SOLIDS SEPARATION

Sedimentation and clarification are used interchangeably for potable water; both refer to the separating of solid material from water.

Since most solids have a specific gravity greater than 1, gravity settling is used remove suspended particles. When specific gravity is less than 1, floatation is normally used.

1. various types of sedimentation exist, based on characteristics of particles

    a. *discrete or type 1 settling*; particles whose size, shape, and specific gravity do not change over time
    b. *flocculating particles or type 2 settling;* particles that change size, shape and perhaps specific gravity over time
    c. type 3 (hindered settling) and type IV (compression); not used here because mostly in wastewater

2. above types have both dilute and concentrated suspensions

    a. dilute; number of particles is insufficient to cause displacement of water (most potable water sources)
    b. concentrated; number of particles is such that water is displaced (most wastewaters)

3. many applications in preparation of potable water as it can remove:

    a. suspended solids
    b. dissolved solids that are precipitated

Examples:

- plain settling of surface water prior to treatment by rapid sand filtration (type 1)
- settling of coagulated and flocculated waters (type 2)
- settling of coagulated and flocculated waters in lime-soda softening (type 2)
- settling of waters treated for iron and manganese content (type 1)

Ideal Settling Basin (rectangular)

- steady flow conditions (constant flow at a constant rate)
- settling in sedimentation basin is ideal for discrete particles
- concentration of suspended particles is same at all depths in the inlet zone
- once a particle hits the sludge zone it stays there
- flow through period is equal to detention time

L = length of basin

v_{pi} = settling velocity of any particle

H = height of basin

v_o = settling velocity of the smallest particle that has 100 % removal

v_h = horizontal velocity of flow

W = width of basin

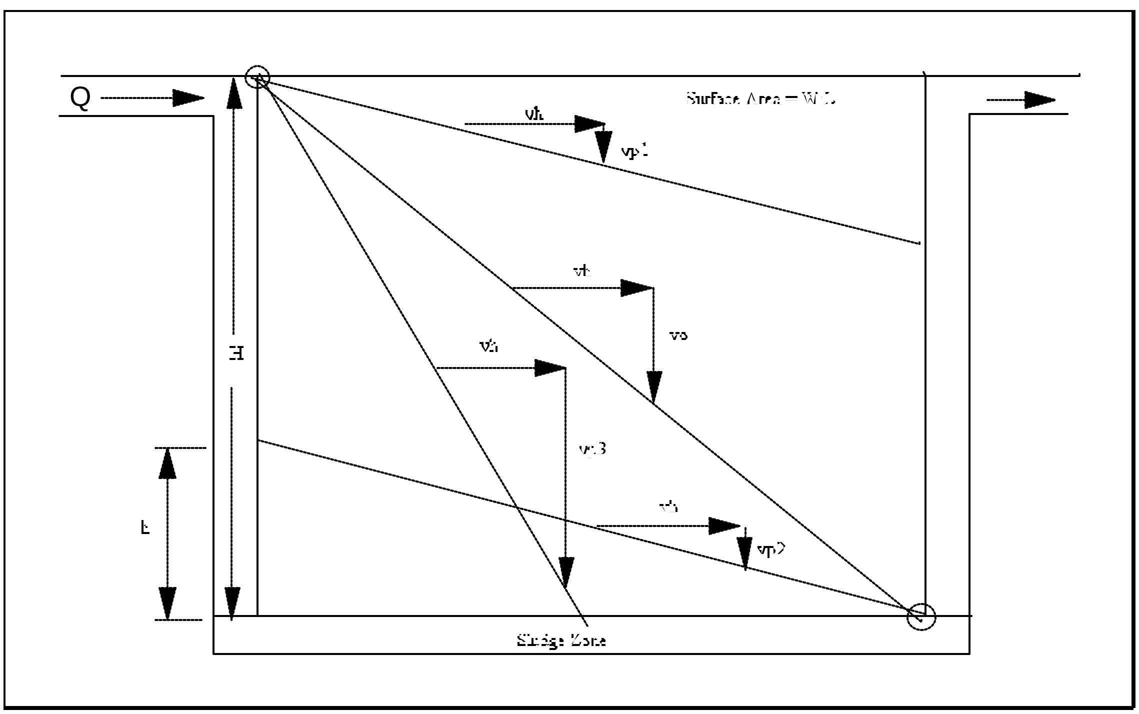

Figure 1: **Ideal Settling Basin**

- particle entering at Point 1 has a trajectory as shown to intercept the sludge zone at Point 2

- vertical detention time, t = depth of tank / ideal settling velocity

$$t_v = \frac{H}{v_o} \tag{1}$$

- horizontal detention time also equals flow through velocity, v_h

$$t_h = \frac{L}{v_h} \tag{2}$$

where

$$v_h = \frac{Q}{H \cdot W} \tag{3}$$

thus

$$t_h = \frac{L \cdot W \cdot H}{Q} \tag{4}$$

- equating t's

$$\frac{L \cdot W \cdot H}{Q} = \frac{H}{v_o} \tag{5}$$

or

$$v_o = \frac{Q}{L \cdot W} \tag{6}$$

or

$$v_o = \frac{Q}{A_p} \tag{7}$$

where

A_p = is the plan area of the settling basin
v_o = overflow rate at which 100 % of the given particles are removed

Ideal Settling Basin (circular)

- same principals as for rectangular apply

- try solving it as an example problem

Overflow expression (Eq. 7) shows that settling is independent of depth

- provided for
  - sludge bed depth
  - rakes
  - resuspension
  - scouring
  - wind turbulence

- fractional removal as not all particles have settling velocity of v_o
  - faster ones ($v_p > v_o$) will settle out as they intercept sludge
  - slower ones ($v_p < v_o$) will not settle out
  - fractional removal (R)

$$R = \frac{h}{H} = \frac{v_p}{v_o} \qquad \textbf{(8)}$$

Design Data

- rectangular
  - depth: 3-5 m
  - length: 15-90 m
  - width: 3-24 m

- circular
  - depth: 3-5 m
  - diameter: 4-60 m

Type 1 Settling

- discrete settling of individual particles
  - plain sedimentation

Theoretical(Terminal Settling) STUDENTS RESPONSIBLE

- easiest situation to analyze as based on fluid mechanics
- particle suspended in water has initially two forces acting on it

(1) gravity ☞ $f_g = \rho_p g V_p$

where

ρ_p = particle density
g = gravitational constant

V_p = volume of the particle

(2) buoyancy ☞ $f_b = \rho_w g V_p$

where

ρ_w = density of water

Since these forces are in opposite directions, there will be net force or movement. However, if the density of the particle is different than that for water, the particle will accelerate in the direction of the force:

$$f_{net} = (\rho_p - \rho_w) g V_p$$

This net force causes acceleration

Once motion is initiated, a third force acts on the particle, drag.

$$f_d = (1/2) C_D A_p \rho_w v^2$$

where

C_D = drag coefficient
A_p = cross-sectional area of particle perpendicular to direction of movement
v = velocity

Acceleration continues at a decreasing rate until a steady velocity is attained, ie. drag force equals driving force:

$$(\rho_p - \rho_w) g V_p = (1/2) C_D A_p \rho_w v^2$$

For spherical particles it can be shown that:

$$V_p / A_p = (2/3) d$$

Using in above equation:

$$v_t^2 = (4/3) g [(\rho_p - \rho_w) d / C_D \rho_w]$$

Expressions for CD change with flow regimes:

$C_D = 24/R_e$	*laminar*	Re < 1
$C_D = 24/R_e + 3/R_e^{0.5} + 0.34$	*transitional*	$10^3 > Re > 1$
$C_D = 0.4$	*turbulent*	$Re > 10^3$

$$R_e = \phi v_t \rho_w d / u$$

where

ϕ = shape factor, 1.0 for perfect spheres
u = dynamic viscosity of fluid

To determine terminal settling velocity, above equations must be solved simultaneously.

Non-Theoretical

- fractional removal determined by method developed by Camp 1946
- suspension is placed in column and completely mixed and then allowed to settle quiescently

Particle placed at the surface has an *average* settling velocity of:

$$v_o = \text{distance travelled/time of travel} = Z_o/t_o$$

Another particle placed at distance Z_p, terminal velocity less than the surface particle, but arrives at the same time, has a settling velocity of:

$$v_p = Z_p/t_o$$

which is < v_o; but arrives at sampling port a same time

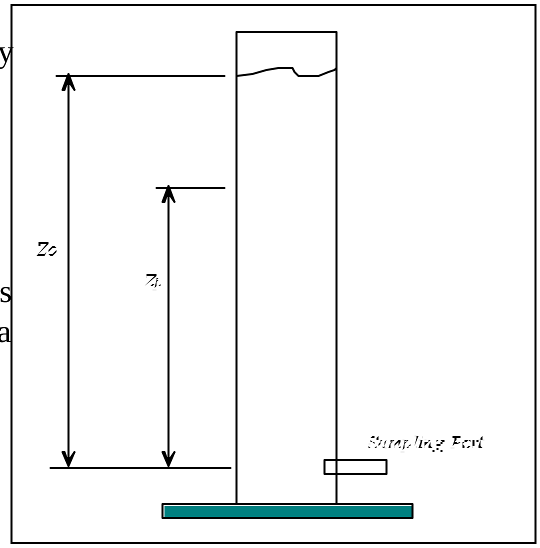

Figure 2: Type 1 Settling Column

Thus, the travel time for both particles is equal, where

$$t_o = Z_o/v_o = Z_p/v_p \quad \text{and} \quad v_p/v_o = Z_p/Z_o = h/H$$

Thus some generalized statements can be made concerning the above relationships.

1. All particles having a diameter equal to or greater than d_o, i.e. have settling velocity greater than v_o, will arrive at or pass the sampling port in time t_o. *(Assume equal S_s)*

2. article with diameter d_p<d_o will have a settling v_p<v_o, will arrive at or pass the sampling port in time t_o, provided its position is below Z_p.

3. If the suspension is uniformly mixed, i.e. particles are randomly distributed,. then the fraction of particles with size d_p having settling velocity v_p which will arrive at or pass the sampling port in time t_o will be $Z_p/Z_o=v_p/v_o$. Thus the removal efficiency of any size particle from suspension is the ratio of the settling velocity of that particle to the settling velocity v_o defined as Z_o/t_o.

These principles can be used to determine the settleability of any given suspension, using shown apparatus. Theoretically depth is not a factor but for practical reasons, 2 m is usually chosen.

Procedure:

1) Determine C_o of completely mixed suspension at time zero.
2) Measure C_1 at time t_1. All particles comprising C_1 have a settling velocity less than Z_o/t_1, where $v_1 = Z_o/t1$. Thus, the mass fraction of particles removed with $v_1<Z_o/t_1$ is given by $r_1 = C_1/C_o$.
3) Repeat process with several times t_i, with the mass fraction of particles being $v_i<Z_o/t_i$
4) Values are then plotted on a graph to obtain Figure 3, where the fraction of particles remaining for any settling velocity can be determined
5) For any detention time t_o, an overall percent removal (r_o) can be obtained. That is, all particles having a settling velocity greater that $v_o=Z_o/t_o$, will be removed 100% (un-hatched area in Figure 3; 1-r_o). The remaining particles have a $v_i<v_o$ (hatched area in Figure 1), and will be removed according to ratio v_i/v_o.

6) If the equation relating v an r are known, than the area can be found through integration using Eq. 9.

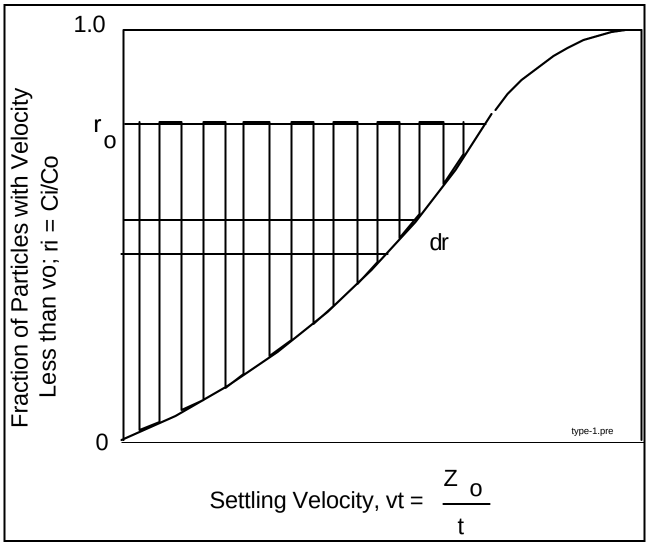

Figure 3: Fraction Remaining

$$R = 1 - r_o + \int_0^{r_o} \frac{v_i}{v_o} dr \qquad \textbf{(9)}$$

where R is the total fraction removed. However, in most cases this is not possible. Consequently, the relationship is integrated over finite intervals according to Eq. 10.

$$R = (1 - r_o) + \frac{1}{v_o} \sum_0^{r_o} v_i \Delta r \qquad \textbf{(10)}$$

Example: Settling analysis is run on a Type-1 suspension in a typical 2 m column. Data as follows.

Time, min	0	60	80	100	130	200	240	420
Conc., mg/L	300	189	180	168	156	111	78	27

What is the removal efficiency in a settling basin with a loading rate of 25 m^3/m^2*d (m/d)?

1. Calculate mass fraction remaining and corresponding settling rates.

Time (min)	60	80	100	130	200	240	420
MF remaining	0.63	0.60	0.56	0.52	0.37	0.26	0.09
$v_t \times 10^{-2}$ (m/min)	3.3	2.5	2.0	1.55	1.0	0.83	0.48

where, mass fraction (MF) remaining = C_i / C_o and $v_t = Z_o/t$

2. Plot mass fraction remaining vs settling velocity as shown in Figure 4
3. Determine velocity (v_o), which equals surface loading rate = 25 m^3/m^2-d (1.7×10^{-2} m/min)
4. Determine from graph r_o = 54 %.
5. Integrate curve

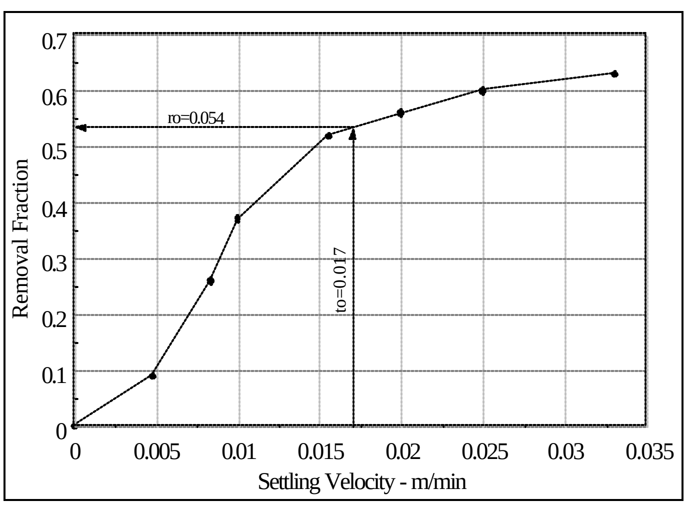

Figure 4: Fraction Removal for Example

6. Removal efficiency (R) = 1 - r_o + [Integrated Area]

Element	Δr	$v_t \times 10^{-2}$	$\Delta r \bullet v_t \times 10^{-2}$
1	0.02	1.6	0.03
2	0.15	1.25	0.19
3	0.11	0.91	0.10
4	0.17	0.66	0.11
5	0.09	0.24	0.02
		Total =	0.45

Removal = (1 - 0.54) + 0.45/1.7
= 0.46 + 0.26
= 0.72 or 72 %

USING RESULTS

Primary sedimentation systems have θ_H = 1.5 to 2.5 h, with average overflow rates of 32-48 m/d and peak at 80 - 120 m/d.

! Rectangular (most common)

" depth 3-5 m
" length 15-90 m (30-40 typical)
" width 3-24 m (6-10 typical)

! circular

" depth 3-5 m
" diameter 5-60 m (15-30 typical)

<u>Example</u>: Use Type 1 Data used in class with Q = 2 m^3/s with overflow rate of 25 m/d.

A = Q/25
= 172,800/25 ==>assume width = 10 m (rectangular)
= 6912 m^2

gives L = 6912/10 ==> 691 m (which is too long)

use multiple number of basins; try width = 10 and length = 50 m

number of basins = 6912/500
= 13.8 ==> 14 (always even for rectangular)

flow to each = 172,800/14
= 12,343 m^3/d

know t_d = vol/Q

assume t_d = 2.5 h

vol. = 2.5/24*12343 = 1286 m^3

depth = 1286/10*50 = 2.6 m

Type-2 Settling

Involves flocculated particles in dilute suspensions. Stokes equations cannot be used because the particles are constantly changing shape and size.

Analysis is similar to the discrete particle suspension, except that the concentrations removed are calculated. This is done by modifying the settling column to have various sample ports as shown. Is a batch test.

$$x_{ij} = (1 - C_i/C_o) \times 100$$

where

x_{ij} = mass fraction percent removed at the *i*th depth at the *j*th time interval

The sample concentrations are plotted in a contour map showing the isoremoval lines. The slope on any point on the isoremoval line is the instantaneous velocity of the fraction of particles represented by that line. As the velocity increases so does the slope, which is consistent for flocculating suspensions.

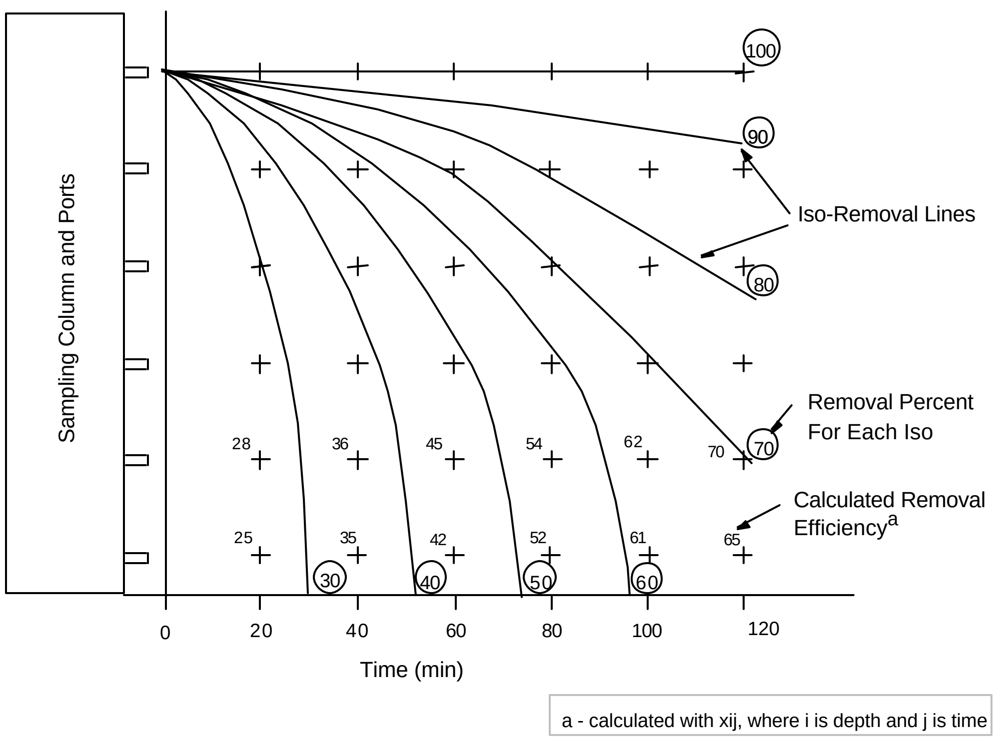

Figure 5: Type II Removal

Using this method the overall removal percentage can be calculated for any predetermined detention time.

Example - Type II Suspension:

The following table gives the sampling concentrations for a Type II column analysis. The initial solids concentration is 250 mg/L. What is the overall removal efficiency of settling basin 3m deep and a detention time of 1h and 45 min.

Depth m	Time of sampling, min 30	60	90	120	150	180
0.5	133	83	50	38	30	23
1.0	180	125	93	65	55	43
1.5	203	150	118	93	70	58
2.0	213	168	135	110	90	70
2.5	220	180	145	123	103	80
3.0	225	188	155	133	113	95

1. Determine *removal* rate at each depth and time using $x_{ij} = (1 - C_i/C_o)x100$

Depth m	Normalized Concentrations - Percent (Time of sampling, min) 30	60	90	120	150	180
0.5	47	67	80	85	88	91
1.0	28	50	63	74	78	83
1.5	19	40	53	63	72	77
2.0	15	33	46	56	64	72
2.5	12	28	42	51	59	68
3.0	10	25	38	47	55	62

2. Plot iso-concentration lines as shown in Figure
3. Construct vertical line at t_o =105 min
4. Removal efficiency (R) calculated by:

$$R = R_{intercept} + \frac{1}{H} \sum (Z_i \cdot \Delta R)$$

where, $R_{intercept}$ = 43%

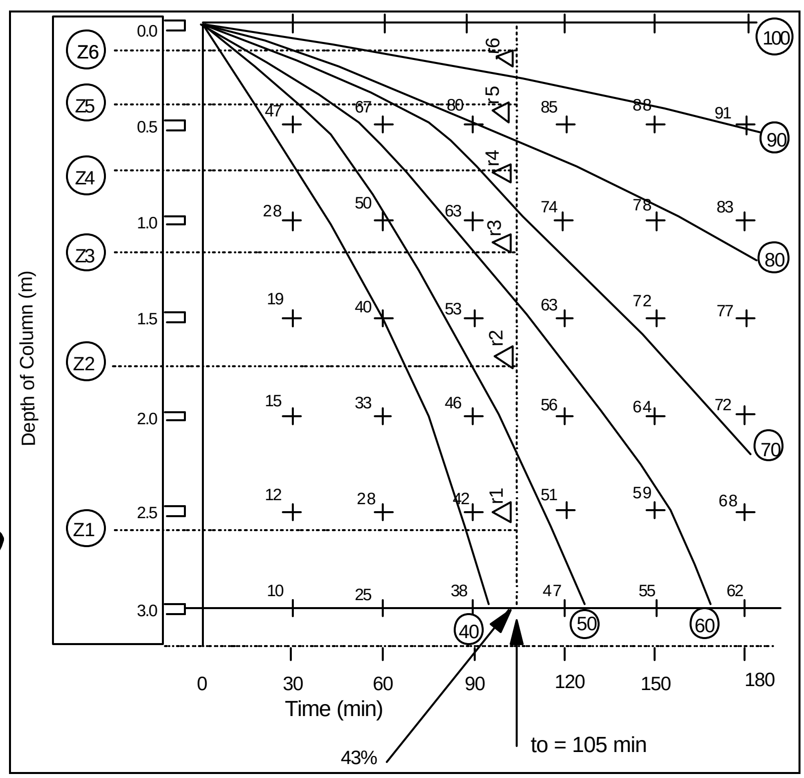

Figure 6: Type II Example

Integrating results in:

Element	ΔR	Zi	$\Delta R \cdot Z_i$
r_1	0.07	2.55	0.179
r_2	0.1	1.73	0.173
r_3	0.1	1.13	0.113
r_4	0.1	0.72	0.072
r_5	0.1	0.39	0.039
r_6	0.1	0.12	0.012
			$\sum 0.588$

$$R = 0.43 + \frac{1}{3} \sum (0.588)$$

$$R = 0.63$$

To improve efficiency, slow down v_o, calculate t_d and re-integrate (iterative proceedure).

Hydraulic Characteristics of Settling Basins

The actual flow through characteristics are not the same as assumed for ideal settling basins. Using tracer dyes at the inlet, the tracer will not appear at the same time, i.e. no dispersion like plug flow. Instead the dye appears as shown in Figure 7.

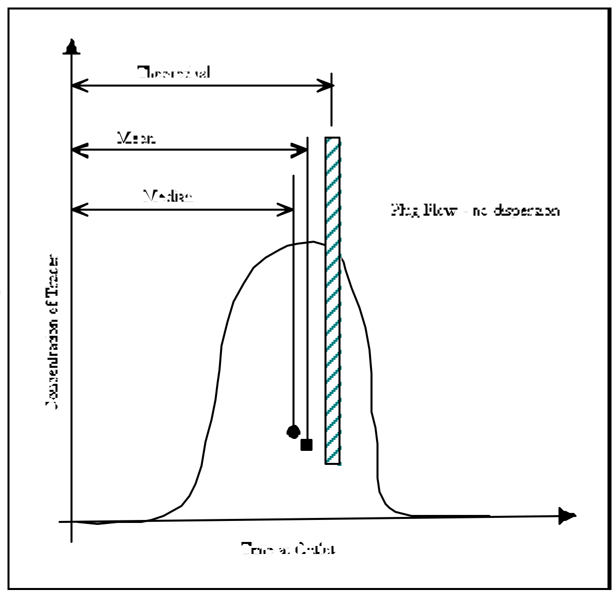

Figure 7: Hydraulic Characteristics

Depth of the settling basins is provided to:

- Collect sludge without scouring
- reduce effect of wind velocity
- reduce agitation of settled sludge under turbulent conditions
- increase conjunction of flocculent particles
- reduce short-circuiting
    - rectangular < outer feed < center feed
- decrease flow turbulence