters the sedimentation unit at the very top of the water column (remember particles are assumed to be uniformly distributed with depth). This particle will be removed if the fluid residence time in the ideal zone is long enough for it to settle and hit the bottom of the tank (the sludge zone).

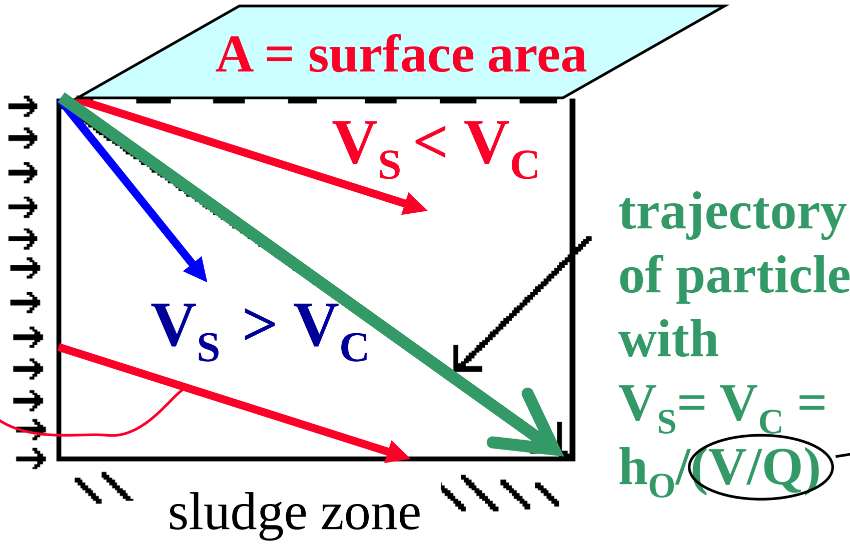
The residence time of fluid in the tank is ______**$\theta = V/Q$**______.

The maximum distance (vertical) the particle needs to travel is ______**h_O**________________.

$\therefore$ The particle will be removed if its settling velocity (V_S) is > ____**$h_O/(V/Q)$**______ . This particle (with $V_S = h_O Q/V$) will just make it to the sludge zone. Define this velocity as the ______**critical velocity**______ (V_C).

Note: we get partial removal of some particles with $V_S < V_C$, if they enter the tank below the top of the water column.

Uniform distribution of particles over depth



$V/Q = \theta$

If all particles coming into the ideal zone have $V_S > V_C$ we will remove ___**100**___ % of them.

Note that the volume of the ideal zone $V = h_O A$ **surface area of ideal settling zone**

so $V_C = h_O/(V/Q) = \cancel{h_O}Q/\cancel{h_O}A = Q/A$

∴ the critical velocity of a tank is its flow rate divided by its surface area.

The term Q/A is referred to as the ______**over flow rate**__________ or the ______**surface loading rate**______ ____________ and is the major design variable for sedimentation tanks (Q/A is just an embodiment of V_C).

In theory, all you have to do is dimension the tank such that (Q/A) < V_S and you'll get 100% removal.

Note that for a given flow rate (Q) just need (theoretically) to have some surface area (A) and removal is predicted to be <u>independent</u> of depth !!

$$V_C = h_O/(V/Q) = \cancel{h_O}Q/\cancel{h_O}A$$

∴ We can save a lot of money and make the tank real shallow- **<u>RIGHT</u>**?

NO!

<u>Problems with shallow depths</u>:

- For a given Q and A_S, as h_O $\underline{\ \downarrow\ }$, horizontal velocity $\underline{\ \uparrow\ }$
  ∴ greater likelihood for particle scour ("hit and stick" assumption breaks down).

- with shallow depths wind mixing can produce turbulence which reaches to the tank bottom and causes particle scour.

- need room for sludge removal devices (scrapers, etc.).

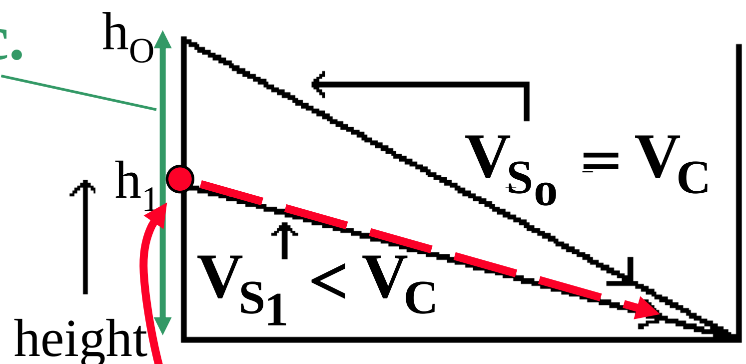
Removal of Particles with $V_S < V_C$

If $V_S < V_C$ <u>is there any removal</u>? Why or Why not?

YES!

There is some removal of particles with $V_s < V_C$ because particles are uniformly distributed over the depth of the clarifier. Those which enter @ heights $< h_O$ do not have to fall so far and may be removed.

Same conc. top to bottom @ inlet



$$V_{S_1} = h_1/(V/Q)$$

For particles with $\boxed{V_{S1} = h_1/(V/Q) < V_C}$, have ___**100**___ % removal for those which enter the reactor at height $< h_1$. Have ___**0**___% removal for those which enter at height $> h_1$.

Since the particle concentration is uniform over depth, the overall fraction (removed) of particles with $V_S = V_{S1}$ is: $\dfrac{h_1}{h_0} = \dfrac{h_1 / (V/Q)}{h_0 / (V/Q)} = \dfrac{V_{S_1}}{V_C}$

So the fractional removal of a slow settling particle is the ratio of its settling velocity to the critical velocity.

In a typical wastewater suspension, one finds a continuum of particle sizes and, therefore, a continuum of V_S values.

The spectrum of particles settling velocities can be determined by:

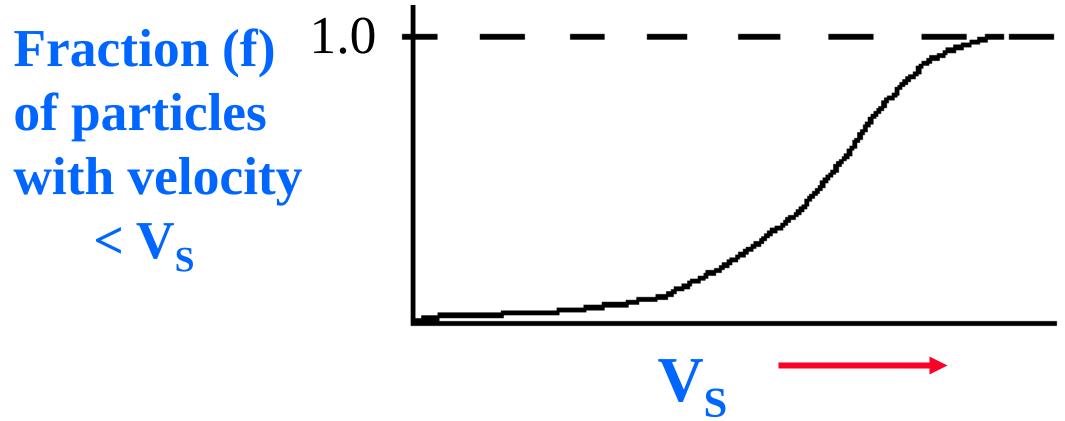
1. sieve analysis and density measurements
   i.e., given ρ_S and d_P, the Stokes settling velocity can be calculated for each size fraction.

$$\boxed{\textbf{recall, } V_S = \frac{g}{18\mu}(\rho_s - \rho_\ell)\, d_p^{\,2}}$$

2. From a settling column (more on this in a minute).

a lab test.

In either case the data may be used to construct a velocity distribution curve.



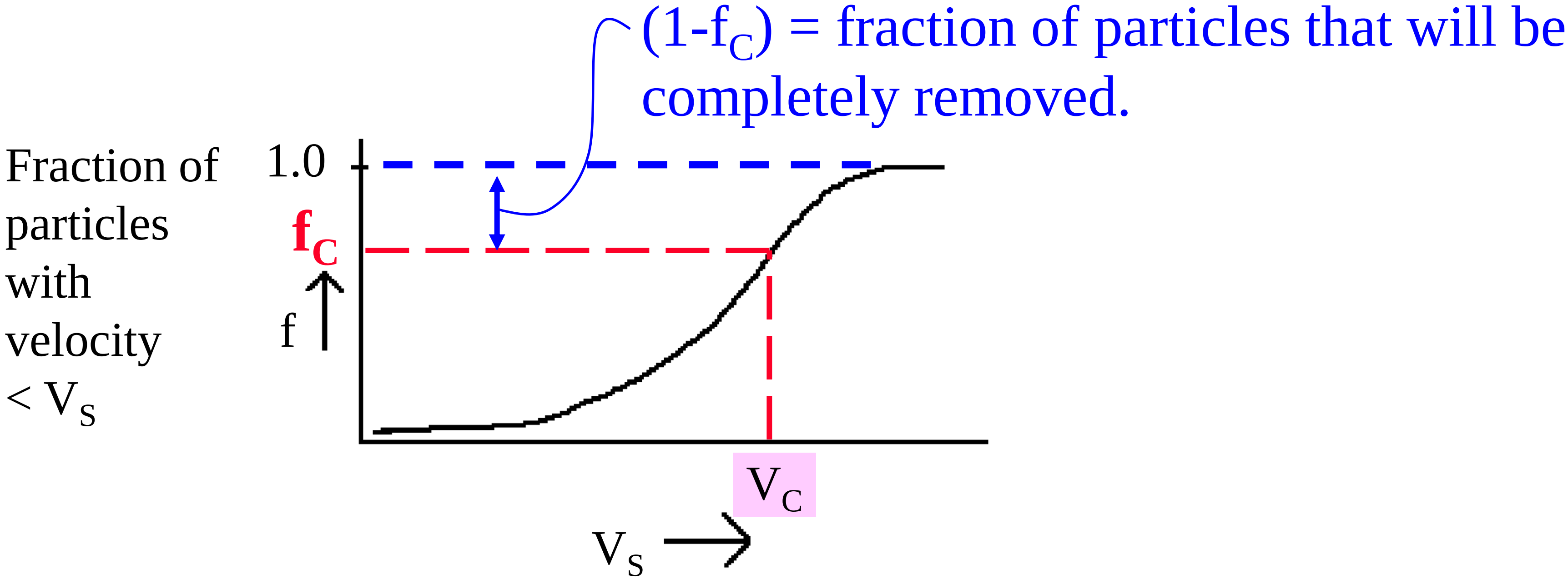
As $V_S \uparrow$, then the fraction (f) with settling velocity < $V_S \uparrow$ until all particles are accounted for.

We can use this curve to calculate the overall removal efficiency for a given design.

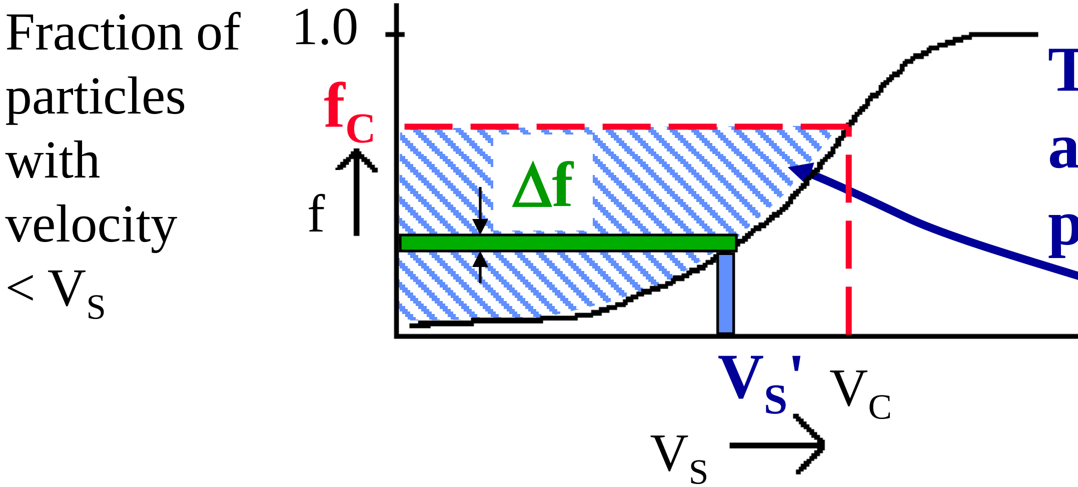
R^o

Example: If the overflow rate = $Q/A_S = V_C$ then:

1. We know we will have 100% removal of particles with $V_S > V_C$. Let the fraction of particles with velocity $< V_C = f_C$ (from the graph)



$\therefore$ the fraction with $V_S > V_C$ = **1 - f_C** and will be 100% removed.



This term is just the area under the hatched part of the curve.

2. For some incremental fraction of particles **Δf** with a an average settling velocity $V_S' < V_C$ we will have a fractional removal of : V_S'/V_C

∴ the total amount removed will be: $\Delta f (V_S'/V_C)$

For "n" incremental fractions the amount removed will be:

$$\sum_{i=1}^{n} \frac{V_{S_i}}{V_C} \Delta f$$

or, in differential form, for all particles with $V_S < V_C$ the amount removed is:

$$\int_0^{f_c} \frac{V_s}{V_c}\, df = \frac{1}{V_c} \boxed{\int_0^{f_c} V_s \, df}$$

3. The total (overall) fractional removal is the sum of the removal of particles with $V_S > V_C$ and particles with $V_S < V_C$

$$\underline{\text{Overall fraction removed}} = R^o = 1 - f_C + \frac{1}{V_c}\int_0^{f_c} V_s \, df$$

This term accounts for 100% removal of particles with $V_S > V_C$

This term accounts for fractional removal of particles with $V_S < V_C$

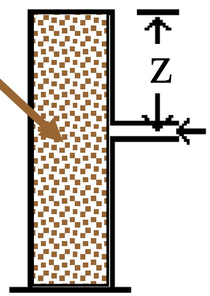
Determination of V_S vs. f distribution by settling column

1. Set up a column with a sampling port at some depth = z.

Start with a uniform suspension of particles with an initial suspended solids concentration = C_O.

C_O = wt./volume (or use turbidity)

$C = C_O$
@ time = 0



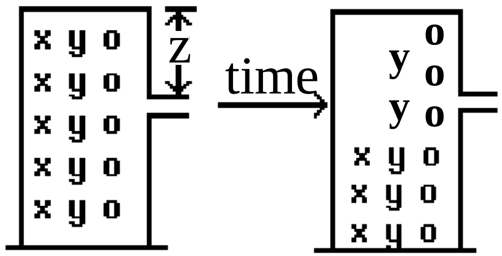
sampling port

2. At various times (t) withdraw samples and measure the suspended solids concentration $C_{(t)}$

Data Analysis: At some time = t_i, all particles with a settling velocity > z/t_i will be completely removed.

However, all particles with $V_S < z/t_i$ will be present in their original concentration! I.E., each particle of this type which falls below depth = z is replaced from above.

Illustration:

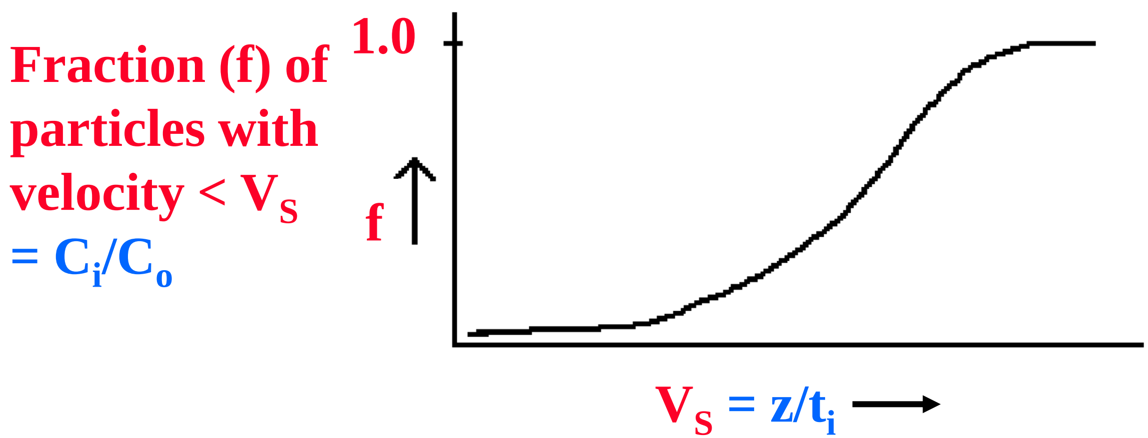


t = 0, uniform suspension

t = t_i, complete removal of particle type x, particle type y and o still present in original concentration at depth = z

So, if C_i = concentration measured @ time = t_i , then the fraction (f) of particles with V_S < z/t_i = **C_i/C_o**.

∴ have all necessary data to construct f <u>vs</u>. V_S plot.



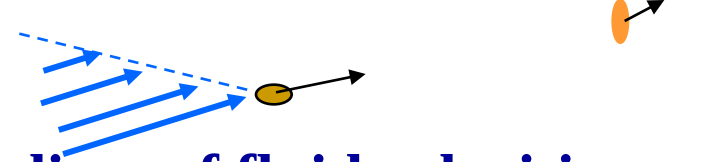
<u>Flocculent Settling</u> (Class II)

Primary settling serves as a good example. Particles contact one another and coalesce as they settle so that their settling velocity increases.

Particle contact is caused by:

a. ______**differential**______ sedimentation: large fast-settling particles overtake smaller slow-settling ones, and they stick together.

b. hydraulic disturbances (fluid shear)



gradient of fluid velocities

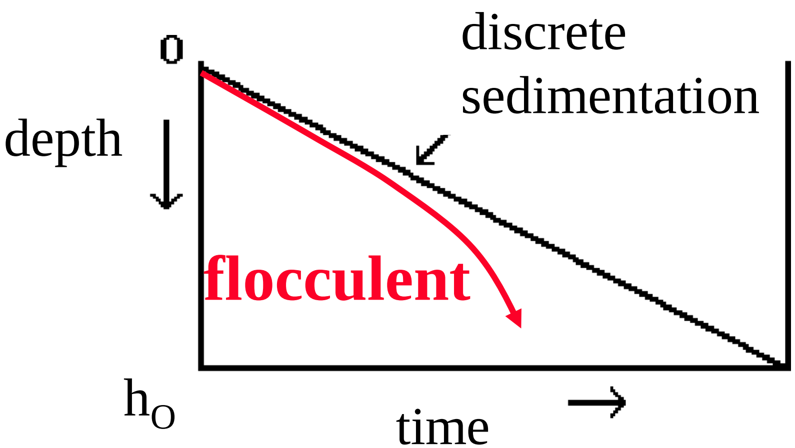
c. brownian motion

Particles continue to grow in size as they settle until they:

a. hit bottom

b. get so big that fluid shear breaks them up.

Typical particle trajectory in flocculent settling:



∴ In flocculent settling particle removal efficiency is governed by:

a. **Overflow rate (Q/A)**

b. **Depth, h_o (greater chance for aggregation if deeper)**

c. **Concentration and type of particles**

There is no suitable mathematical model to predict the effect of flocculation on sedimentation. Process design is commonly based on laboratory tests.

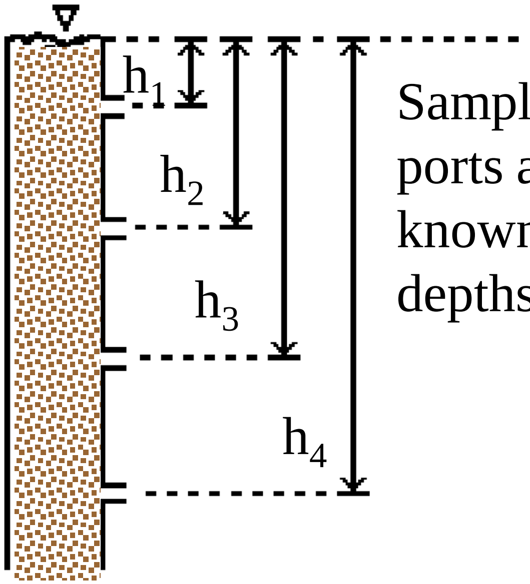
The Quiescent Settling Test: Performed in a large column. Column depth should be greater than the expected design depth for the sedimentation tank. Column diameter must be large enough to make "wall effects" negligible (typically 6" or ≈ 15 cm)

Test:

1. initially start with uniform mixture of the test suspension @ time = 0

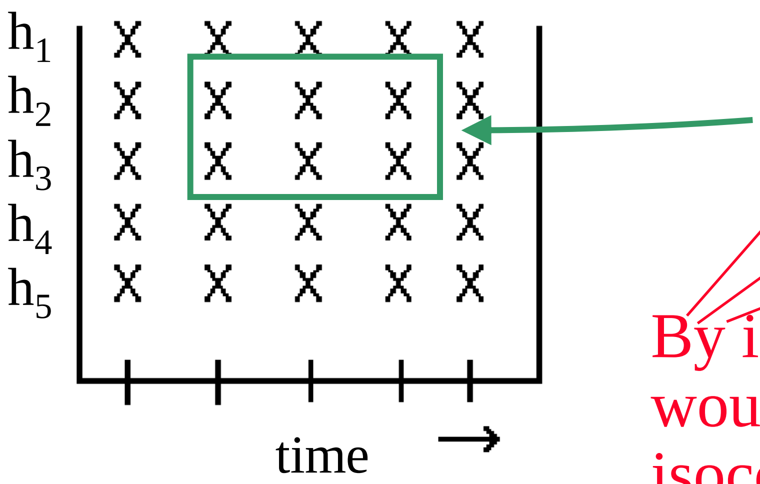
2. let settle and sample each port at time intervals

3. Measure the concentration in each sample and calculate the % removal of solids as:

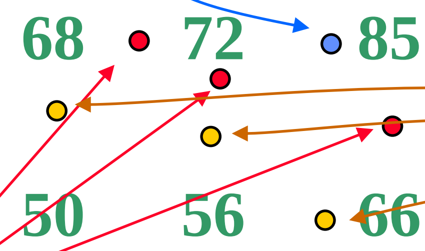


$$R^{o}_{sample} = \%\ removal = \left(\frac{T.S.S._{initial} - T.S.S._{sample}}{T.S.S._{initial}} \right) 100$$

4. Plot R^o_{sample} on an h(depth) vs. time grid



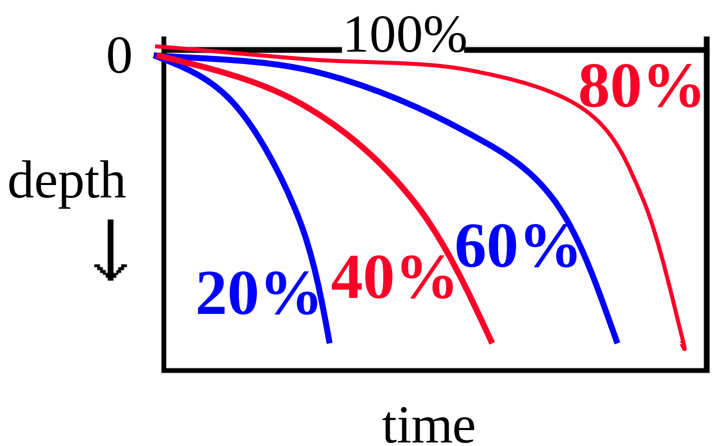
And this point would be on the line for 80% removal.



By interpolation, these points would be on the 70% isoconcentration line.

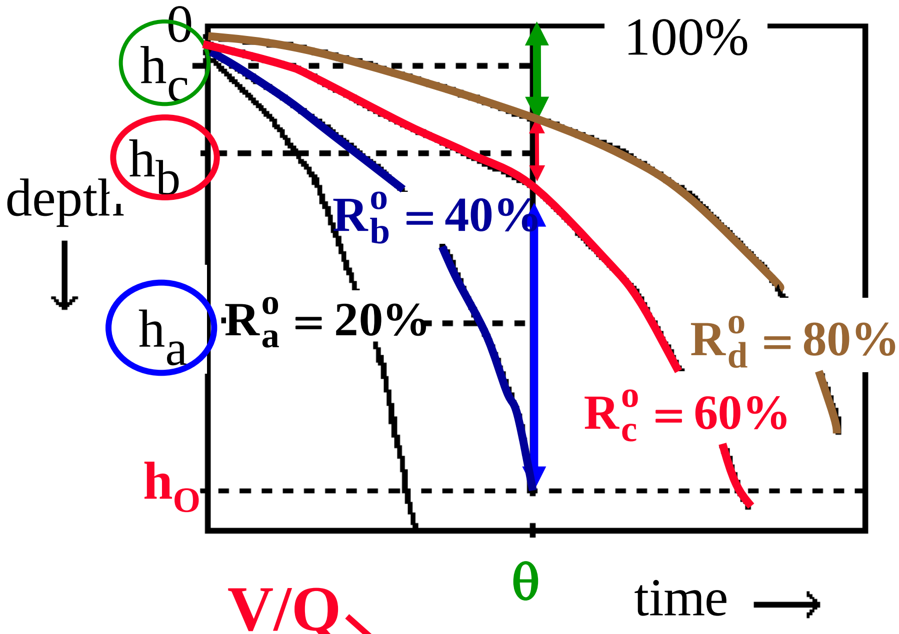
And these would be points on the line for 60% removal

5. Draw contours on the plot for equal % removal (isoconcentration lines)

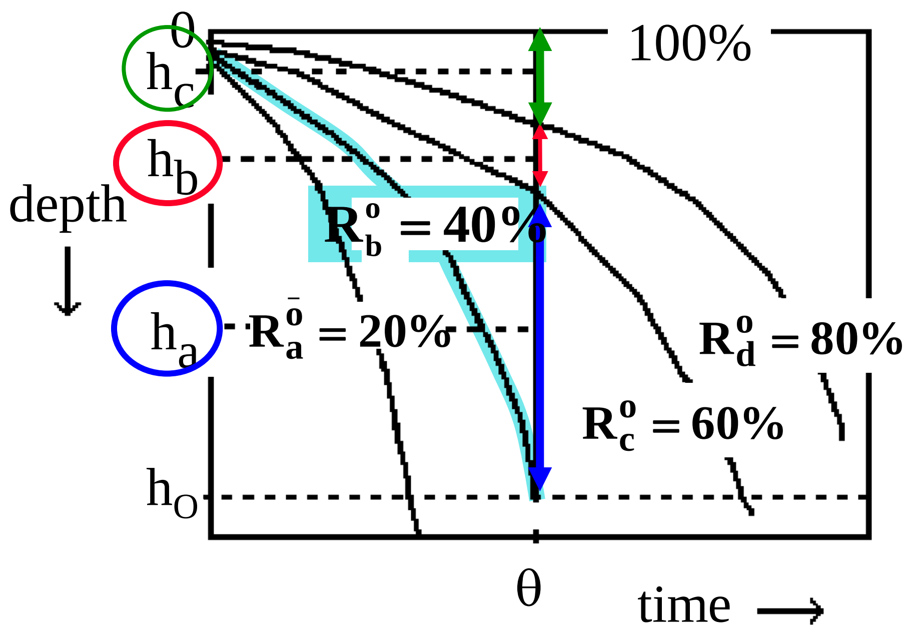


[see pp 120-123 in Environmental Engineering by Peavy et al.]

6. For any tank depth, h_O, and hydraulic retention time, $\theta = V/Q$, the total % removal may be determined as follows:



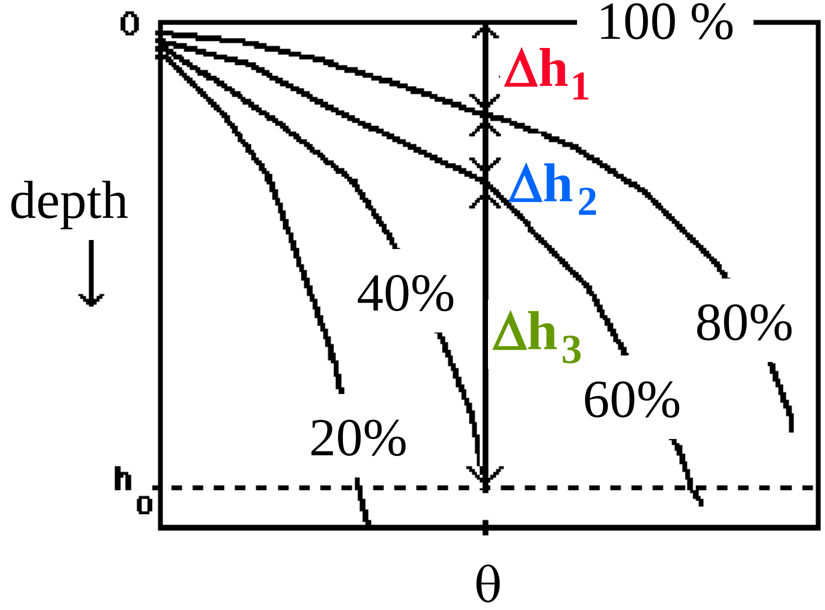
Suppose h_O and θ are as shown above. [Note $V_C = h_O/\theta = Q/A$]
Then $R^o_b = 40\%$ of the particles had settling velocities $V_S > V_C$ and are completely removed. Of the remaining ($100\% - R^o_b = 60\%$) particles, the fraction ($R^o_c - R^o_b = 20\%$) have an average settling velocity of $V_S = \underline{h_a/\theta}$. So the fraction $V_S/V_C = \dfrac{(h_a/\theta)/(h_O/\theta)}{} = h_a/h_O$ will be removed. Continue in this manner to find the total % removed (R^o_{total}) as:



$$\mathbf{R^o_{total}} \approx \overset{\color{magenta}{40\%}}{\boxed{\mathbf{R^o_b}}} + \overset{\color{magenta}{20\%}}{\frac{\mathbf{h_a}}{\mathbf{h_o}}\left(\mathbf{R^o_c} - \mathbf{R^o_b}\right)} + \overset{\color{magenta}{20\%}}{\frac{\mathbf{h_b}}{\mathbf{h_o}}\left(\mathbf{R^o_d} - \mathbf{R^o_c}\right)} + \overset{\color{magenta}{20\%}}{\frac{\mathbf{h_c}}{\mathbf{h_o}}\left(\mathbf{100\%} - \mathbf{R^o_d}\right)}$$

Note: R^o_{total} is f(θ and h_O) and also f(C_O) ← the initial T.S.S. concentration for the test.

Alternate Calculation Procedure:



Look at particle removal (%) over the depth h_O.

See that an average of

$$\frac{(100+80)}{2} = 90\%$$

were removed in depth increment of Δh_1

An additional

$$\frac{(80+60)}{2} = 70\%$$

were removed in depth increment Δh_2

Finally, an additional **(60+40)/2 = 50%** were removed in depth increment Δh_3. Add up each of these % removals and normalize each to the fraction of the total depth which it represents (i.e., the fraction $\Delta h_1/h_O$ = fraction of depth with ____**90**____% removal of particles).

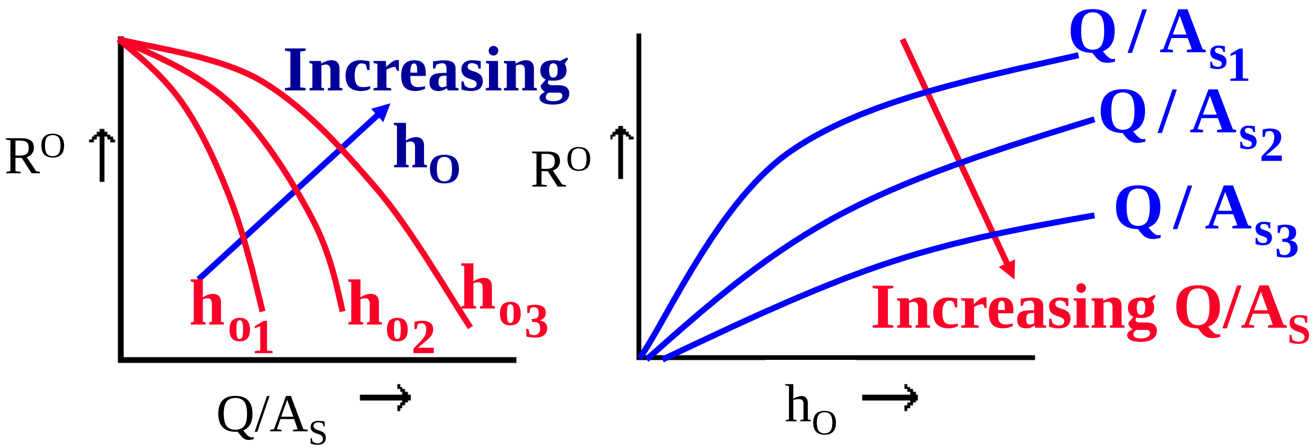
$$\therefore\ R^{o}_{total} = \frac{\Delta h_1}{h_o}(90\%) + \frac{\Delta h_2}{h_o}(70\%) + \frac{\Delta h_3}{h_o}(50\%)$$

↑ For this example

Either approach should give you the same answer.

R^{o}_{total} is still f(h_O, θ, type and concentration of particles).

These calculations can be repeated for different surface loading rates (Q/A_S values) or depths to produce a family of curves.



Primary Sedimentation Units in Wastewater Treatment

Objective: removal of settleable organic particles (subsequent to grit removal)

Design Parameters: depth and overflow rate

- in absence of quiescent settling test use:

h_O = 2 to 5 meters

Q/A_S = 25 to 40 m^3/day-m^2

Configurations:

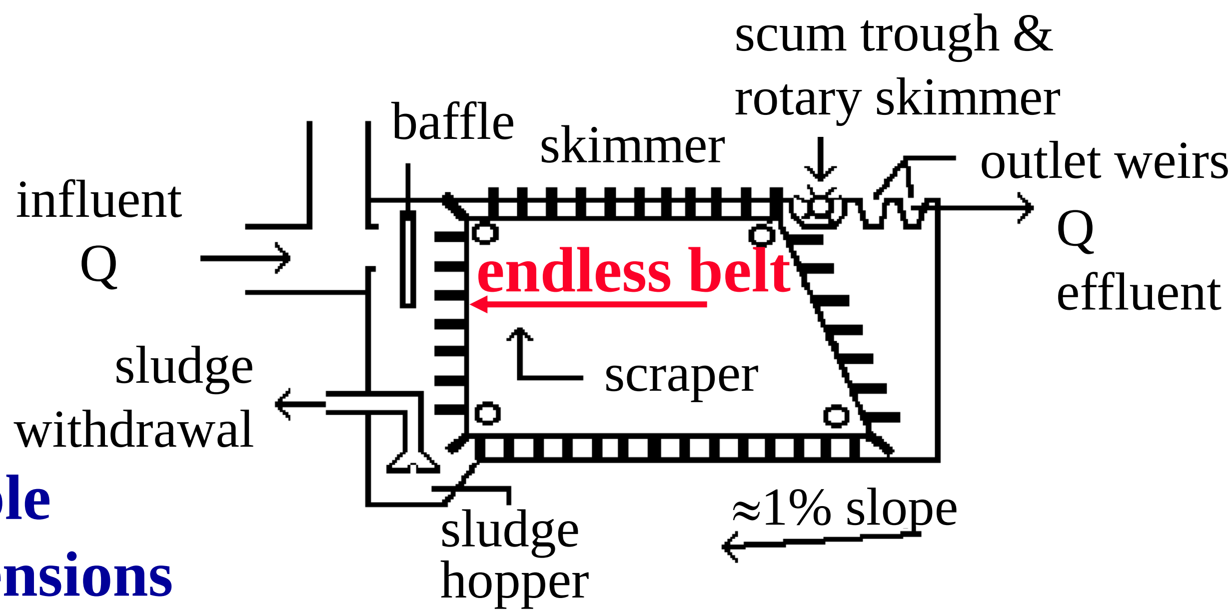
A. Rectangular

L = 15 to 90 m

θ = 1 to 3 hrs

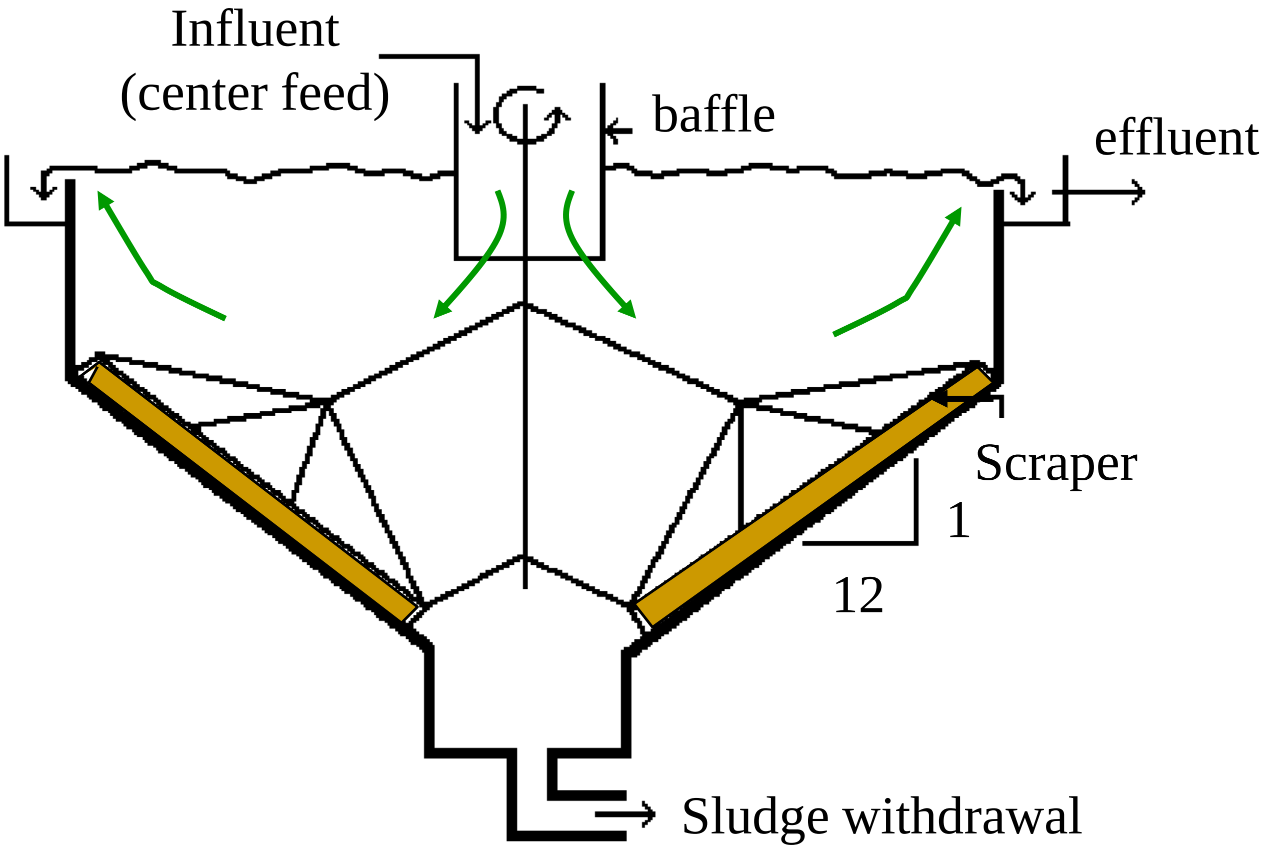
L/W = 3:1 to 5:1

W is dictated by available sludge collector dimensions



B. Circular: can have various configurations

Ex., center feed vs. peripheral feed



Often take design values (such as surface area) and apply a "scale up" factor of 1.25 to 1.75 x Ex., $A_{design} = 1.5\ A_{test}$

This accounts for "non-ideal" field conditions such as:

1. **turbulence**
2. **wind-driven currents or currents from density differences**
3. **dead zones (regions of reactor with stagnant fluid)**
4. **bottom scour**
5. **hydraulic fluctuations (Q ≠ constant)**
6. variable solids conc. and variable nature of solids

Typical removals in primary sedimentation tanks:

25-40 % removal of $BOD_5^{20\,C}$ **50-60**, % removal of T.S.S