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

Physical unit processes I

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

#1

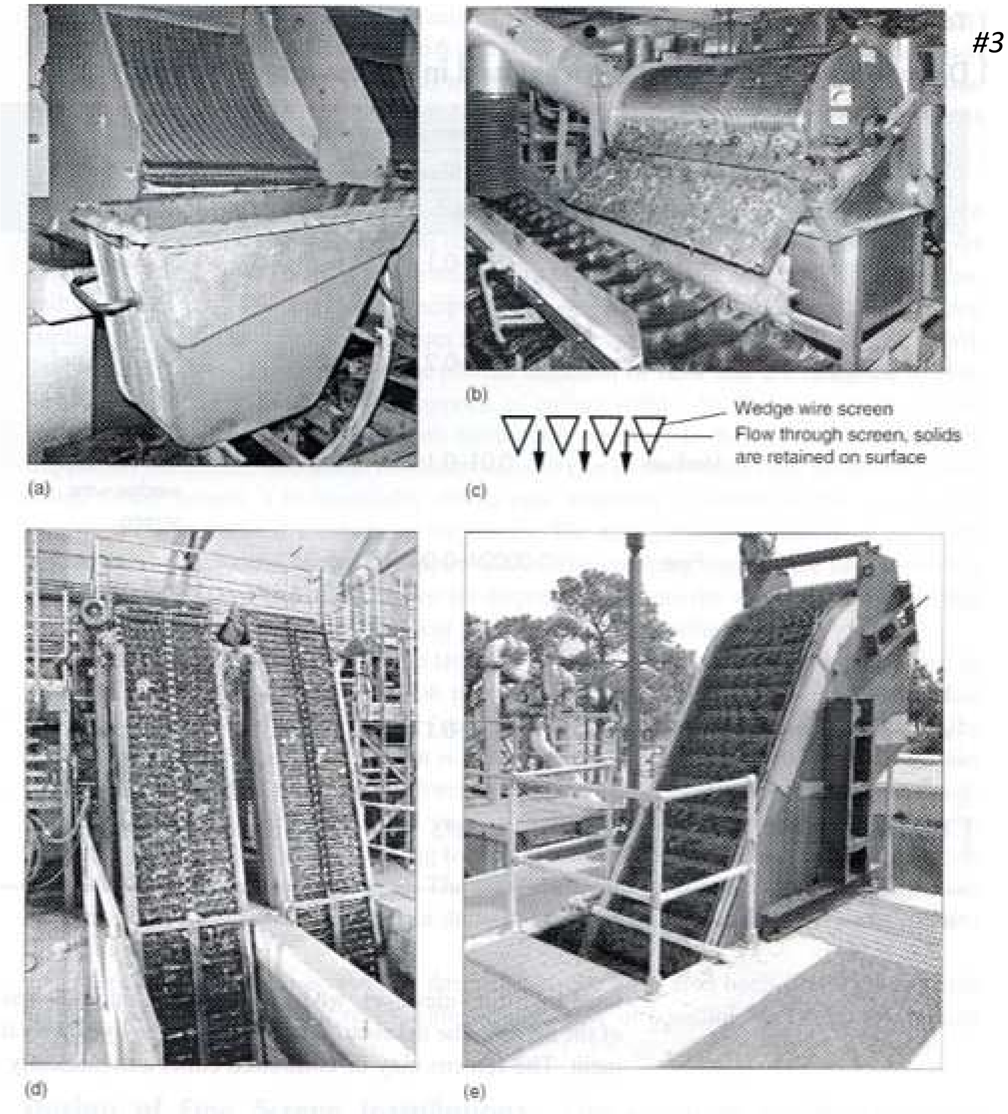
Mechanically-cleaned bar screen

#2

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

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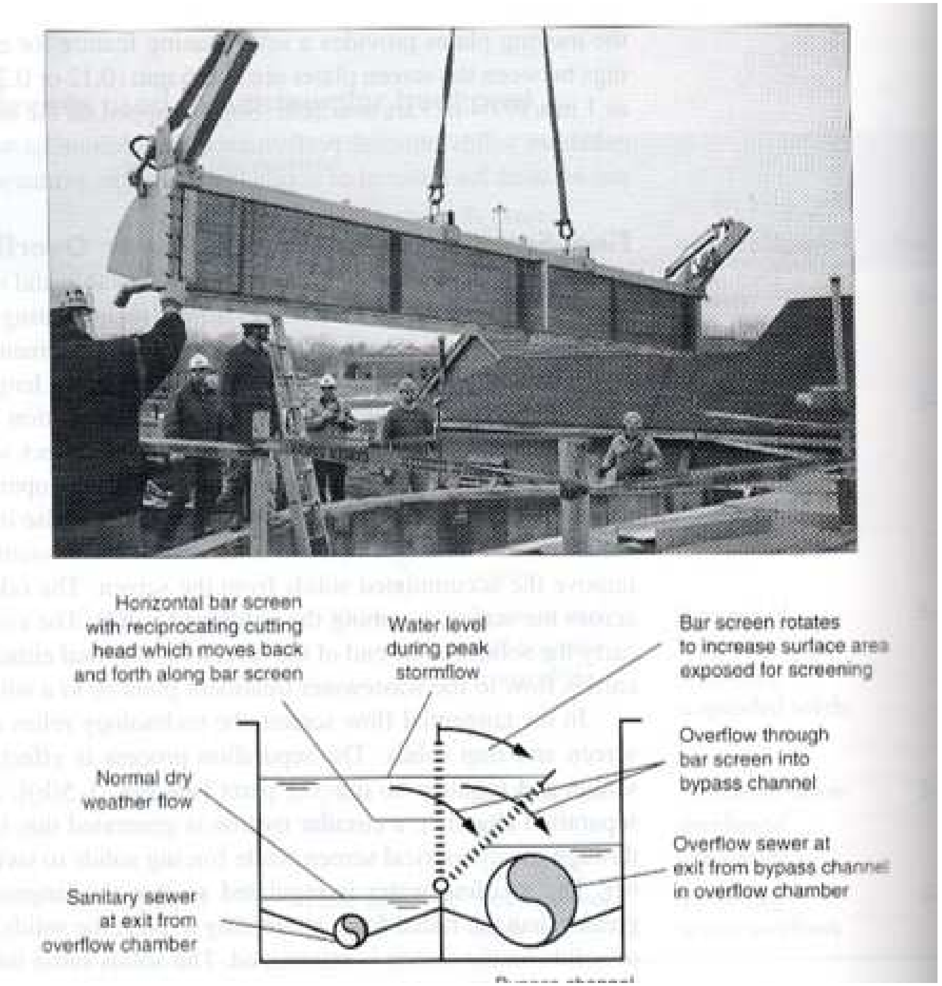
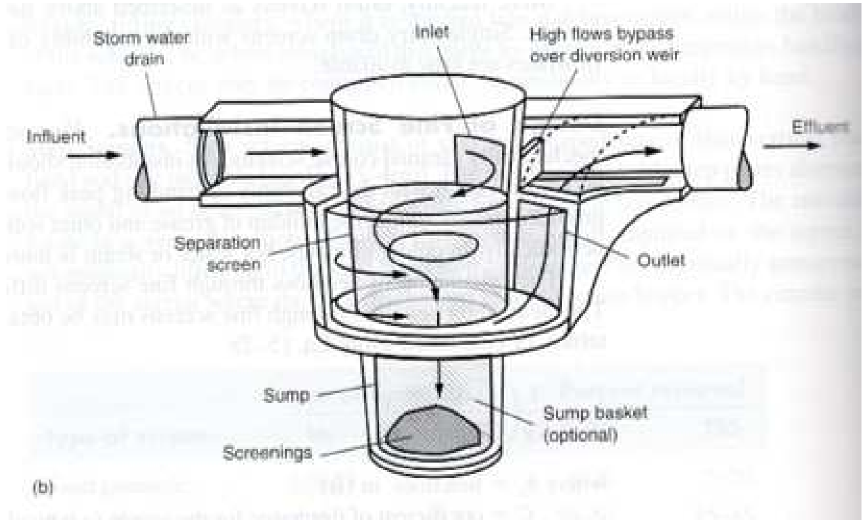




Devices used for the screening of CSOs:
(a) view of horizontal screen during installation and its operating mechanism;
(b) tangential flow device with separation screen

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 – **<u>Discrete particle settling</u>**
  - 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 – **<u>Flocculent settling</u>**
  - Particles grow as they settle
  - Settling velocity increases as particles grow in size
  - ex) primary settling & upper part of secondary clarifier

#5

Types of settling (cont'd)

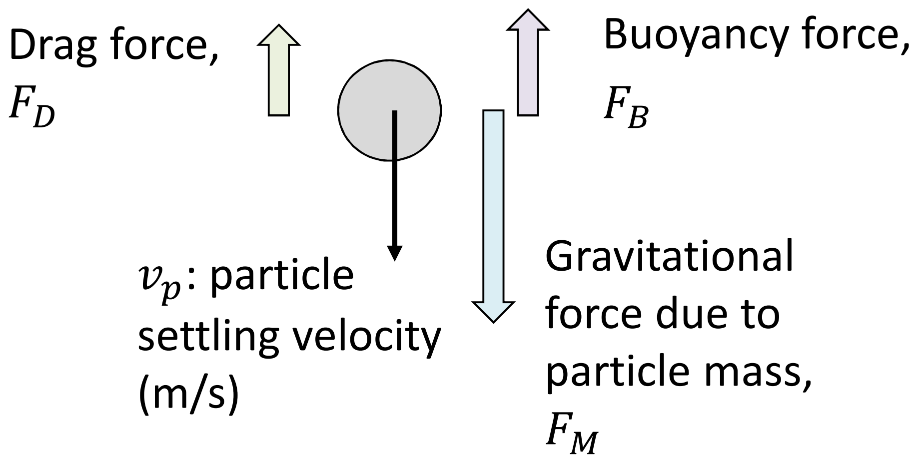
- Class III settling – **<u>zone (or hindered) settling</u>**
  - At higher solids concentration than Class I or II – interparticle forces are sufficient to hinder the settling of neighboring particles
  - Mass of particles settles as a unit; a solid-liquid interface develops at the top
  - ex) major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

- Class IV settling – **<u>compression settling</u>**
  - 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)



$$F_B = \rho_w g V_p$$

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

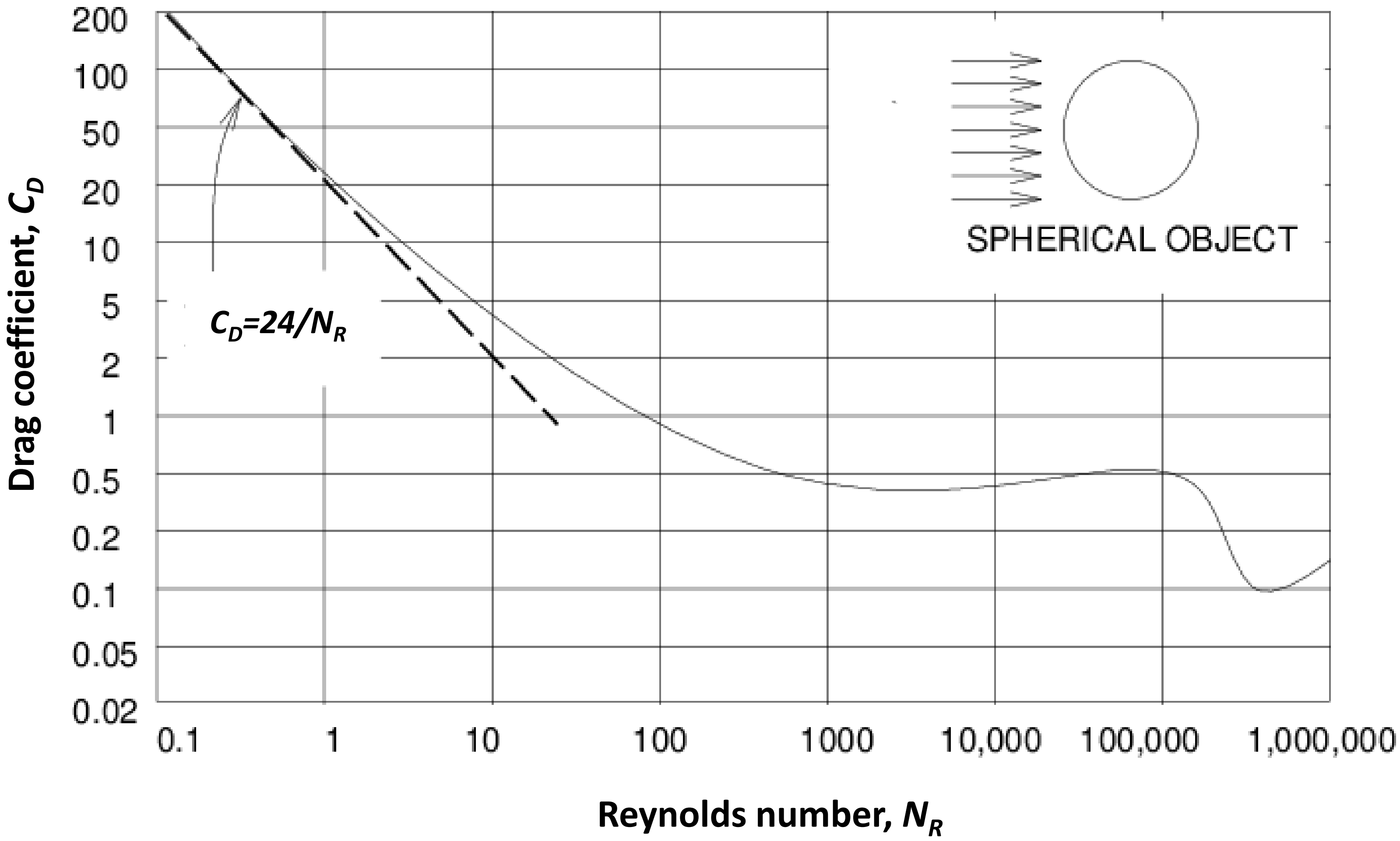
$$N_R = \frac{v_p d_p \rho_w}{\mu} = \frac{v_p d_p}{\upsilon}$$

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

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

Correlation between N_R and C_D

#6



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

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

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

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

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

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

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

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

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

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

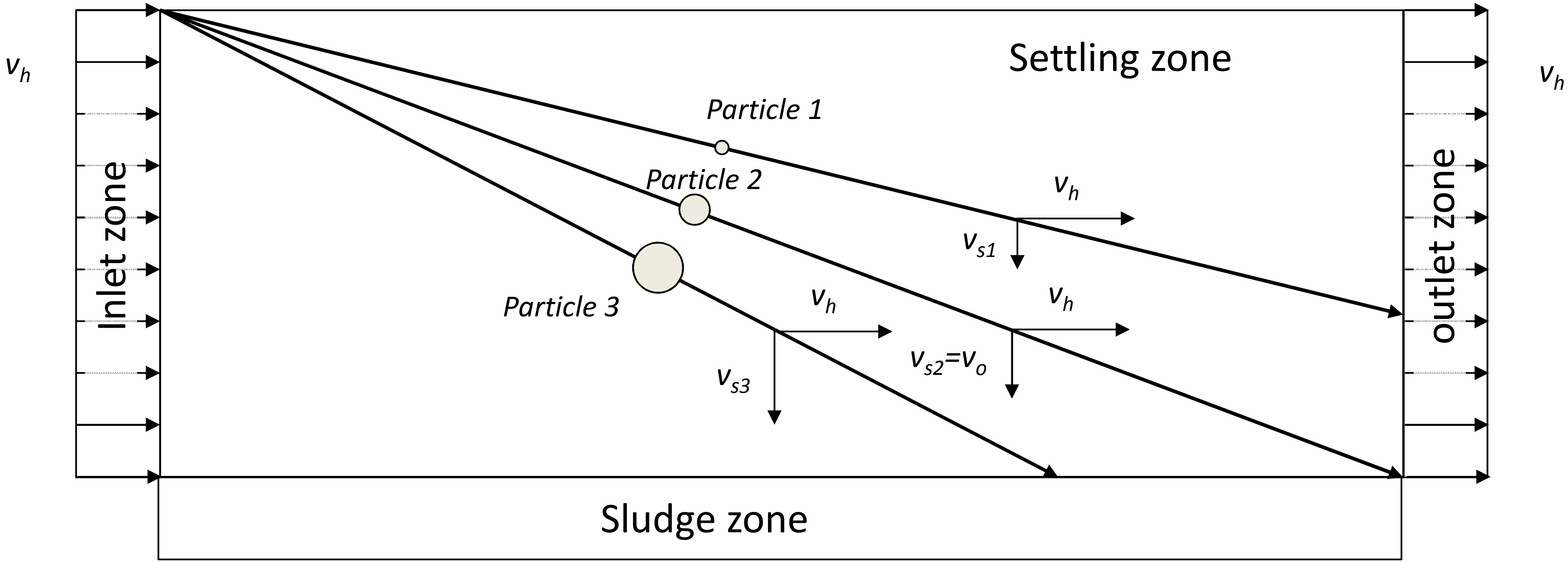
$$= 1.65 \times 10^{-2}\ m/s$$ *(close to the assumption)*

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], $$\frac{L}{v_h} = \frac{H}{v_o}$$

⇨ $$\boxed{v_o = \frac{Q}{A}}$$

*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

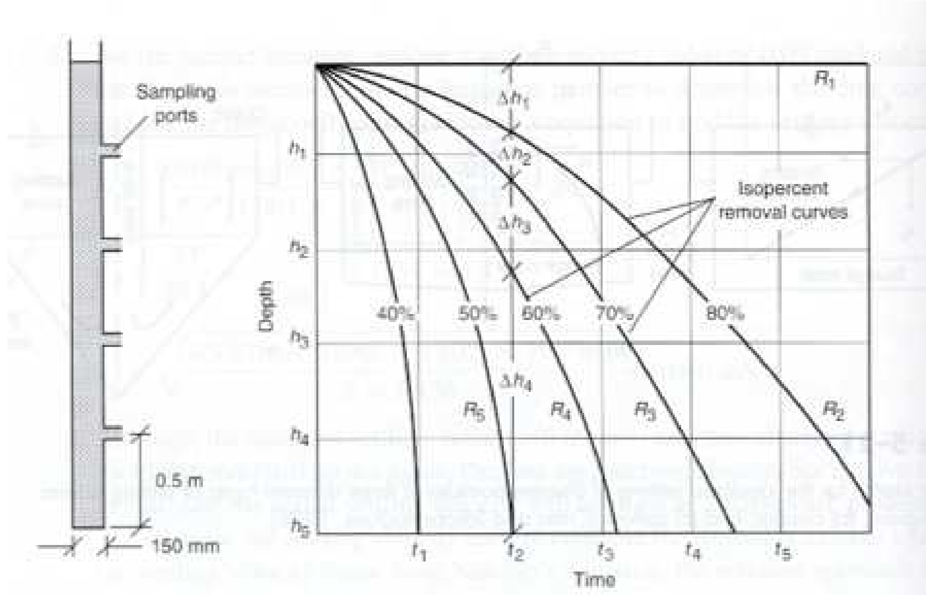
$1 - x_c$ = fraction of particles with $v_p(x)$ greater than v_o

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

#7



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

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

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

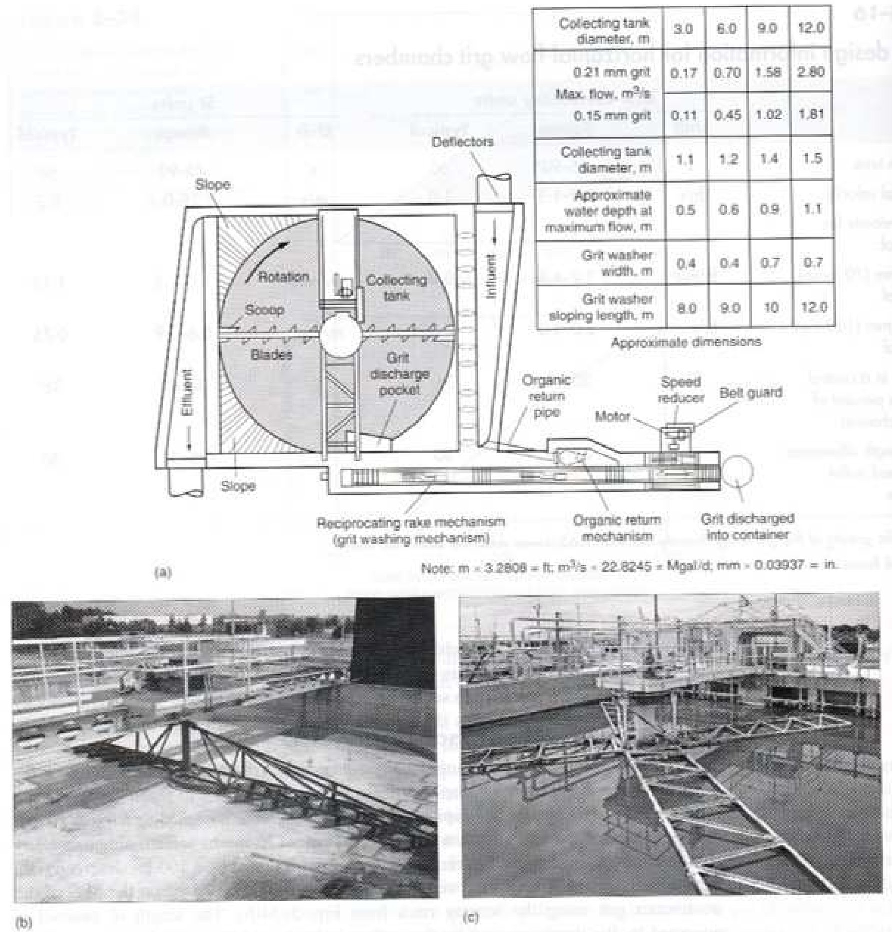
Grit removal

- 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
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

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.

#8

Types of grit chambers (2)

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

#9

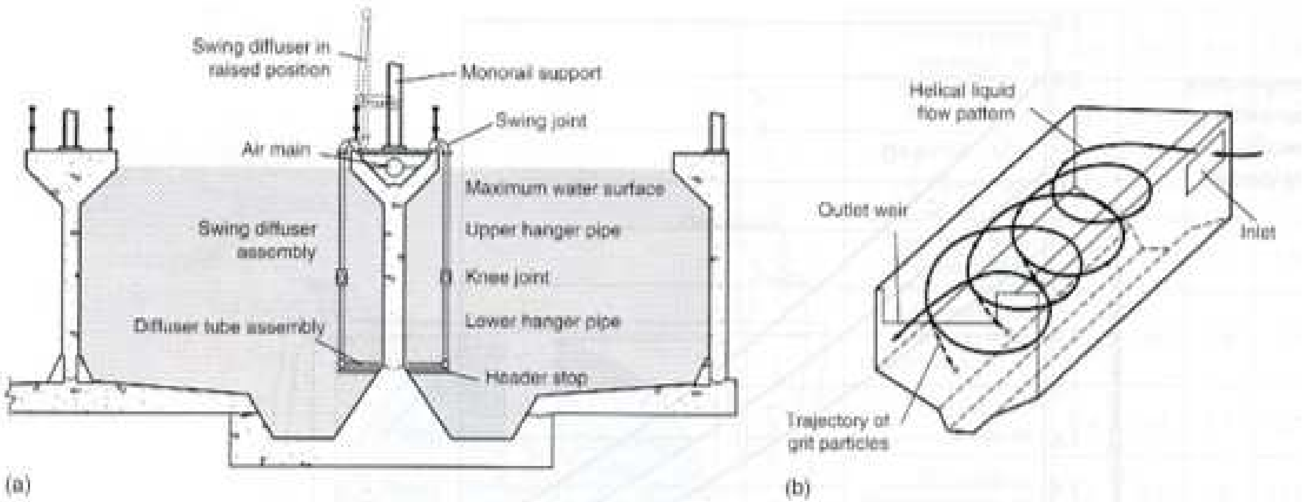


Figure 5-37

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

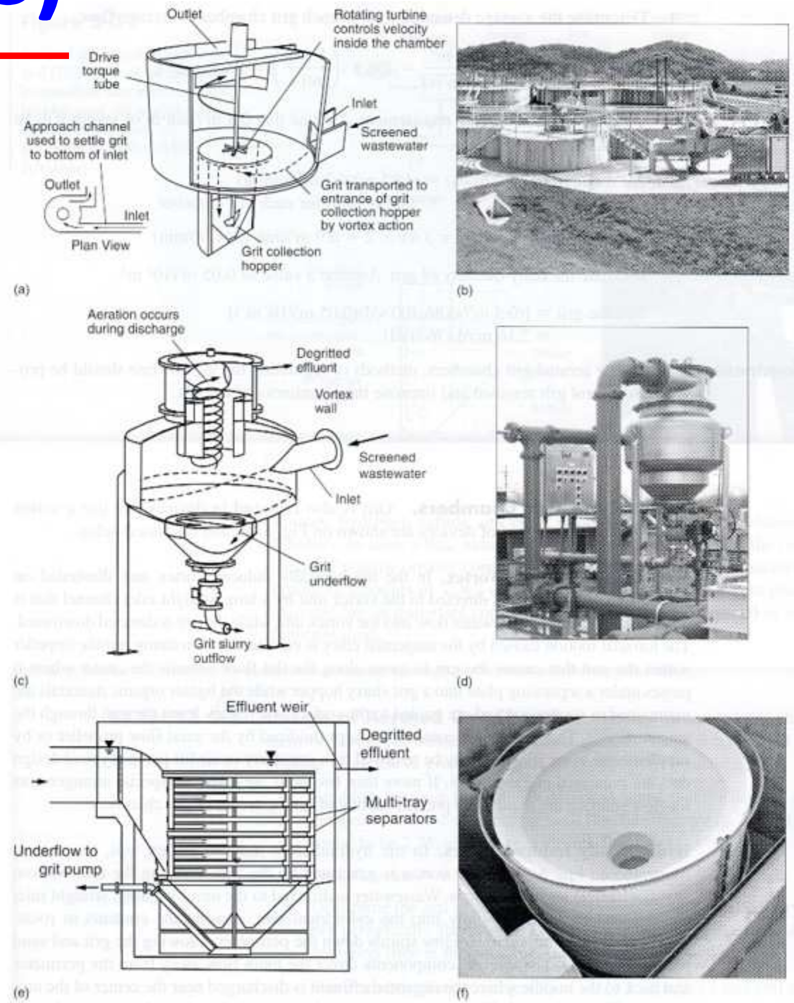


Figure 5–40

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**

#11

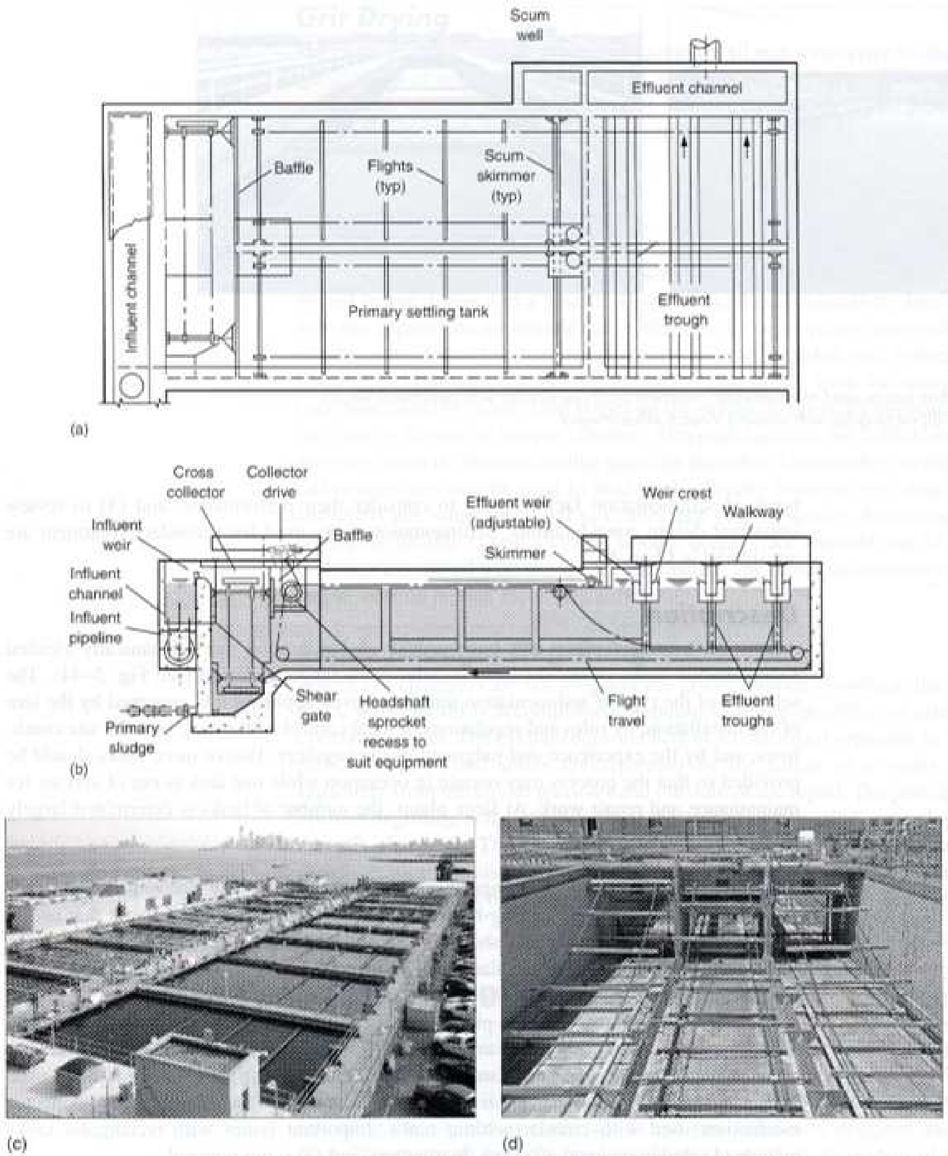


Figure 5-45
Typical rectangular primary sedimentation tank: (a) plan, (b) section, (c) view of large rectangular sedimentation tank with weirs similar to those shown on (b), and (d) view of empty tank with sludge removal mechanism.

Types of primary sedimentation tanks (2)

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

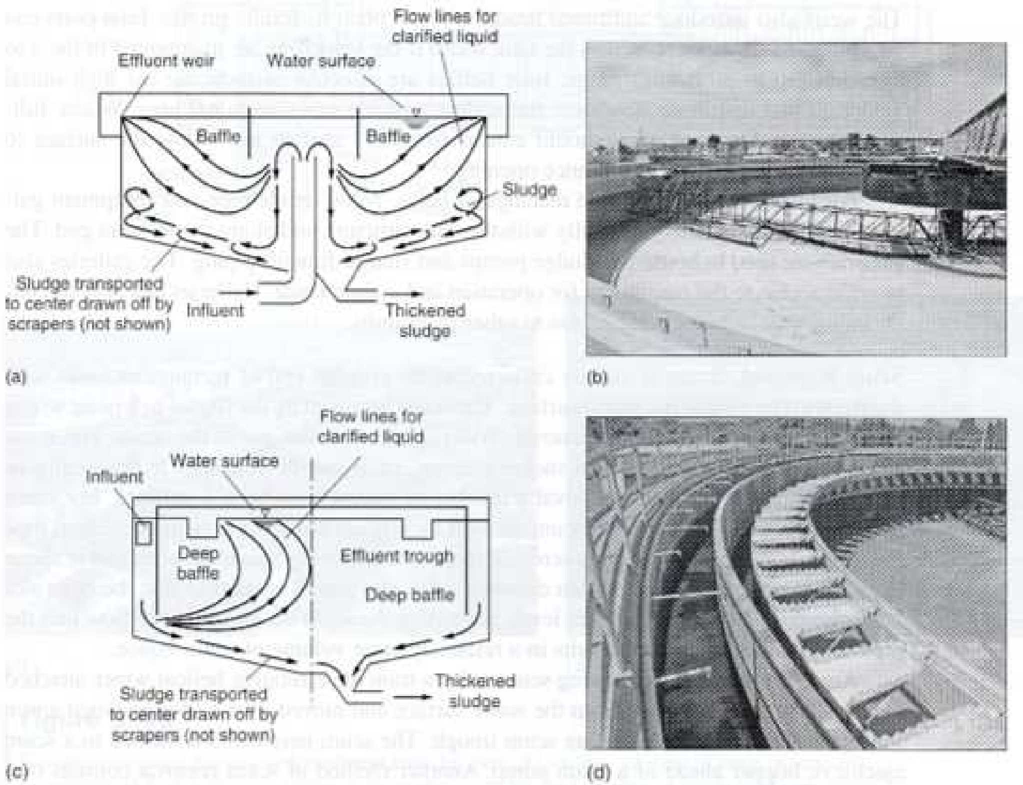


Figure 5-46

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.

#12

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

References

#1) http://techalive.mtu.edu/meec/module21/Collection.htm

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