Settling tanks ("clarifiers")

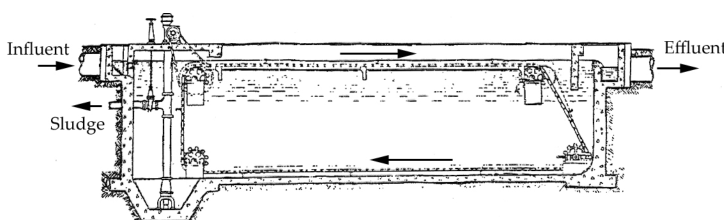
(Nazaroff & Alvarez-Cohen, Section 6.C.1)
(Mihelcic & Zimmerman, Section 10.7, augmented)

www.coffeyville.com/Water.htm

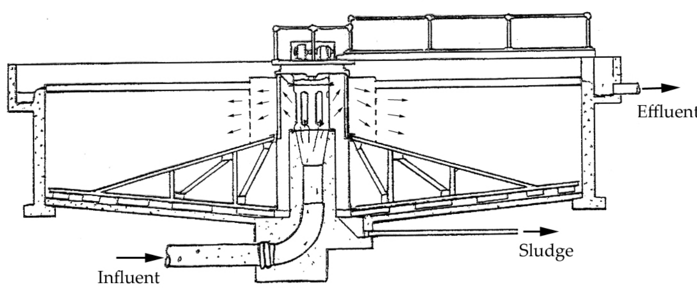
Settling tanks, also called sedimentation basins or clarifiers, are large tanks in which water is made to flow very slowly in order to promote the sedimentation of particles or flocs.

In water and wastewater treatment plants, these are so large that they are situated outdoor and usually have their surface exposed to the air.

Sedimentation basins come in two shapes, rectangular and circular.



A rectangular sedimentation basin



A circular sedimentation basin

(Taken from D.S. Sarai, 2006)

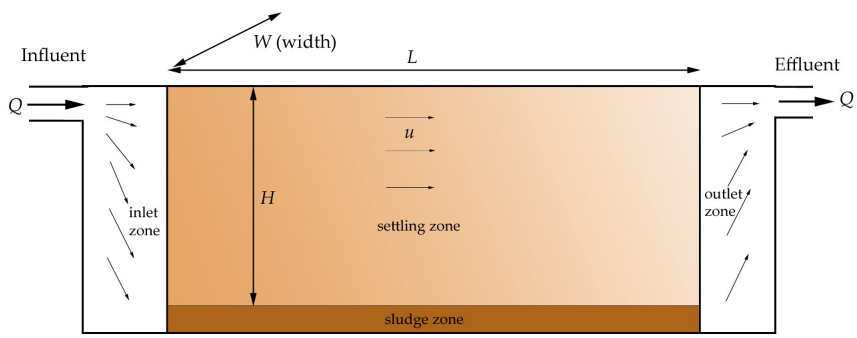
(www.norfolk.gov/Utilities/produce/process.asp)

A rectangular settling tank

A circular settling tank

(www.huntingburg.org/waste_water_photos.htm)

Consider what goes on in a rectangular settling basin.



Key parameters are:

H = depth of settling zone
L = length of settling zone
W = width of settling zone
V = volume of settling zone
Q = volumetric flowrate
u = flow speed
θ = transit time = hydraulic retention time

Relations are:

$$u = \frac{Q}{HW}$$

$$\theta = \frac{L}{u} = \frac{HLW}{Q} = \frac{V}{Q}$$

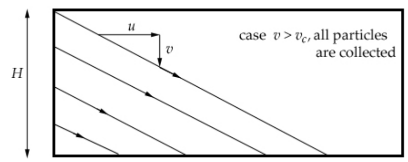
If a particle settles with vertical speed v, its vertical fall over the length of the tank is

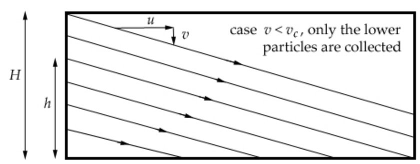
$$h = v\theta = v\frac{L}{u}$$

This length h is either longer than the settling depth H or it is not.

❑ If $h \geq H$, then the particle hits the bottom before the end of the tank and is collected.

❑ If $h < H$, then the particle may or may not hit the bottom, depending on the level at which it starts. If it starts close to the bottom, it will settle on the bottom, but if it starts too high it won't fall down enough and will escape with the outflow.





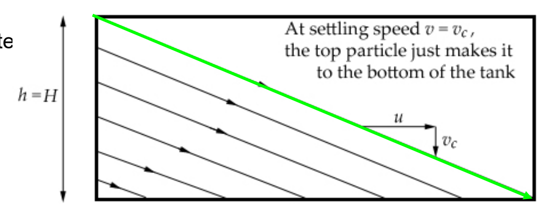
It is easy to show that, if $h < H$, the particles in the lowest h portion of the tank are collected and that those starting within the top $H - h$ portion do not get collected.

This leads us to define a critical settling speed, namely the settling speed of the particles that get barely all collected.

$$h = H \quad \text{for} \quad v = v_c = \frac{H}{\theta} = \frac{Hu}{L}$$

In terms of the volumetric flowrate

$$v_c = \frac{H}{L}\frac{Q}{WH} = \frac{Q}{WL} = \frac{Q}{A}$$



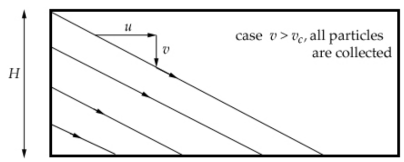
This critical speed is called the *overflow rate*.

Note that, in this definition, Q is not divided by the cross-sectional area WH but by the horizontal area (footprint) of the tank, $WL = A$.

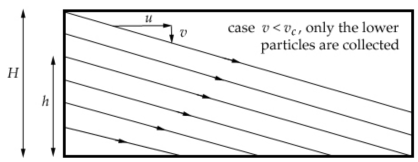
Collecting efficiency:

For particles settling with speed v faster than v_c, the collection efficiency is 100%.

For particles settling with speed v slower than v_c, the collection efficiency is $\frac{h}{H}$.

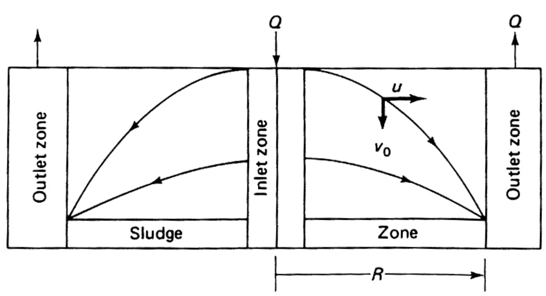


$$\eta = 1 \quad (100\%)$$



$$\eta = \frac{h}{H} = \frac{vL}{uH} = \frac{v}{v_c} \quad (<1)$$

And, how does it work in a <u>circular</u> sedimentation tank?



The radial velocity u varies with the radius r, decreasing so that the volumetric flow through the enlarging cross-section remains constant:

$$u = \frac{Q}{2\pi\, r\, H}$$

The slope of the settling curve $z(r)$ obeys the equation (with z positive downward)

$$\frac{dz}{dr} = \frac{v}{u} = \frac{2\pi\, rH\, v}{Q} \quad \Rightarrow \quad h = \int_{R_{inner}}^{R_{outer}} \frac{dz}{dr}\, dr = \frac{(\pi\, R_{\text{outer}}^2 - \pi\, R_{\text{inner}}^2)Hv}{Q} = \frac{AHv}{Q}$$

The collecting efficiency is

$$\eta = \frac{h}{H} = \frac{Av}{Q} = \frac{v}{(Q/A)} = \frac{v}{v_c}$$

same as for the rectangular tank except for revised definition of the horizontal area A!

Typical design values for sedimentation basins

Parameter	Range	Typical values	Units
RECTANGULAR BASIN			
Length	15 – 90	25 – 40	m
Depth	3 – 5	3.5	m
Width	3 – 24	6 – 10	m
CIRCULAR BASIN			
Diameter	4 – 60	12 – 45	m
Depth	3 – 5	4.5	m
WATER TREATMENT			
Overflow rate	35 – 110	40 – 80	m/day
WASTEWATER TREATMENT			
Overflow rate	10 – 60	16 – 40	m/day

(*Source*: Tchobanoglous & Schroeder, 1985)

For reference, an Olympic swimming pool is 50 m long, 25 m wide and 2 m deep.

Important remark on performing an efficiency analysis
(not in the textbook)

The answer depends on your assumptions! So, be careful on how you set up your analysis.

Let us explore three different cases:

1. No mixing at all
2. Transverse mixing only
3. Thorough mixing.

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1. No mixing at all: In this case, the water flow is smoothly proceeding from upstream to downstream, and particles gently settle downward along the way. The assumption is that there is no turbulence capable of kicking water or particles upward or backward.

The analysis performed earlier applies, and we find

$$\eta = 1 \quad \text{if} \quad v \geq v_c$$
$$= \frac{v}{v_c} \quad \text{if} \quad v < v_c$$

2. <u>Transverse mixing only</u>: In this case we consider that the flow creates some turbulence capable of stirring the fluid vertically and crosswise (the short dimensions of the basin). Particles may be kicked upward and sideways randomly, but not forward or backward. Thus, we consider the system as acting as a *Plug Flow Reactor* (PFR).

$$\frac{dC}{dx} = -\frac{v}{uH}C \quad \Rightarrow \quad C(x) = C(0)\exp\left(-\frac{vx}{uH}\right)$$

$$\Rightarrow \quad C(L) = C(0)\exp\left(-\frac{vL}{uH}\right) = C(0)\exp\left(-\frac{v}{v_c}\right)$$

The efficiency is

$$\eta = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} = 1 - \frac{C(L)}{C(0)} = 1 - \exp\left(-\frac{v}{v_c}\right)$$

This is a function that varies from zero at v = 0 to 1 as v tends toward infinity.

The value for $v = v_c$ is η = 1 – exp(–1) = 0.632 = 63.2%.

63.2% is less than the 100% obtained under quiet conditions.

3. <u>Thorough mixing</u>: In this case, we consider the entire basin as well-mixed not only vertically and transversely but also longitudinally (turbulence can now kick particles in any of the three dimensions of space). Thus, we now consider the system as acting as a *Continuously Mixed Flow Reactor* (CMFR).
The analysis proceeds with a single-volume budget for the whole basin

$$V\cancel{\frac{dC}{dt}} = Q\,C_{\text{in}} - Q\,C_{\text{out}} - (vWL)\,C$$

In steady-state balance with $C_{\text{out}} = C$ of inside, we have

$$C_{\text{out}} = C = \frac{Q}{Q + vWL}C_{\text{in}} = \frac{1}{1 + \frac{v}{v_c}}C_{\text{in}}$$

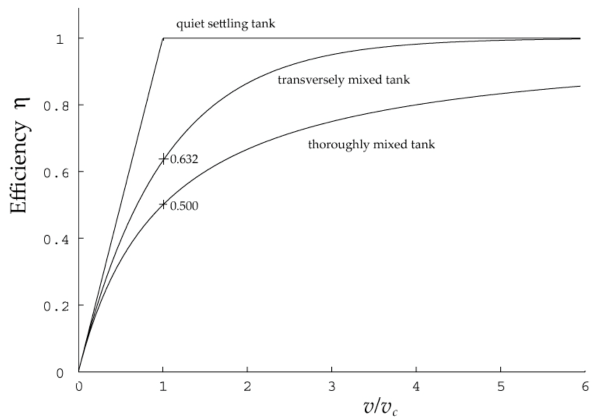
and the efficiency is

$$\eta = \frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}} = 1 - \frac{C_{\text{out}}}{C_{\text{in}}} = 1 - \frac{1}{1 + \frac{v}{v_c}} = \frac{v}{v + v_c}$$

This is again a function of v/v_c that starts from zero and levels off to one.

For $v = v_c$, the efficiency is 1/(1+1) = 1/2 = 50%.

Comparison of the three efficiencies



Needless to say, the quiet settling tank is the best, and the thoroughly mixed one is the worst.

Settling tanks are large structures, and we seek to minimize their size. This is accomplished by maximizing their efficiency. Hence, it is essential to operate these systems with a flow that is as quiet as possible.

A complication

In settling analysis and design, the particle distribution is usually not known. What is known instead is the outcome of a lab test with a settling column.

A 1- to 2-m long column is filled with the turbid water and is left unperturbed in the vertical position for some time. During this time, particles fall down and accumulate on the bottom. The amount of mass collected on the bottom is measured in the course of time.

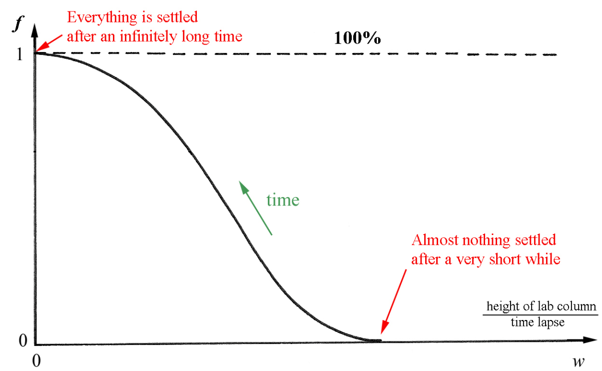
The complication arises from the fact that particles are **not** sorted by size with the bigger ones (those falling faster) being collected first and the smaller ones (those taking more time to fall) being collected afterwards.

Rather, all types of particles are collected immediately, because some of the smaller particles happen to be near the bottom and settle pretty quickly. What we see arriving at the bottom is a mix of particles, initially made up of many big ones and few small ones, later fewer big ones and more small ones, and ultimately small ones only. In other words, the proportion in the mix changes over time.

Example of settling at the bottom of a 1.5-m tall column in the laboratory

Elapsed time (minutes)	Mass collected at bottom (mg)	Fraction of mass (%)
5	9.7	4%
10	46	19%
15	92	38%
20	131	54%
30	186	77%
60	227	94%
∞	242	100%

It is helpful to plot the mass fraction of particles settled as a function of the inverse of time, as done in this figure.



Theory

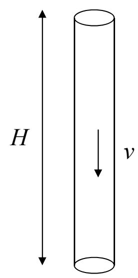
Let $m(v)$ be the (unknown) particle mass distribution, defined such as
$m(v)\,dv$ = mass fraction of particles with settling speed between v and $v+dv$.

The collection efficiency in the **settling tank** (not the lab column) is then given by

$$\eta_{\text{overall}} = \int_0^\infty \eta(v)\,m(v)\,dv \qquad \text{with} \quad \eta(v) = \frac{v}{v_c} \quad \text{for} \quad v < v_c$$

$$\eta(v) = 1 \quad \text{for} \quad v > v_c$$

$$= \int_0^{v_c} \frac{v}{v_c} m(v)\,dv + \int_{v_c}^\infty m(v)\,dv$$



Now, in the **lab column**:

In time t, vertical distance covered is vt.

If $vt < H$, then fraction vt/H has been collected;
If $vt > H$, then 100% has settled,

The fraction collected at the bottom of the lab column as a function of time is:

$$f(t) = \int_0^\infty (\text{fraction settled}) \times (\text{mass fraction present})$$

$$= \int_0^{H/t} \frac{vt}{H} m(v) dv + \int_{H/t}^\infty 1\, m(v) dv \qquad \text{Note: } f(t=0)=0 \text{ and } f(t=\infty)=1$$

We do not know $m(v)$, but our lab experiment has given us $f(t)$.

Now, change the variable from time t to pseudo-velocity $w = H/t$:

$$f(w) = \int_0^w \frac{v}{w} m(v)\, dv + \int_w^\infty m(v)\, dv \qquad \text{Note: } f(w=0)=1 \text{ and } f(w=\infty)=0$$

Thus, for the actual settling tank:

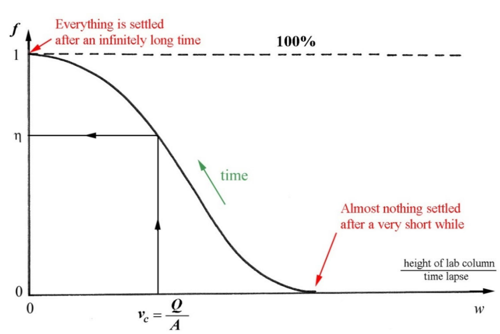
$$\eta_{\text{overall}} = \int_0^{v_c} \frac{v}{v_c} m(v)\, dv + \int_{v_c}^\infty m(v)\, dv$$

While for the lab column:

$$f(w) = \int_0^w \frac{v}{w} m(v)\, dv + \int_w^\infty m(v)\, dv$$

Compare and note that η_{overall} in the actual settling tank is none other than f of the lab taken at $w = v_c$.

Graphically:

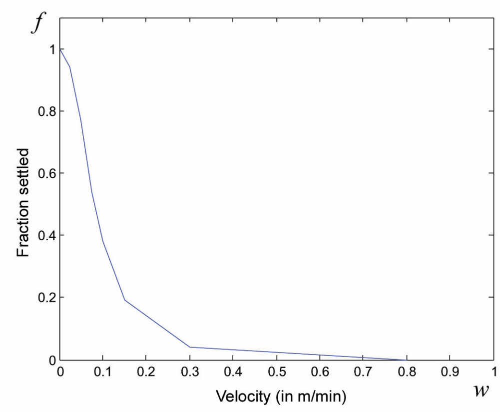


This nicely by-passes the need to know the particle mass distribution $m(v)$!

For the data given earlier, and with v calculated as follows:

$$w = \frac{\text{falling distance}}{\text{falling time}} = \frac{1.5\ \text{m}}{5, 10, \ldots \text{or } 60\ \text{min}}$$

the curve is



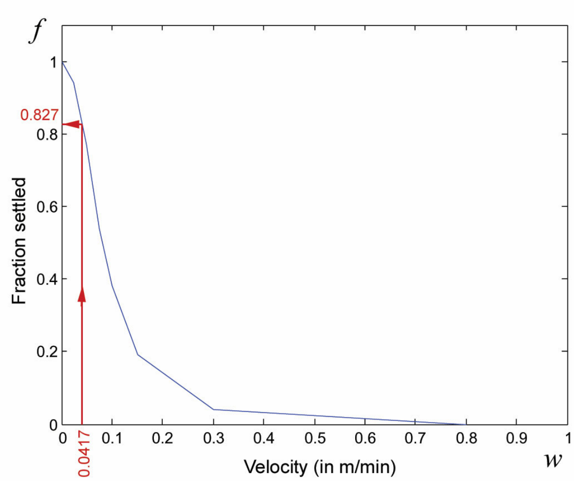
Now suppose that these data were collected for the following application:
- Dimensions of rectangular settling tank: H = 2 m, W = 4 m and L = 12 m
- Flow rate Q = 2 m³/min.

The corresponding overflow rate is:

$$A = LW = (12\ \text{m})(4\ \text{m}) = 48\ \text{m}^2 \quad \Rightarrow \quad v_c = \frac{Q}{A} = \frac{2\ \text{m}^3/\text{min}}{48\ \text{m}^2} = 0.0417\ \text{m/min}$$

From the graph, we determine the f_c value by interpolation

$$f_c = f_1 + \frac{v_c - w_1}{w_2 - w_1}(f_2 - f_1) = 0.827$$



Thus, this clarifier removes 82.7% of the suspended solids.

Note: The tank depth H does not matter. How come?