Problems

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Problem 1

Desing a paddle flocculator by determining the basin dimensions, the paddle configuration, the power requirement, and rotational speeds for the following parameters:

Design flow rate: 50000 m^3/d

T=22 min

Three flocculator compartments with G = 40, 30, 20 s^{-1}

Water temperature= 15°C

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill

Problem 2

A cross flow horizontal shaft, paddle-wheel flocculation basin is to be designed for 25000m^3/d, a mean velocity gradient 0f 26.7s^{-1} (at 10^{o}C) and a detention time of 45 min. The GT value should be from 50000 to 100000. Taperred flocculation is to be provided, and three compartments of equal depth in series is to be used. The G values determined from laboratory tests for the three compartments are 50 s^{-1}, 20 s^{-1}, and 10 s^{-1}. The compartments are separated by slotted, redwood baffle fences. The basins should be 15 m in width to adjoin the settling basin.

Determine GT value, basin dimensions, paddle-wheel desing, power to be imparted to the water in each compartment, rotational speed of each horizontal shaft in rpm, rotational speed range if 1:4 variable speed drives are employed, the perihephal speed of the outside paddles in m/s.

Ref: Reynolds, T. D., and P. A. Richards. Unit Operations and Processes in Environmental Engineering. 2nd ed. Boston, MA: PWS Publishing Company, 1996.

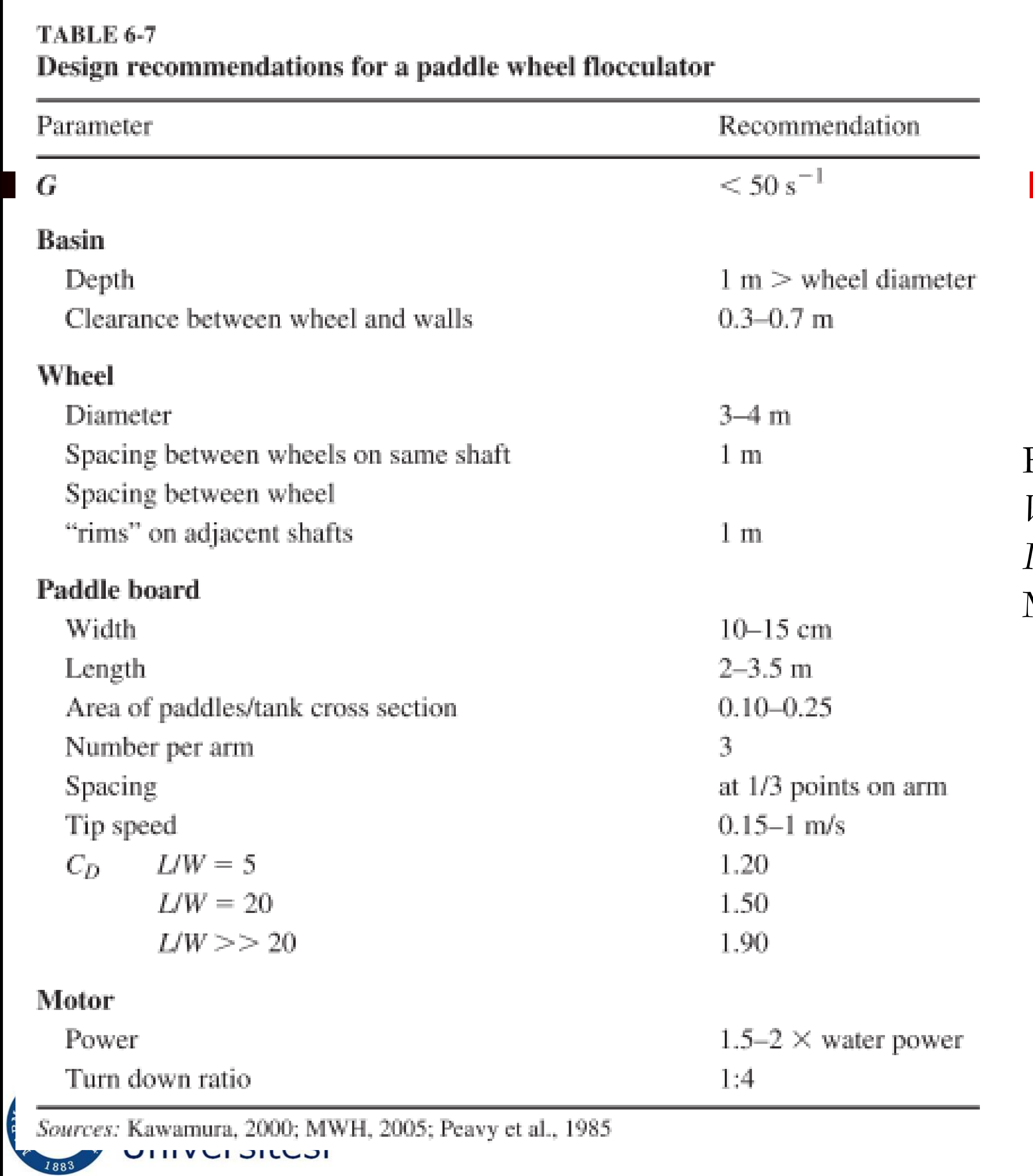

TABLE 6-7

Design recommendations for a paddle wheel flocculator

Parameter	Recommendation
G	$< 50\ \mathrm{s}^{-1}$
Basin	
Depth	1 m > wheel diameter
Clearance between wheel and walls	0.3–0.7 m
Wheel	
Diameter	3–4 m
Spacing between wheels on same shaft	1 m
Spacing between wheel “rims” on adjacent shafts	1 m
Paddle board	
Width	10–15 cm
Length	2–3.5 m
Area of paddles/tank cross section	0.10–0.25
Number per arm	3
Spacing	at 1/3 points on arm
Tip speed	0.15–1 m/s
C_D $L/W = 5$	1.20
$L/W = 20$	1.50
$L/W >> 20$	1.90
Motor	
Power	1.5–2 × water power
Turn down ratio	1:4

Sources: Kawamura, 2000; MWH, 2005; Peavy et al., 1985

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill

ENVE 301
Environmental Engineering Unit Operations

Lecture 11
Sedimentation I

SPRING 2014

Assist. Prof. A. Evren Tugtas

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Sedimentation

- Sedimentation is a solid-liquid separation utilizing gravitational settling to remove suspended solids.
- Sedimentation has been practiced since the humans started to store water in containers
- The castellae and piscinae of the Roman aqueduct system performed the function of settling tanks, even though they were not originally intended for that purpose

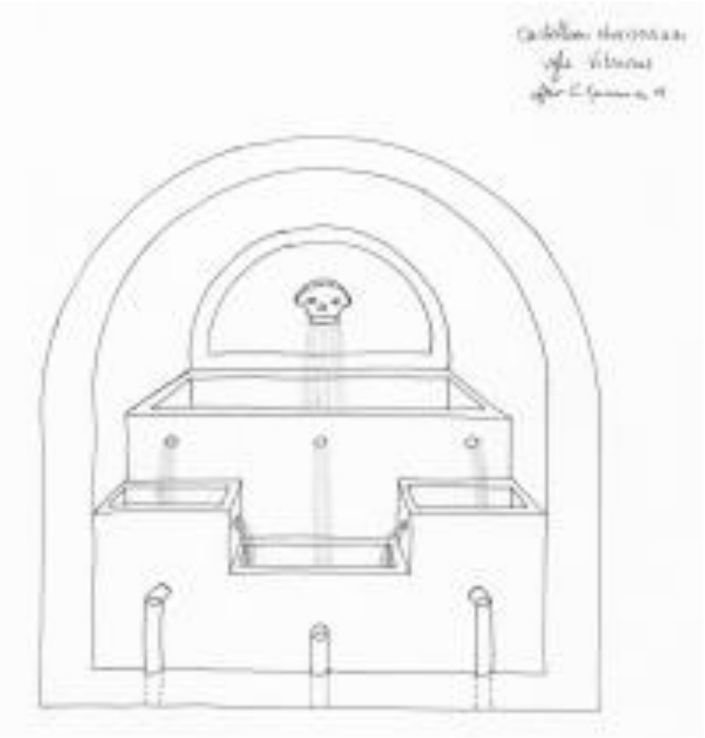
Principles of Sedimentation

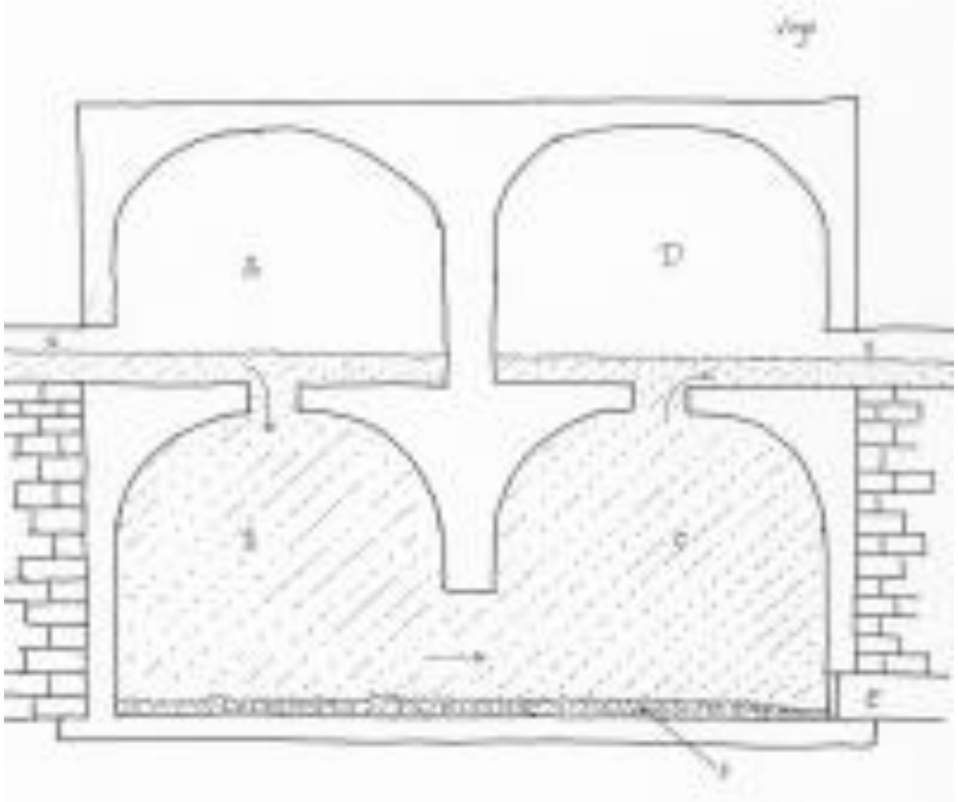
- Most of the suspended particles present in water have specific gravity > 1.
- In still water, these particles will therefore, tend to settle down under gravity.

Plain sedimentation - when impurities are separated from water by the action of gravity alone

Coagulant aided sedimentation - when the particles are too small to be removed by gravity and aided with coagulants to increase size and agglomeration

Early Sedimentation Units





Ref: http://www.romanaqueducts.info/castellaeintro/castellae.htm

Sedimentation

- **Water Treatment**
  - Plain settling of surface waters prior to treatment by a rapid sand filtration unit
  - Settling of coagulated and flocculated waters prior to rapid sand filtration
  - Settling of coagulated and flocculated waters in a lime-soda type softening plant
  - Settling of treated waters in an iron or manganese removal plant
- **Wastewater Treatment**
  - Grit or sand and silt removal
  - Suspended solids removal in primary clarifiers
  - Biological floc removal in activated sludge final clarifiers
  - Humus removal in trickling filter final clarifiers

Sedimentation Theory

- Particle-fluid separation processes are difficult to describe by theoretical analysis, mainly because the particles involved are not regular in shape, density, or size.
- The various regimes in settling of particles are commonly reffered to as
  - Type – 1: Discrete particle settling
  - Type – 2: Flocculant settling
  - Type – 3: Hindered (zone) settling
  - Type – 4: Compression settling

Settling Regimes
Type – I – Discrete particle settling

Type I settling (discrete of free settling) is the settling of discrete particles in low concentration, with flocculation and other interparticle effects being negligible

- These particles settle at constant settling velocity
- They settle as individual particles and do not flocculate during settling
- ***Examples:*** Settling of sand, grit
- ***Applications:*** Presedimentation for sand removal prior to coagulation

Settling Regimes
Type – II – Flocculant settling

Type II settling is the settling of flocculent particles in a dilute suspension.

As coalescence occurs, particle masses increase and particles settle more rapidly.

- Particles flocculate during sedimentation.
- These types of particles occur in alum or iron coagulation

Settling Regimes
Type – III – Hindered (zone) settling

Type III settling, settling in which particle concentration causes interparticle effects.

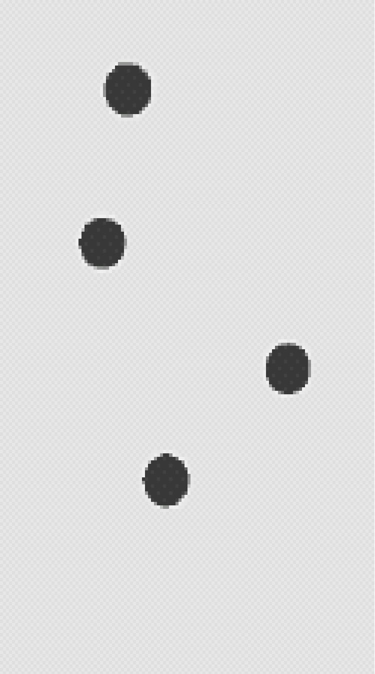
- Flocculation and rate of settling is a function of particle concentration
- Particles remain in a fixed position relative to eachother, and all settle at a constant velocity
- Mass of particles settle as a zone
- Zones of different particle concentrations (different layers) may develop as a result of particles with different settling velocities
- State of compression is reached at the bottom.

Settling Regimes
Type – IV – Compression settling

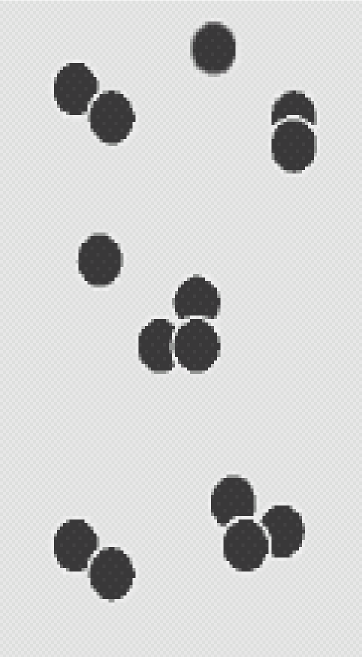
Type IV settling, settling of particles that are of such a high concentration that the particles touch eachother and settling can occur only by compression of the compacting mass.

- Compression settling occurs at lower depths of the sedimentation tanks
- Rate of compression is dependent on time and the force caused by the weight of solids above the compression layer.
- Both dicrete and flocculant particles may settle by zone ot compression settling
- However, flocculent particles are the most common type encountered.

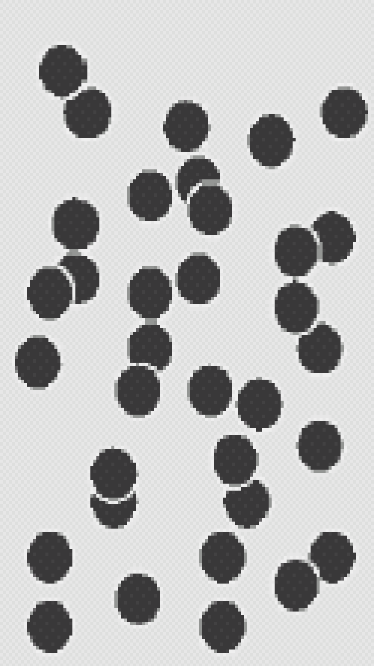
Settling Types



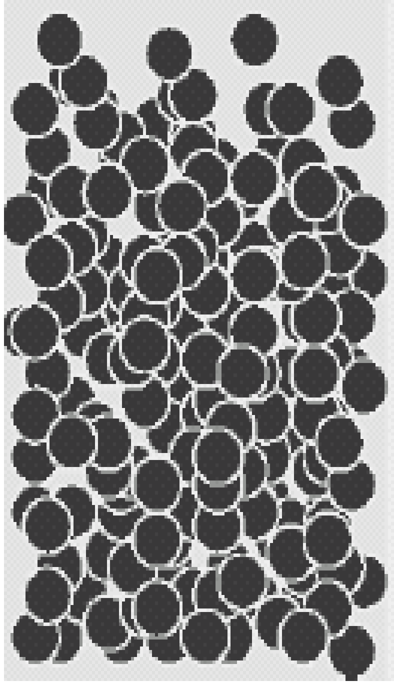
Discrete settling



Flocculent settling



Hindered settling



Compression settling

Sedimentation Theory
Type – I – Discrete particle settling

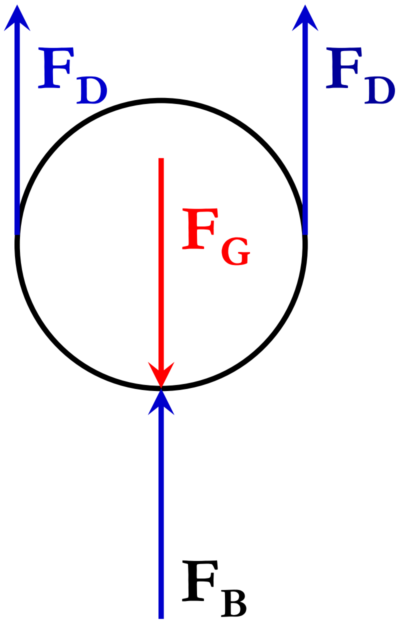
- Settling of discrete particles in low concentration, with flocculation and other interparticle effects being negligible
- When particles settle discretely, the particle settling velocity can be calculated and the basins can be designed to remove a sepcific particle size → **STOKE's LAW**
- Particle falling in a fluid accelerates until the frictional resistance, or drag on the particle is equal to the gravitational force of the particle. → **Isaac NEWTON**
- Settling velocity remains constant → **Terminal velocity**

Sedimentation Theory
Type – I – Discrete particle settling

- Terminal settling velocity depends on various fluid and particle properties.
- To calculate the <u>settling velocity</u> →
    - **Particle shape** is assumed to be **spherical**
    - **Particles** that are **not spherical →** can be expressed in terms of a **sphere of an equal volume.**

Sedimentation Theory
Type – I – Discrete particle settling

- The general equation for terminal settling of a single particle is derived by equating the forces upon a particle



Forces acting on a free falling particle in a fluid

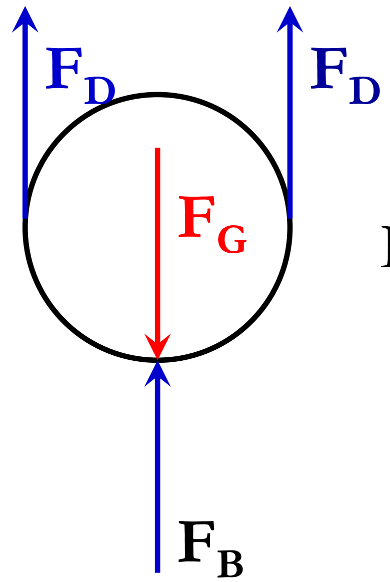
F_D: Drag Force

F_B: Buoyancy Force

F_G: Gravitational Force

$$\boxed{F_D=F_G-F_B}$$

Sedimentation Theory
Type – I – Discrete particle settling



$$\boxed{F_D = F_G - F_B}$$

Drag Force on a particle traveling in a resistant fluid:

$$\boxed{F_D = \frac{C_D \upsilon^2 \rho A}{2}}$$

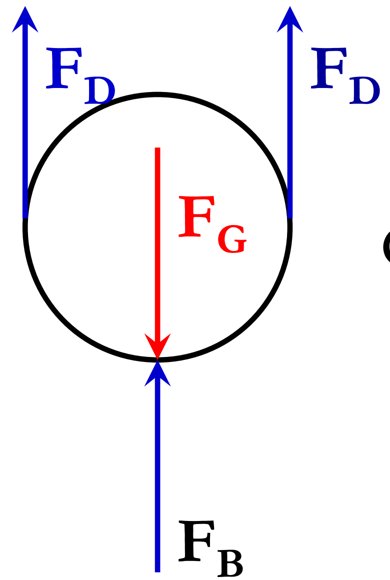
C_D : Drag coefficient

υ : settling velocity

ρ : density of fluid

A : projected area of particle in the direction of flow

Sedimentation Theory
Type – I – Discrete particle settling



$$\boxed{F_D = F_G - F_B}$$

Gravitational Force:

$$\boxed{F_G = \rho_p g \forall}$$

ρ_p : density of particle
g : gravitational accelaration
$\forall$: volume of particle

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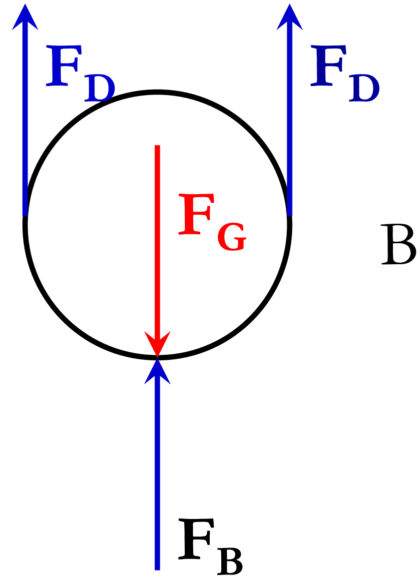
Sedimentation Theory
Type – I – Discrete particle settling



$$\boxed{F_D=F_G-F_B}$$

Buoyancy Force:

$$\boxed{F_B = \rho g \forall}$$

ρ : density of fluid

g : gravitational accelaration

$\forall$: volume of particle

Sedimentation Theory
Type – I – Discrete particle settling

$$\boxed{F_D = F_G - F_B}$$

$$F_D = \frac{C_D v^2 \rho A}{2} \qquad F_B = \rho g \forall \qquad F_G = \rho_p g \forall$$

$$\frac{C_D v_t^2 \rho A}{2} = \rho_p g \forall - \rho g \forall$$

$$\frac{C_D v_t^2 \rho A}{2} = \forall g (\rho_p - \rho)$$

$$\boxed{v_t = \sqrt{\frac{2 \forall g (\rho_p - \rho)}{C_D \rho A}}}$$

Terminal settling velocity of a particle of any shape

Sedimentation Theory
Type – I – Discrete particle settling

Terminal settling velocity of a particle of a solid spherical particle (d: diameter of a sphere):

$$\forall = \frac{4}{3}\pi r^3$$

$$A = \pi r^2$$

$$\boxed{v_t = \sqrt{\frac{4gd(\rho_p - \rho)}{3C_D\rho}}}$$

Stoke's equation

Sedimentation Theory
Type – I – Discrete particle settling

- Terminal velocity (v_t) is independent of horizontal and vertical movement of the liquid
- Drag coefficient depends on the nature of the flow around the particle.
- Nature of the flow can be described by the Reynolds number (Re)

$$Re = \frac{\rho \upsilon d}{\mu}$$

ν: Velocity of particle relative to fluid

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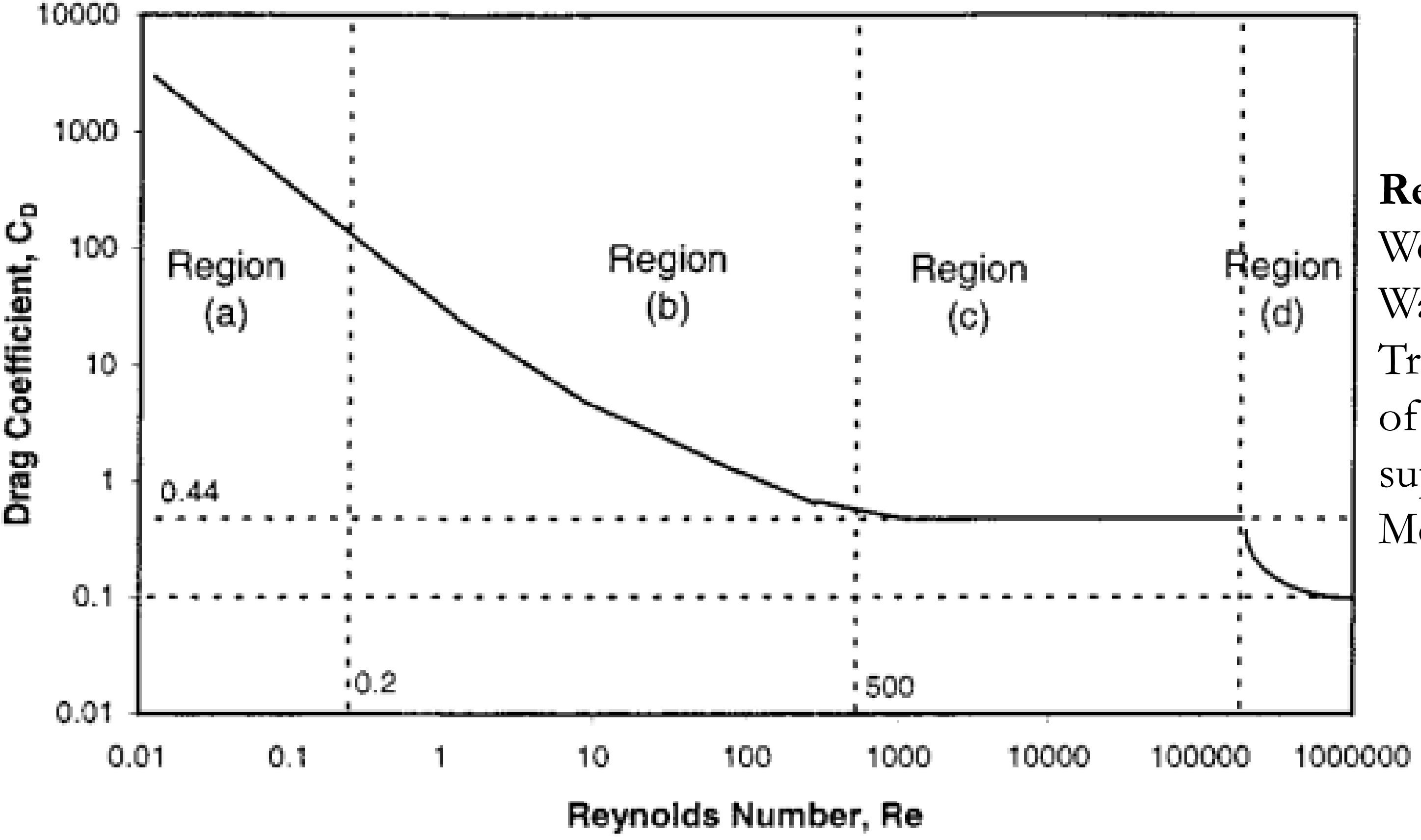
Sedimentation Theory
Type – I – Discrete particle settling

- Value of C_D decreases as the value of Re increases



Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

FIGURE 7.6 Variation of drag coefficient, C_D, with Reynolds number, Re, for single-particle sedimentation.

Sedimentation Theory
Type – I – Discrete particle settling

- $10^{-4} < Re < 0.2$ → Laminar Flow

$$C_D = \frac{24}{Re}$$

- Stoke's equation for laminar flow conditions becomes

$$\boxed{v_t = \frac{g(\rho_p - \rho)d^2}{18\mu}}$$

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Sedimentation Theory
Type – I – Discrete particle settling

- $0.2 < Re < 500$ to 1000 → Transition zone

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

- It is very difficult to represent the transition zone
- However, for many particles found in natural waters, the density and diameter yield Re numbers around the transition zone.

Sedimentation Theory
Type – I – Discrete particle settling

- $500\text{-}1000 < Re < 2\times10^5$ → Turbulent flow zone

$$C_D = 0.44$$

- Stoke's equation becomes

$$\boxed{v_t = 1.74\sqrt{\frac{g(\rho_p - \rho)d}{\rho}}}$$

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Sedimentation Theory
Type – I – Discrete particle settling

- $Re > 2x10^5$ → Boundary – layer turbulance
- Drag force decreases considerably with the development of turbulance at the surface of the particle

$$C_D = 0.1$$

- This region is unlikely to be encountered in the sedimentation in water treatment

Sedimentation Theory
Type – I – Discrete particle settling

Particle Shape

- Settling velocity of a nonspherical particle is lower than the spherical particle having same density and volume
- A simple shape factor (Θ) is determined

$$C_D = \frac{24}{Re}\Theta$$

- Typical values for shape factor

Particle Type	**Shape Factor**
Sand	2.0
Coal	2.25
Gypsum	4.0
Graphite flakes	22

Settlement in Tanks

- Particles whose terminal settling velocity exceeds the liquid upflow velocity will be retained

$$\nu_t > \frac{Q}{A}$$

- In an horizontal flow rectangular settling tanks, settling particles have both <u>horizontal</u> and <u>rectangular</u> parts.

$$L = \frac{tQ}{HW}$$

L: Horizontal distance travelled
H: Depth of water
W: Width of tank
t: time of travel

- Vertical distance travelled

$$h=\nu t$$

Settlement in Tanks

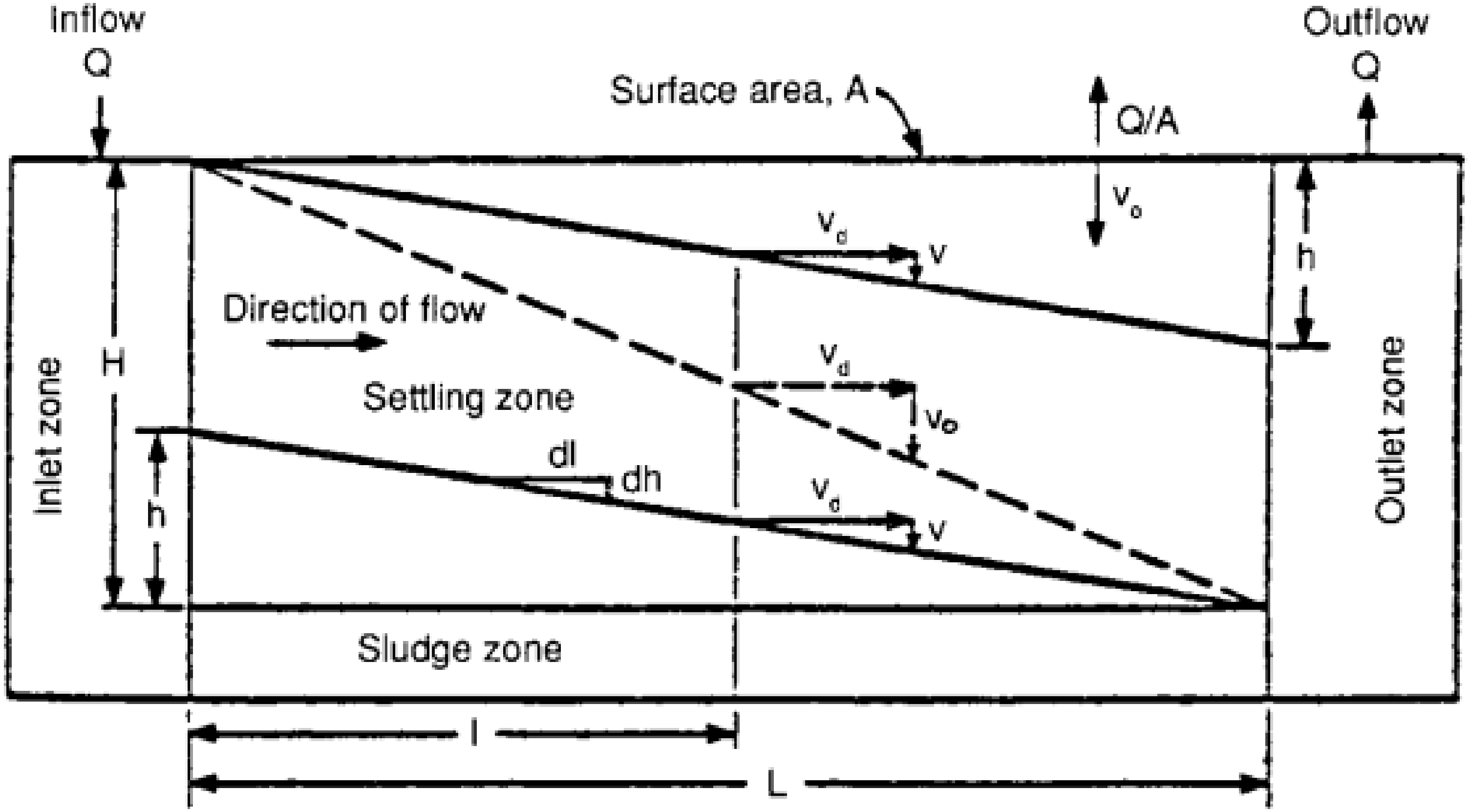


FIGURE 7.7 Horizontal and vertical components of settling velocity. (*Source:* Fair, Geyer, and Okun, 1971.)

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

Settlement in Tanks

- Settling time of for a particle that has entered the tank at a given level, h

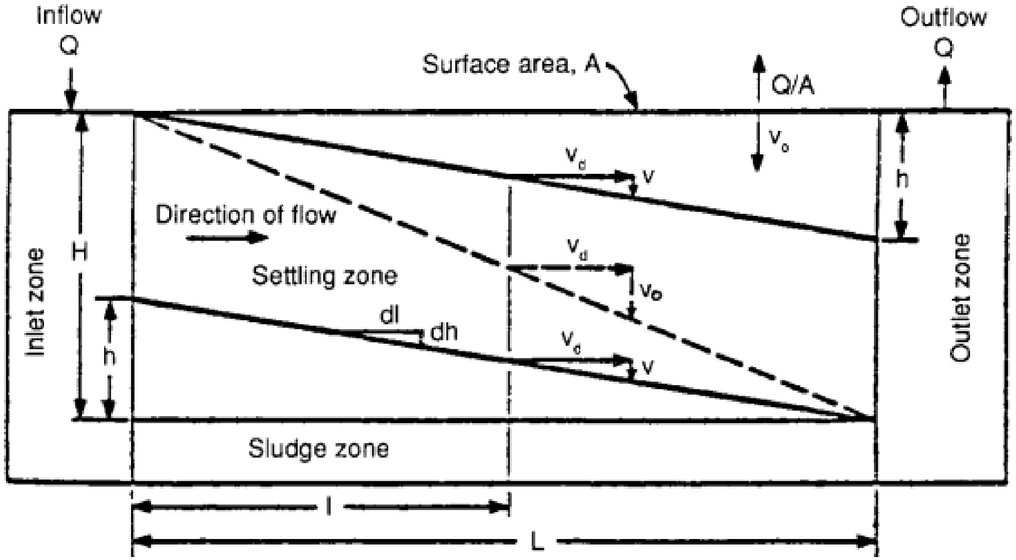
$$t = \frac{h}{\nu}$$

- Substitute into

$$L = \frac{tQ}{HW}$$

$$L = \frac{hQ}{\nu HW}$$

$$\nu = \frac{hQ}{LHW}$$



Settlement in Tanks

- If all particles with a settling velocity of ν are allowed to settle, then h = H and consequently this case is defined as **surface-loading** or **overflow rate** of the ideal tank

$$\nu = \frac{hQ}{LHW}$$ becomes $$\nu_c = \frac{Q}{L_c W}$$

$$\boxed{\nu_c = \frac{Q}{A}}$$

•Critical velocity
•Overflow velocity
•Surface loading

- L_c is the length of tank which settlement ideally takes place

Settlement in Tanks

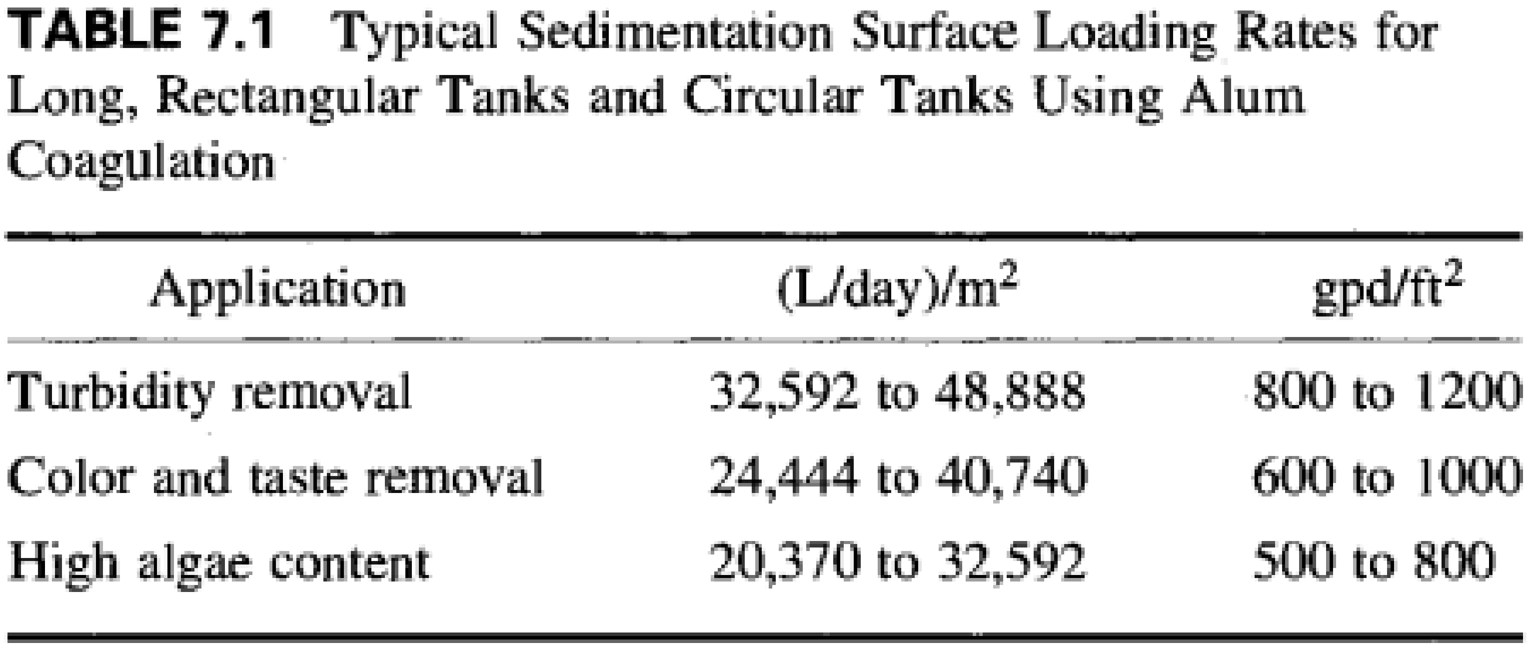


TABLE 7.1 Typical Sedimentation Surface Loading Rates for Long, Rectangular Tanks and Circular Tanks Using Alum Coagulation

Application	(L/day)/m^2	gpd/ft^2
Turbidity removal	32,592 to 48,888	800 to 1200
Color and taste removal	24,444 to 40,740	600 to 1000
High algae content	20,370 to 32,592	500 to 800

Ref: American Water Works Association. Water Treatment Plan Desing 4th ed. McGraw Hill, 1998

Settlement in Tanks

- All the particles with settling velocity greater than critical velocity are **removed**.
- Particles with settling velocity less than critical velocity are removed in proportion to the ratio $\mathbf{\nu:\nu_c}$
- Particles with settling velocity $\mathbf{\nu^1 < \nu_c}$ need a tank length $\mathbf{L^1 > L}$
- Fraction removed can be calculated by;

$$\frac{\nu^1}{\nu_c} = \frac{L_c}{L^1}$$

Settlement in Tanks

- Settling efficiency for the ideal condition is independent on the height (H) of the tank **(Hazen's Law)**

$$v_c = \frac{Q}{L_c W}$$

- In reality, depth is important because it can affect the stability

Particle Settling Efficiency

- Variation in particle size and density produce a distribution of settling velocities
- Settling velocity distribution can be determined bu
  - Settling column tests
  - Sieve analysis and hydrometer tests

Particle Settling Efficiency

- Settling column tests produce information on
  - x_c (fraction of particles with settling velocities less than or equal to critical velocity (ν_c)
  - Critical velocity (ν_c)

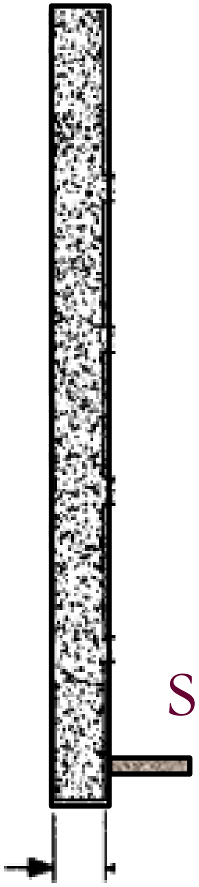
$$F_t = (1 - x_c) + \int_0^x \frac{\nu}{\nu_c} dx$$

Settling Velocity Analysis Curve for Type I

- Settling column depth=2 – 3 m
- Settling column diameter=200mm (at least 100 times the largest particle size)
- Initial suspended solids concentration is noted
- Sample is mixed completely to ensure homogenous mixture
- Suspension is allowed to settle quiescently
- Samples are drawn at time intervals from a sampling port (one port)—height is not important

$$\nu_i = \frac{h}{t_i}$$

Settling Velocity Analysis Curve for Type I



Sampling port

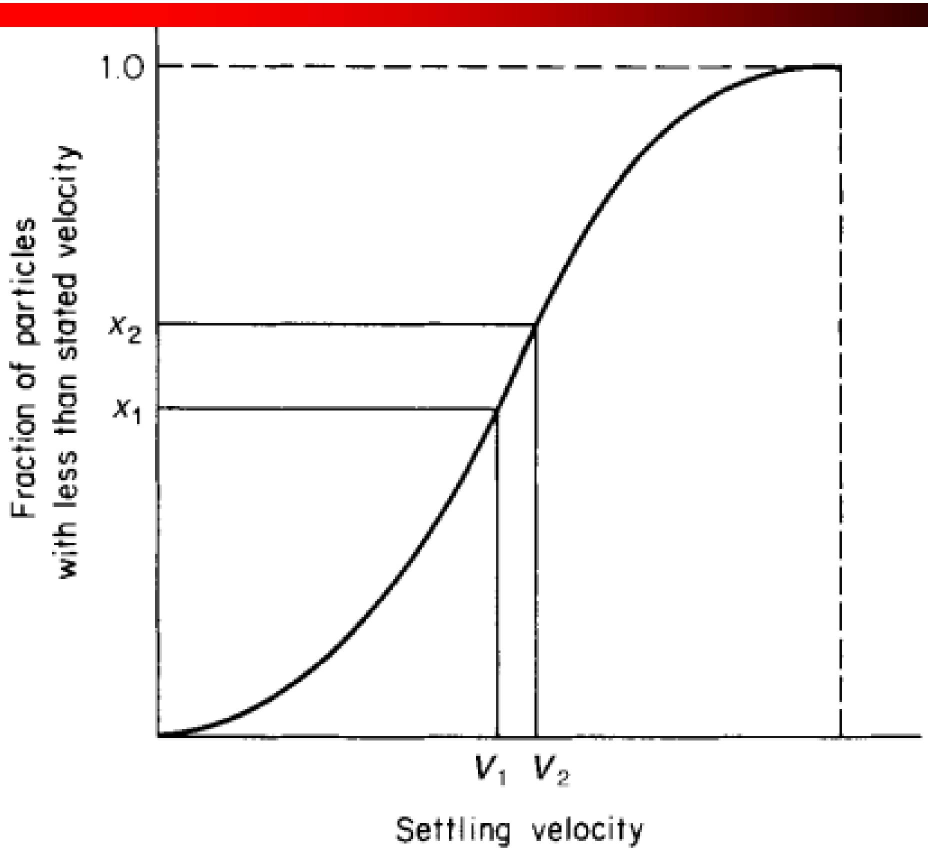


FIGURE 7.8 Settling-velocity analysis curve for discrete particles. (*Source:* Camp, 1936; Metcalf and Eddy, Engineers, 1991. *Wastewater Engineering*, 3rd ed. New York: McGraw-Hill. Reproduced by permission of the McGraw-Hill Companies.)

Ref: American Water Works Association. Water Quality and Treatment: A handbook of community water supplies. 5th ed. McGraw Hill, 1999

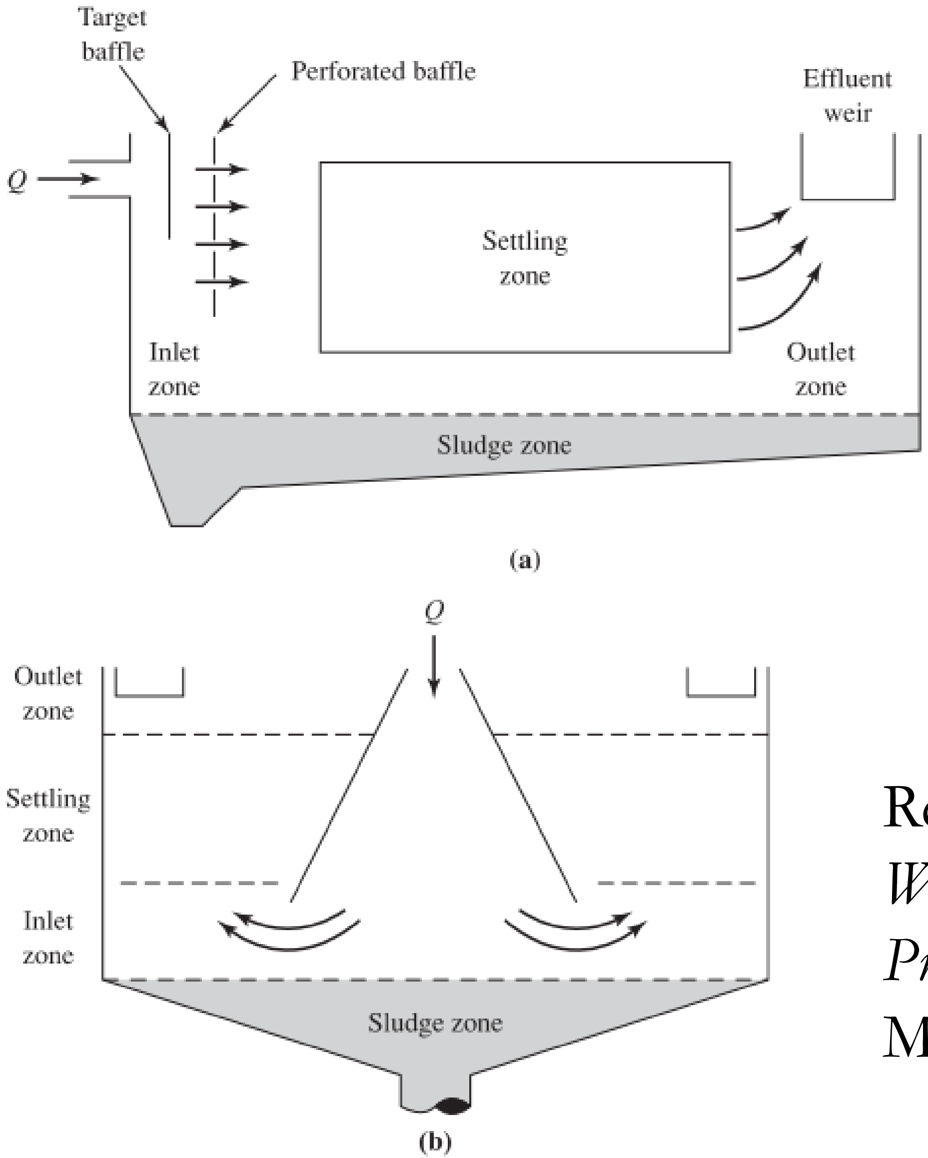


FIGURE 10-4
Zones of sedimentation: (*a*) horizontal flow clarifier; (*b*) upflow clarifier.
(*Source:* Davis and Cornwell, 2008.)

Ref: Davis M.L. *Water and Wastewater Treatment: Design Principles and Practice*. 2010. McGrawHill

Sieve Analysis for Type I Settling

- Sieve analysis is a simple and cheap way for the settling velocity analysis
- Samples are shaken in sieves until the retained fraction is constant
- Cumulative distribution curve is drawn