Physical unit processes I

Physical unit processes

- Physical unit processes used in wastewater treatment
  - Screening
  - Coarse solids reduction
  - Flow equalization
  - Mixing and flocculation
  - Grit removal
  - Sedimentation (primary/secondary)
  - Flotation
  - Aeration
  - Depth filtration
  - Membrane filtration
  - VOC removal
  - Air stripping
  - Carbon adsorption

Today’s class

Physical processes used for solid/liquid separation

- Simple preliminary treatment methods: screens
- Particle settling
  - Fundamentals: settling types & theory
  - Particle removal in sedimentation basins
  - Practical application: grit removal & primary sedimentation

Screen

- A device with openings, generally of uniform size, used to retain solids found in the wastewater treatment plant influent or in the combined sewer overflows

- Goal: to remove coarse materials that could i) damage subsequent process equipment, ii) reduce overall treatment process reliability and effectiveness, or iii) contaminate waterway

- Classification (by opening size)
  - Coarse screens: >6 mm
  - Fine screens: 0.5-6 mm

- Major issue: **headloss** (more significant for smaller opening size)

Coarse screens (bar racks)

- Used to protect pumps, valves, pipelines, and other apparatus from damage or clogging by rags and large objects
- Manually-cleaned (old and/or small plants) vs. mechanically cleaned screens

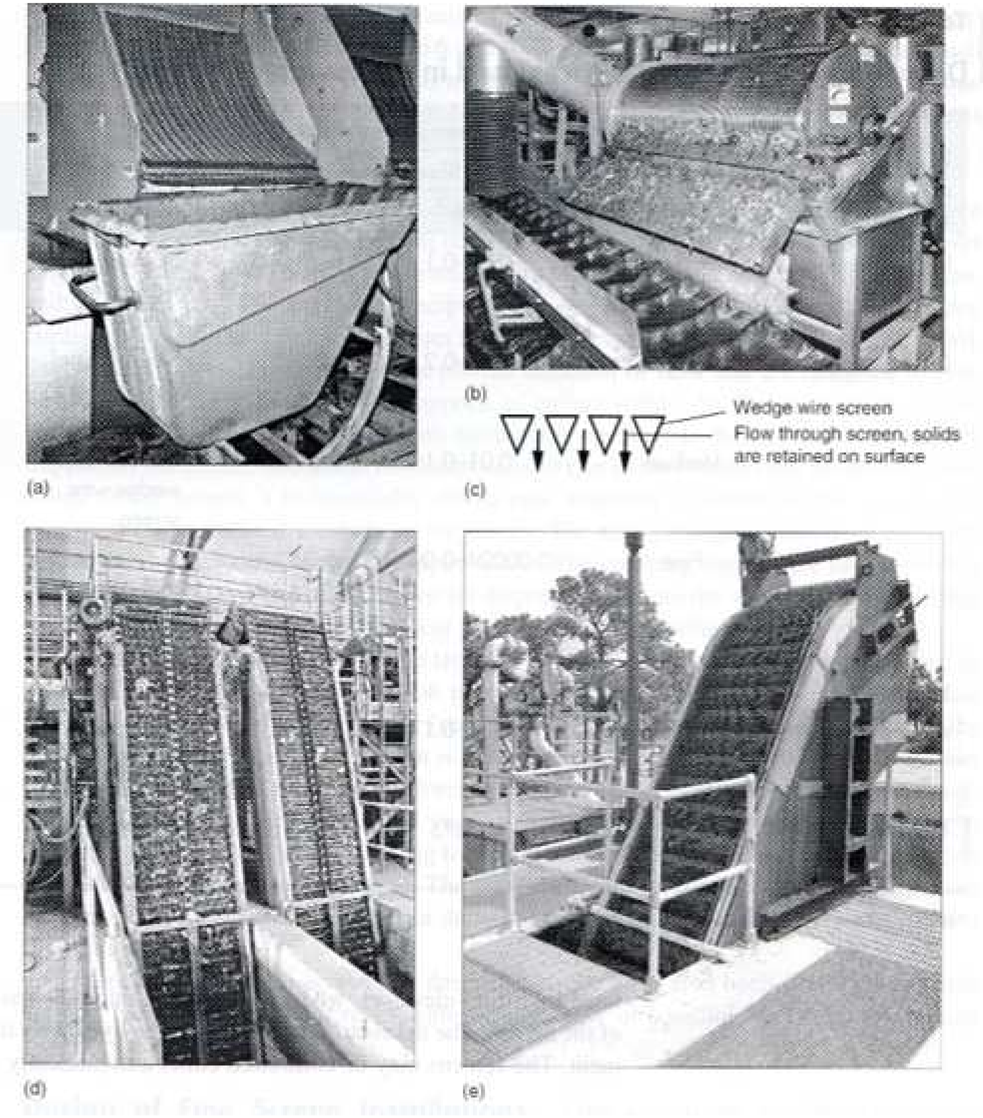
Manually-cleaned bar screen

Mechanically-cleaned bar screen

Fine screens – uses

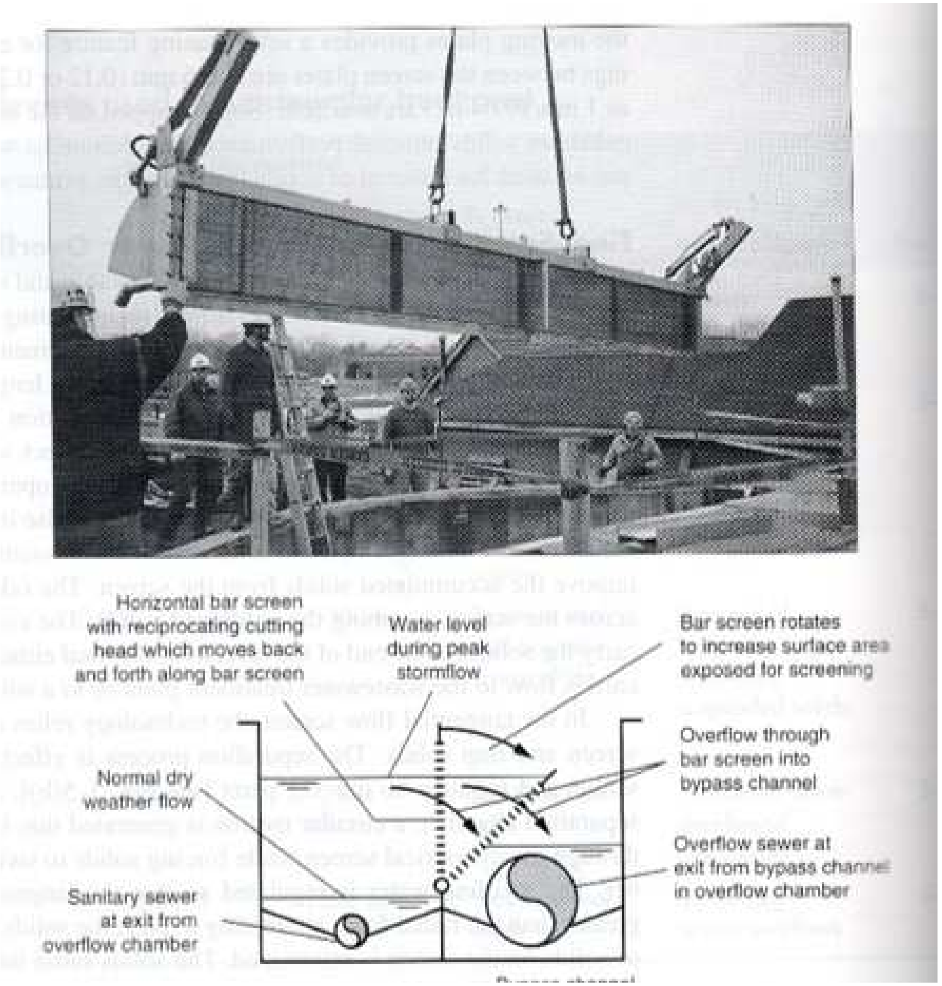
- Additional preliminary treatment following coarse bar screens
- Primary treatment as a substitute for primary clarifiers
- CSO treatment
- Non-point source pollution (surface runoff) control

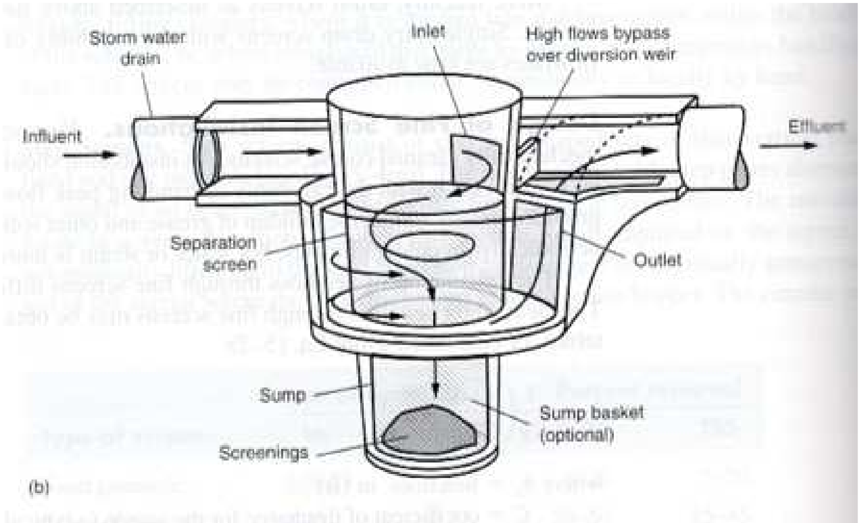
Fine screens – examples



Typical fine screens for preliminary & primary treatment: (a) Static wedge wire; (b) wedge-wire drum screen; (c) section through wedge wire screen; (d) traveling band screen; and (e) step screen

Fine screens – examples





Devices used for the screening of CSOs:
(a) view of horizontal screen during installation and its operating mechanism;
(b) tangential flow device with separation screen

Screenings

- **Materials retained on screens**
- **Characteristics**
  - Screenings retained on coarse screens
    - Mainly inert materials (rocks, branches, pieces of lumber, leaves, paper, tree roots, plastics, rags, …)
    - Some accumulation of oil and grease and organic matter may occur

  - Screenings retained on fine screens
    - Small rags, paper, plastic materials, razor blades, grit, undecomposed food waste, feces, …
    - Slightly lower specific weight, higher moisture content, and high organic matter content than screenings on coarse screens
    - Biodegradable organic matter putrefies to generate odor, so additional care is required

Screenings – handling, processing, disposal

- Screening handling and processing
  - Major goal: volume reduction
  - Dewatering and compaction

- Screening disposal
  1) Removal by moving to disposal areas (landfill) – most common
  2) Burial on the plant site (only for small plants)
  3) Incineration
  4) Discharge to grinders or macerators and return to the wastewater

Particle settling fundamentals – Types of settling

- Class I settling – **Discrete particle settling**
  - At low solids concentration
  - Particles settle as individual entities, no significant interaction with neighboring particles
  - ex) removal of grit and sand particles

- Class II settling – **Flocculent settling**
  - Particles grow as they settle
  - Settling velocity increases as particles grow in size
  - ex) primary settling & upper part of secondary clarifier

Types of settling (cont’d)

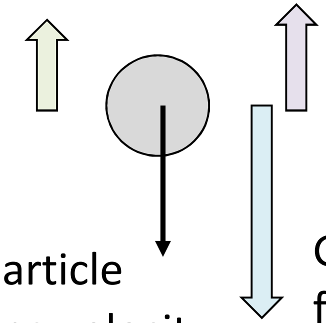
- Class III settling – **zone (or hindered) settling**
  - At higher solids concentration than Class I or II – interparticle forces are sufficient to hinder the settling of neighboring particles
  - Mass of particles settles as a unit; a solid-liquid interface develops at the top
  - ex) major part of secondary clarifier

- Class IV settling – **compression settling**
  - When solids concentration is sufficiently high – a structure is formed
  - Settling occurs only by compression of the structure by the weight of particles
  - Observed phenomenon is more like squeezing of water out of the structure
  - ex) bottom of deep secondary clarifier, sludge-thickening facilities

Particle settling theory – discrete particles

- Force applied to a settling particle

  (Assumption: spherical particle)



Drag force, F_D

Buoyancy force, F_B

v_p: particle settling velocity (m/s)

Gravitational force due to particle mass, F_M

$$F_B = \rho_w g V_p$$

ρ_w = water density (kg/m^3)

g = gravity acceleration (9.81 m/s^2)

V_p = particle volume (m^3)

$$F_M = \rho_p g V_p$$

ρ_p = particle density (kg/m^3)

$$F_D = \frac{C_D A_p \rho_w {v_p}^2}{2}$$

C_d = drag coefficient (unitless)

A_p = cross-sectional area of particles in the direction of flow (m^2)

Particle terminal velocity

- The terminal velocity of particle is achieved when the three forces are balanced:

$$F_M = F_B + F_D$$

⇨

$$\boxed{v_{p(t)} = \sqrt{\frac{4g}{3C_D}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p}}$$

$v_{p(t)}$= *particle terminal velocity (m/s)*

d_p= *particle diameter (m)*

Drag coefficient, C_D

- Divide the flow regime into three regions – laminar, transitional and turbulent – based on Reynolds number

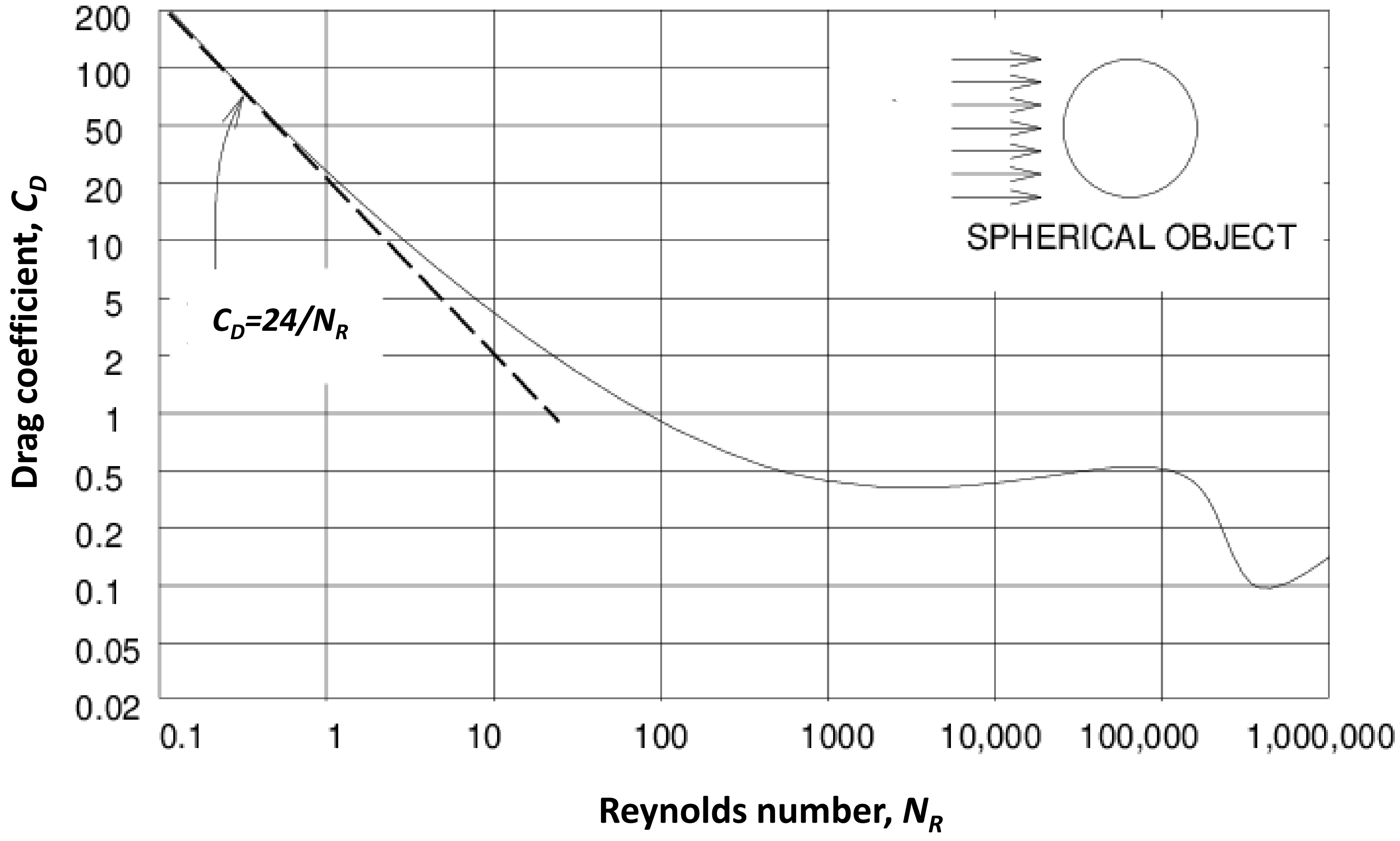
- **Reynolds number, N_R**
  - A dimensionless number to describe the relative amount of impelling force to viscous force
  - High N_R → more turbulence

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

μ = dynamic viscosity of water [N-s/m^2]

ν = kinematic viscosity of water [m^2/s]

Correlation between N_R and C_D



Correlation between N_R and C_D

1) Laminar region: $N_R < 1$

$$C_D = \frac{24}{N_R} \quad \Rightarrow \quad \boxed{v_{p(t)} = \frac{g(\rho_p - \rho_w){d_p}^2}{18\mu}}$$

"Stokes' Law"

2) Transitional region: $1 < N_R < 2000$

Use following eq. for approximation of C_D:

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

3) Turbulent region: $N_R > 2000$

Assume $C_D \approx 0.4$

Accounting for deviation from a sphere

- For non-spherical particles
  - Use "sphericity" to account for shape variation

$$\Psi = \frac{(A/V)_{sphere}}{(A/V)_{particle}}$$

Ψ = *sphericity*

$\Psi \approx 0.8$ for sharp, angular sand

$\Psi \approx 0.94$ for worn sand

  - Apply "effective spherical diameter" in the equations

$$d_p{}' = \Psi \cdot d_p$$

$d_p{}'$ = *effective spherical diameter*

d_p = *characteristic length*

[Typical sphericity for different shapes]

Particle	Sphericity	Characteristic length
Sphere	1.00	Diameter
Cube	0.806	Height
Cylinder (h=10r)	0.691	Length
Disc (h=r/10)	0.323	Diameter

Particle settling velocity

Q: Determine the terminal settling velocity of a spherical bacterial floc having a density of 1.050×10^3 kg/m^3 when the floc size is i) 10^{-4} m and ii) 10^{-3} m, respectively. Assume the flocs are spherical. Assume the temperature is 20°C. ($\rho_w = 0.998 \times 10^3$ kg/m^3 and $\mu = 1.002 \times 10^{-3}$ N-s/m^2)

Particle settling velocity

i) 10^{-4} m = 0.1 mm

a) Determine $v_{p(t)}$ using Stoke's law

$$v_{p(t)} = \frac{g\left(\rho_p - \rho_w\right){d_p}^2}{18\mu} = \frac{9.81\ m/s^2 \cdot (1.050 - 0.998) \times 10^3\ kg/m^3 \cdot (10^{-4}\ m)^2}{18 \cdot (1.002 \times 10^{-3}\ N - s/m^2)}$$

$$= 2.83 \times 10^{-4}\ m/s$$

b) Check N_R

$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{(2.83 \times 10^{-4}\ m/s) \cdot (10^{-4}\ m) \cdot (0.998 \times 10^3\ kg/m^3)}{1.002 \times 10^{-3}\ N - s/m^2} = 0.028$$

⇨ *N_R<1, so Stoke's law applies as assumed.*

So, $\underline{\boldsymbol{v_{p(t)} = 2.83 \times 10^{-4}\ m/s}}$

Particle settling velocity

ii) 10^{-3} m = 1 mm

a) Determine $v_{p(t)}$ using Stoke's law

$$v_{p(t)} = \frac{g\left(\rho_p - \rho_w\right){d_p}^2}{18\mu} = \frac{9.81\ m/s^2 \cdot (1.050 - 0.998) \times 10^3\ kg/m^3 \cdot (10^{-3}\ m)^2}{18 \cdot (1.002 \times 10^{-3}\ N - s/m^2)}$$

$$= 2.83 \times 10^{-2}\ m/s$$

b) Check N_R

$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{(2.83 \times 10^{-2}\ m/s) \cdot (10^{-3}\ m) \cdot (0.998 \times 10^3\ kg/m^3)}{1.002 \times 10^{-3}\ N - s/m^2} = 28$$

⇨ *N_R>1, so Stoke's law cannot be applied.*

Particle settling velocity

c) Use the N_R *calculated and apply the transient region solution*

$$C_D = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{28} + \frac{3}{\sqrt{28}} = 1.76$$

$$v_{p(t)} = \sqrt{\frac{4g}{3C_D}\left(\frac{\rho_p - \rho_w}{\rho_w}\right)d_p} = \sqrt{\frac{4 \cdot 9.81\ m/s^2}{3 \cdot 1.76}\left(\frac{1.050 - 0.998}{0.998}\right) \cdot 10^{-3}\ m}$$

$$= 1.97 \times 10^{-2}\ m/s$$

The result does not match with the $v_{p(t)}$ *used to get* N_R *(Stoke's solution – 2.83 x* 10^{-2} *m/s)*

Have to assume a smaller $v_{p(t)}$

Particle settling velocity

d) Assume $v_{p(t)}$, calculate N$_R$, then calculate C$_D$, then calculate $v_{p(t)}$ until assumed $v_{p(t)}$ = calculated $v_{p(t)}$

Eventually, if you assume $v_{p(t)} = 1.7 \times 10^{-2}\ m/s$,

$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{(1.7 \times 10^{-2}\ m/s) \cdot (10^{-3}\ m) \cdot (0.998 \times 10^3\ kg/m^3)}{1.002 \times 10^{-3}\ N - s/m^2} = 16.9$$

$$C_D = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{16.9} + \frac{3}{\sqrt{16.9}} = 2.49$$

$$v_{p(t)} = \sqrt{\frac{4g}{3C_D}\left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} = \sqrt{\frac{4 \cdot 9.81\ m/s^2}{3 \cdot 2.49}\left(\frac{1.050 - 0.998}{0.998}\right) \cdot 10^{-3}\ m}$$

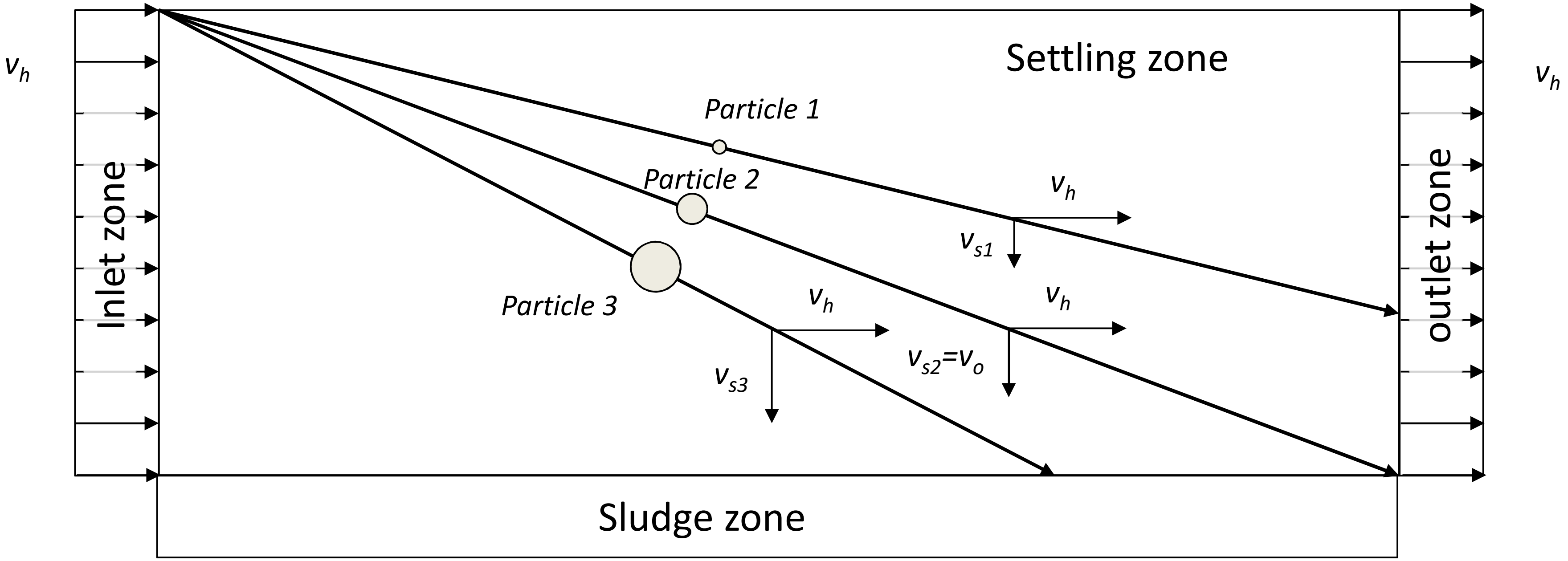
$$= 1.65 \times 10^{-2}\ m/s$$ *(close to the assumption)*

So, $\underline{\boldsymbol{v_{p(t)} \approx 1.7 \times 10^{-2}\ m/s}}$

You may use computer software (e.g, Excel "find solution" function) to automate the calculation!

Particle removal in sedimentation basins

Assume a rectangular sedimentation basin:



particle 1: $v_{s1} < v_o$ → partial removal

particle 2: $v_{s2} = v_o$ → 100% removal

particle 3: $v_{s3} > v_o$ → 100% removal

Particle removal in sedimentation basins

- Designing sedimentation basins
  - Select a particle with a terminal velocity v_o and design the basin such that the particle can just be 100% removed
    - particles with terminal velocity greater than v_o will be 100% removed
    - particles with terminal velocity smaller than v_o will be partially removed

Overflow rate

From the diagram in the previous slide,

(time for water to flow through the settling zone) [1]

= *(settling zone length,* L*) / (horizontal velocity,* v_h*)*

(time for particle with settling vel. of v_o *entering at the top, to settle)* [2]

= *(settling zone height,* H*) / (settling velocity,* v_o*)*

Equating [1] and [2], $\frac{L}{v_h} = \frac{H}{v_o}$

$$\Rightarrow \boxed{v_o = \frac{Q}{A}}$$

v_o = ***overflow rate*** *(m/s)*

A = surface area of settling zone (m^2)

Particle removal rates

- Removal rate for particles with settling velocity less than v_o

$$X_r = \frac{v_p}{v_o}$$

X_r = fraction removed for particles with settling velocity v_p

- Removal rate for particles with a range of different settling

$$Fraction\ removed = (1 - x_c) + \int_0^{x_c} \frac{v_p(x)}{v_o} dx$$

x = fraction of particles having terminal velocity $v_p(x)$

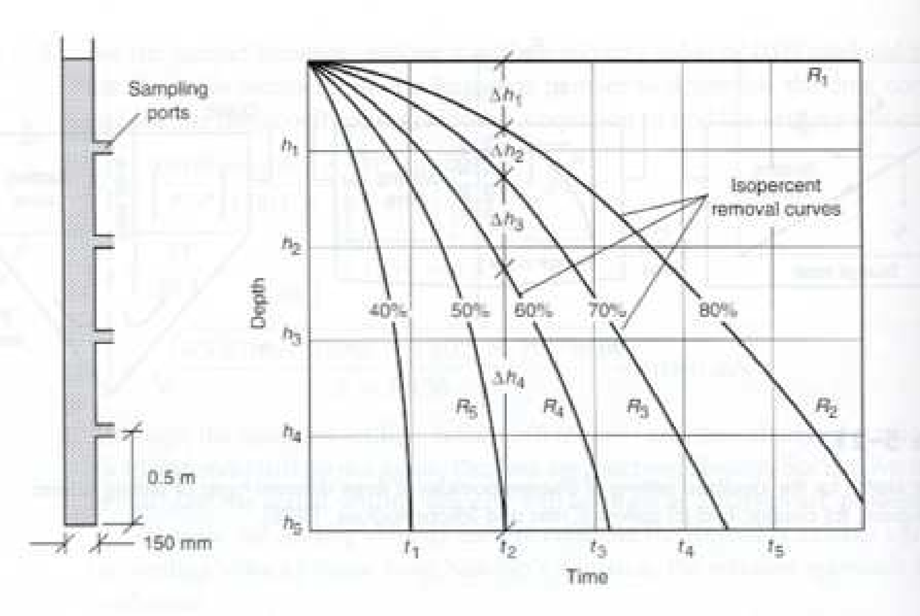
x_c = fraction of particles with $v_p(x)$ smaller than v_o

$1 - x_c$ = fraction of particles with $v_p(x)$ greater than v_o

Estimating settling velocity by experiments

- Issues of theoretical determination of settling velocities
  - A large gradation of particle sizes for wastewater
  - Not easy to estimate terminal settling velocities of a large range of particles using theoretical calculations
  - Flocculant settling occurs in primary sedimentation basins

→ To characterize the wastewater particle settling characteristics, a settling column test is often used and a settling curve is constructed



Particle removal in sedimentation basins

Q: Determine the removal efficiency for a sedimentation basin with an overflow rate of 2 m/h. The settling velocity distribution for the particles in the wastewater is provided below.

Settling velocity, m/h	Number of particles per liter x 10^{-5}
0.0-0.5	30
0.5-1.0	50
1.0-1.5	90
1.5-2.0	110
2.0-2.5	100
2.5-3.0	70
3.0-3.5	30
3.5-4.0	20
total	500

Particle removal in sedimentation basins

Average settling velocity, m/h (A)	# particles/L x 10^{-5} (B)	Fraction removed (C)	# particles removed/L x 10^{-5} (D)
0.0-0.5	30	0.125	3.75
0.5-1.0	50	0.375	18.75
1.0-1.5	90	0.625	56.25
1.5-2.0	110	0.875	96.25
2.0-2.5	100	1.000	100
2.5-3.0	70	1.000	70
3.0-3.5	30	1.000	30
3.5-4.0	20	1.000	23
total	500	1.000	395.00

$(C) = (A) / v_o$ if $(A) < v_o$, $(C) = 1.000$ if $(A) \geq v_o$

$(D) = (C) \times (B)$

Particle removal in sedimentation basins

$$Total\ fraction\ removed = \frac{Total\ \#\ of\ particles\ removed}{Total\ \#\ of\ particles\ in\ the\ influent} \times 100\ (\%)$$

$$= \frac{500 \times 10^5/L}{395 \times 10^5/L} \times 100\ (\%) = 79\%$$

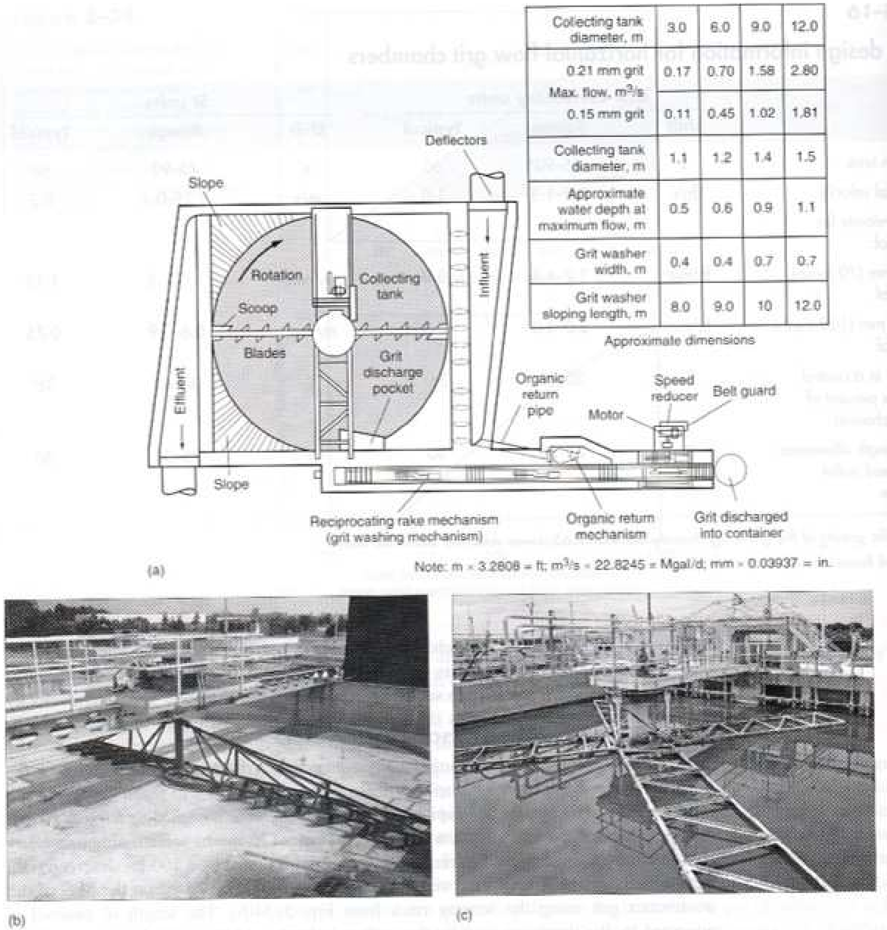
Grit removal

- Grit: sand, gravel, cinders, or other heavy solid materials that have settling velocities substantially greater than those of the organic solids in wastewater

- **Necessity of grit removal**
  - Reduce formation of heavy deposits in reactors, pipelines, and channels
  - Reduce the frequency of digester cleaning caused by excessive accumulations of grit
  - Protect moving mechanical equipment from abrasion and accompanying abnormal wear

Types of grit chambers (1)

- **Horizontal-flow grit chambers**
  - Rectangular horizontal-flow grit chambers: oldest type, velocity-controlled
  - Square horizontal-flow grit chambers



Collecting tank diameter, m	3.0	6.0	9.0	12.0
Max. flow, m^3/s 0.21 mm grit	0.17	0.70	1.58	2.80
Max. flow, m^3/s 0.15 mm grit	0.11	0.45	1.02	1.81
Collecting tank diameter, m	1.1	1.2	1.4	1.5
Approximate water depth at maximum flow, m	0.5	0.6	0.9	1.1
Grit washer width, m	0.4	0.4	0.7	0.7
Grit washer sloping length, m	8.0	9.0	10	12.0

Approximate dimensions

Note: m × 3.2808 = ft; m^3/s × 22.8245 = Mgal/d; mm × 0.03937 = in.

Figure 5-35

Typical square horizontal-flow grit chambers: (a) schematic with design information based on clean grit with a specific gravity of 2.65, (b) view of empty basin. The two rakes are used to move settled grit to the periphery for removal and (c) view of square grit chamber.

Types of grit chambers (2)

- **Aerated grit chambers**
  - Air is introduced along one side of a rectangular tank to create a spiral flow pattern

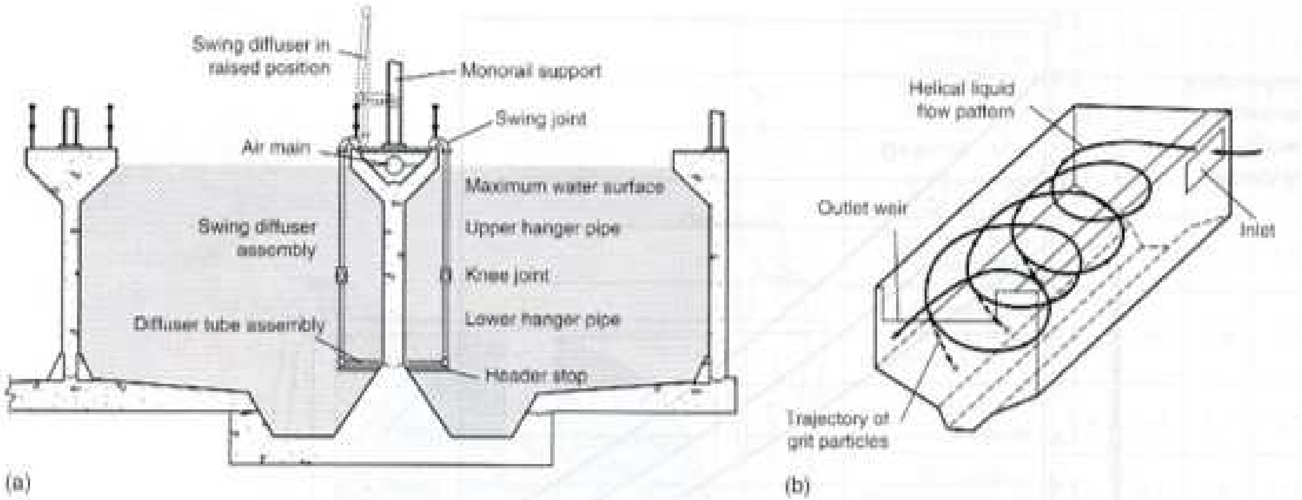


Figure 5-37

Typical aerated grit chamber: (a) cross-section through grit chamber and (b) schematic of helical flow pattern through an aerated grit chamber.

Types of grit chambers (3)

- **Vortex-type grit chambers**
  - Mechanically induced vortex: a rotating turbine impeller enhances the toroidal motion
  - Hydraulically induced vortex: vortex is generated by the flow entering the unit

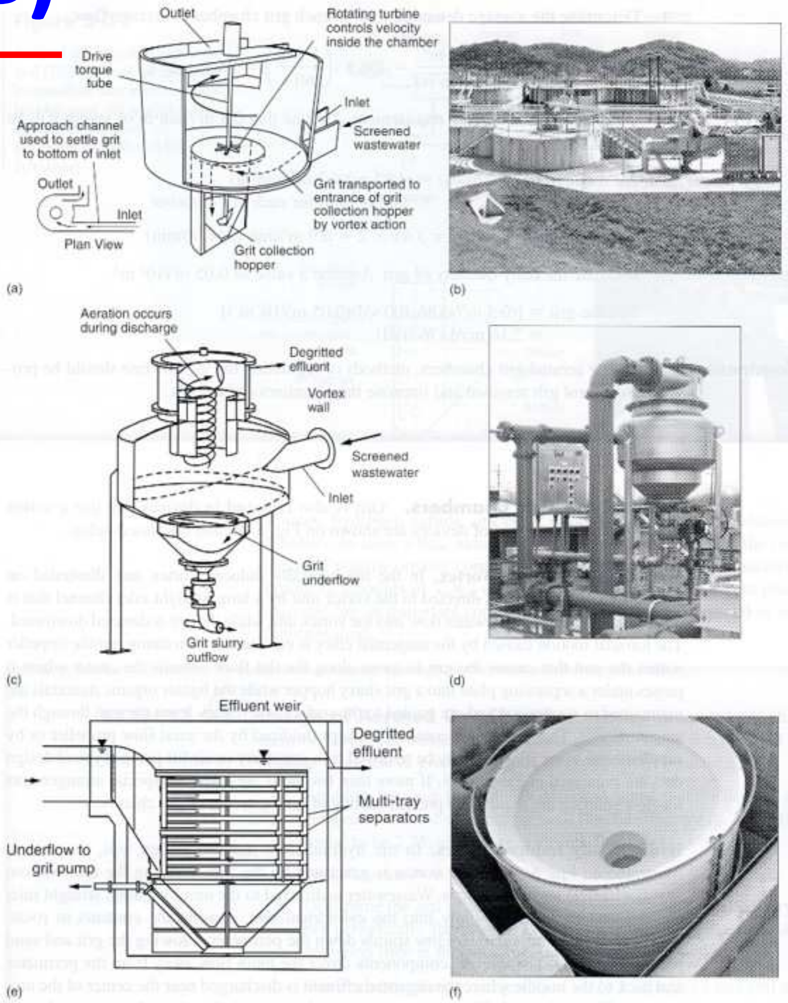


Figure 5-40

Vortex-type grit chambers: (a) schematic Pista® Grit Separator (adapted from Smith & Loveless), (b) view of typical installation (courtesy of Smith & Loveless) (c) schematic of Eutek TeaCup® separator (adapted from Hydro International), (d) view of Eutek TeaCup® separator (courtesy of Hydro International), (e) section through seven-tray Eutek HeadCell® grit separator, and (f) view of Eutek HeadCell of tray grit separator (courtesy of Hydro International).

Primary sedimentation

- **Objective**
  - Remove readily settleable solids and floating material in wastewater
  - Removes 50-70% of SS and 25-40% of BOD

- Sedimentation tanks are also used for…
  - **CSO and stormwater treatment**
    - Apply moderate retention time (10-30 min) to remove a substantial portion of the organic solids in CSO or stormwater before direct discharge
  - **Secondary treatment**
    - Settling of microbial “floc”

Types of primary sedimentation tanks (1)

- **Rectangular tanks**

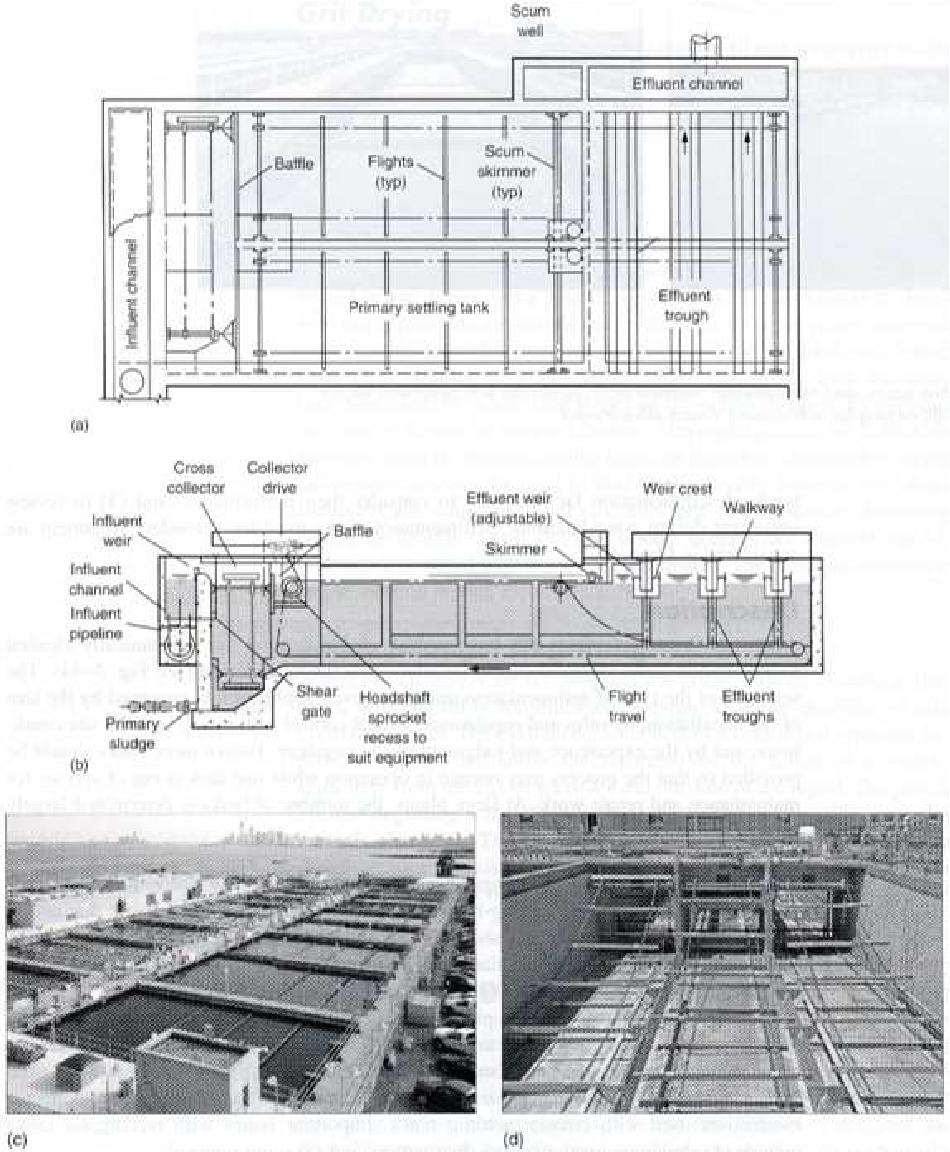


Figure 5–45
Typical rectangular primary sedimentation tank: (a) plan, (b) section, (c) view of large rectangular sedimentation tank with weirs similar to those shown on (b), and (d) view of empty tank with sludge removal mechanism.

Types of primary sedimentation tanks (2)

- **Circular tanks**
  - Both center-feed and periphery-feed types are applicable (center-feed more common)

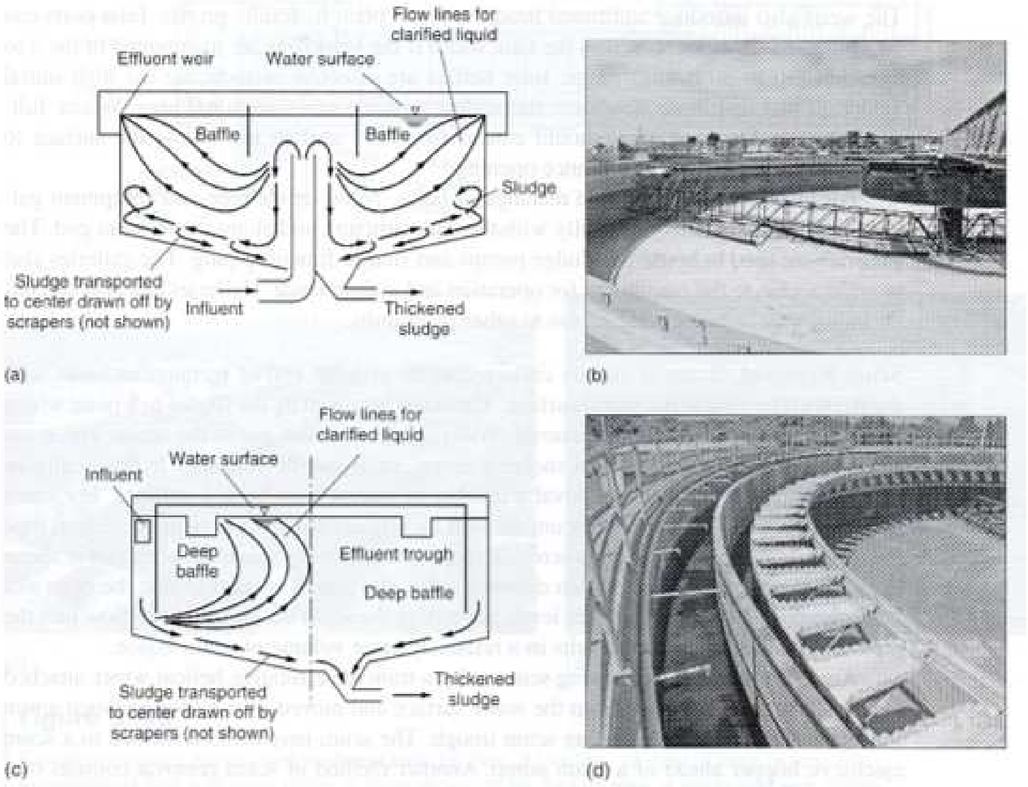


Figure 5-46

Typical circular sedimentation tanks: (a) schematic of center feed, (b) view of center feed unit, (c) schematic of peripheral feed, and (d) view of a peripheral feed unit.

Primary sedimentation - considerations

- Flow distribution
  - Maintain calm, consistent flow with less turbulence esp. at inlet & outlet
  - Minimize vertical flow (minimize sludge resuspension)
  - Examples of inlet designs for rectangular tanks
    - Full-width inlet channels with inlet weirs
    - Inlet channels with submerged ports or orifices
    - Inlet channels with wide gates and slotted baffles

- Sludge removal
  - How to collect settled sludge and where to install pumping facilities

- Scum removal
  - How to collect scum and remove it – manually or automatically?

Primary sedimentation – design considerations

- **Hydraulic retention time**

$$\tau = \frac{V}{Q}$$

τ = HRT (hr)
V = effective tank volume (m^3)
Q = flowrate (m^3/hr)

- **Overflow rate (surface loading rate)**
  - Set based on target particle type and size to be removed (recall the gravity settling theory)

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

v_o = overflow rate (m^3/m^2-d)
A = horizontal tank surface area (m^2)

Primary sedimentation – typical design info.

Item	Unit	Range	Typical
Primary sedimentation tanks followed by secondary treatment			
HRT	h	1.5-2.5	2.0
Overflow rate	$m^3/m^2/d$		
Average flowrate		30-50	40
Peak hourly flowrate		80-120	100
Primary settling with waste activated sludge return			
HRT	h	1.5-2.5	2.0
Overflow rate	$m^3/m^2/d$		
Average flowrate		24-32	28
Peak hourly flowrate		48-70	60

Key references

- Textbook sec 5-1, 5-2, 5-4~5-6

Next class

- Physical processes used for solid/liquid separation
  - Depth filtration
  - Membrane filtration
  - Flotation
- Mixing
  - Fundamentals
  - Types of mixers