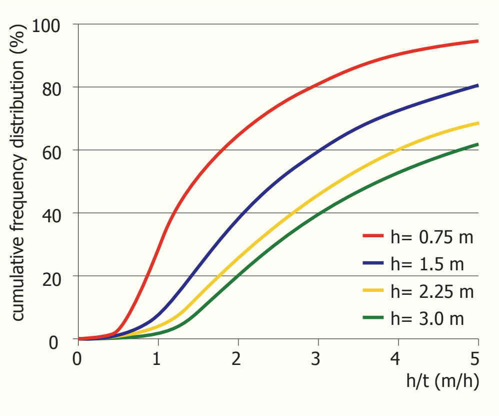
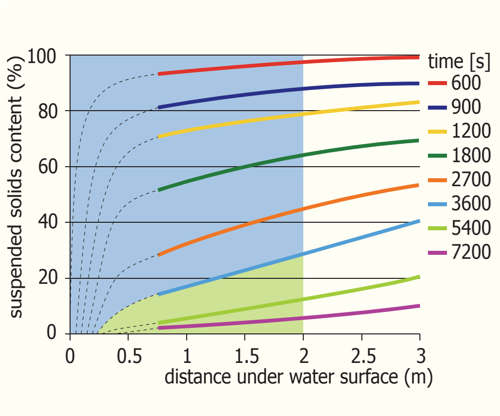
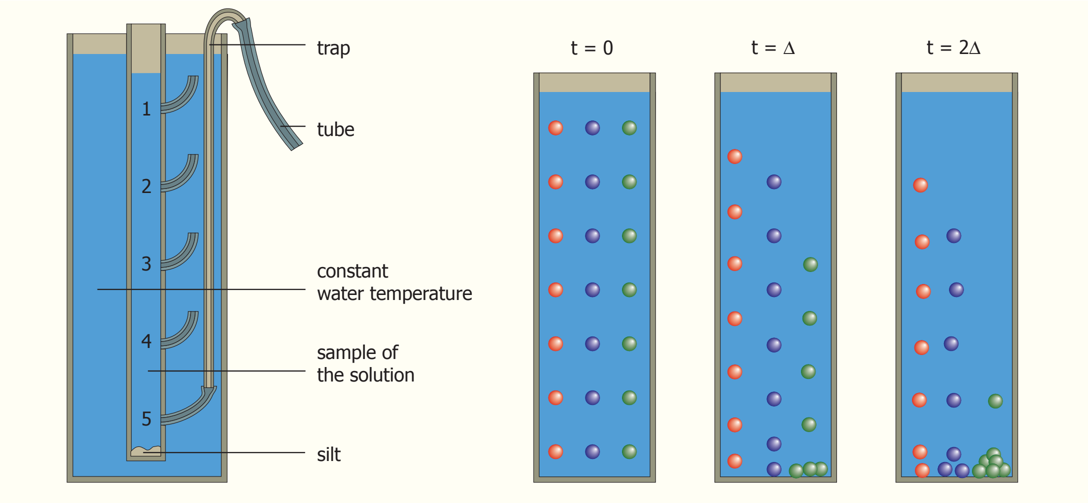
Sedimentation







Contents

This handout is based on *Drinking Water, Principles and Practices* by de Moel et al.

1. Introduction

Sedimentation is a physical process in which suspended particles, like flocs, sand and clay are re-moved from water through gravity. Sedimentation occurs naturally in reservoirs or in compact settling installations. Examples of settling installations are horizontal flow settling tanks, tilted plate settlers and floc blanket installations.

Sedimentation is frequently used in surface water treatment to avoid rapid clogging of sand filters after coagulation and floc formation (Figure 1), and it is applied in groundwater installations for backwash water treatment

In horizontal flow settling tanks (Figure 2) water is uniformly distributed over the cross-sectional area, in the inlet zone. A stable, non-turbulent, flow results in settling of suspended matter in the settling zone. The sludge accumulates on the bottom or is continuously removed. In the outlet zone the settled sludge must be prevented from being re-suspended and washed out with the effluent.

Sedimentation occurs because of the difference in density between suspended particles and water, and it is influenced by density and size of suspended particles, water temperature, turbulence, stability of flow, bottom scour and flocculation.

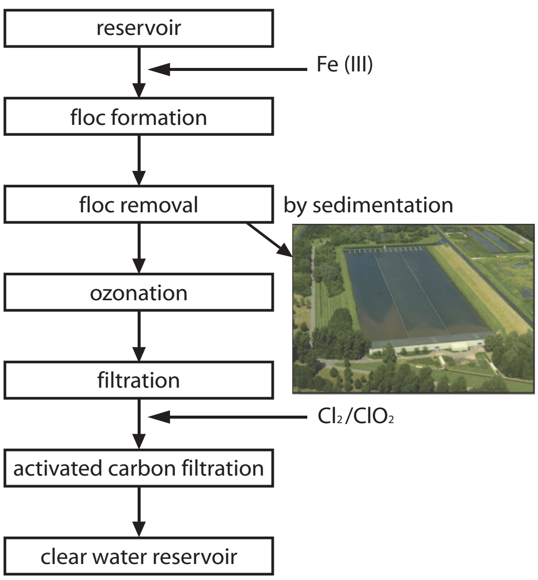


Figure 1 - Process scheme of a surface water treatment plant

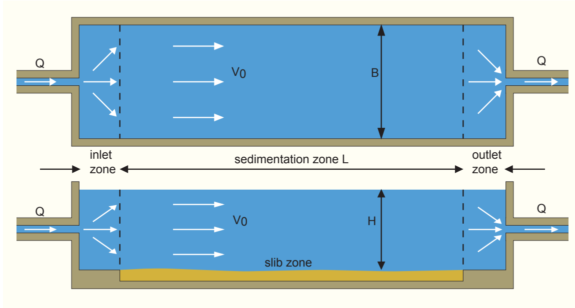


Figure 2 - Horizontal flow settling tank

2. Theory

2.1 *Sedimentation of discrete particles*

Discrete particles are defined as particles that do not change their size, shape or weight during the settling process (and thus do not form aggregates). A discrete particle in a fluid will settle under the influence of gravity. The particle will accelerate until the frictional drag force of the fluid equals the value of the gravitational force, after which the vertical (settling) velocity of the particle will be constant (Figure 3).

The upward directed force on the particle, caused by the frictional drag of the fluid, can be calculated by:

$$F_{up} = c_D \cdot \frac{\rho_w}{2} \cdot v_s^2 \cdot A$$

in which:

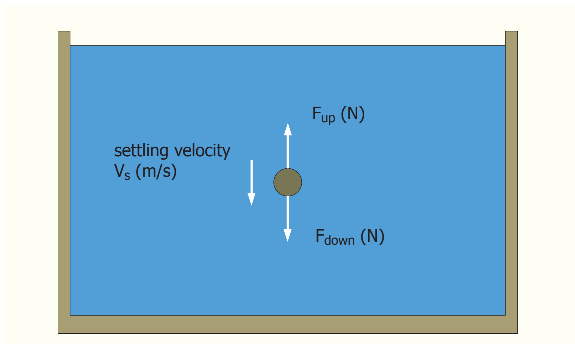


Figure 3 - Forces on a settling particle

F_{up} = force directed upward due to friction (N)
C_D = drag coefficient (-)
ρ_w = density of water (kg/m^3)
v_s = settling velocity (m/s)
A = projected area of the particle (m^2)

The force directed downward, caused by the difference in density between the particle and the water, can be calculated by:

$$F_{down} = (\rho_s - \rho_w) \cdot g \cdot V$$

in which:
F_{down} = force directed downward due to gravity (N)
ρ_s = specific density of particle (kg/m^3)
g = gravity constant (m/s^2)
V = volume of particle (m^3)

Taking into account both forces and assuming that the particle of interest is spherical yields the following equation for settling velocity:

$$v_s = \sqrt{\frac{4}{3 \cdot c_D} \cdot \frac{\rho_s - \rho_w}{\rho_w} \cdot g \cdot d}$$

in which:
d = diameter of spherical particle (m)

The settling velocity is thus dependent on:
- density of both the particle and the fluid
- diameter (size) of the particle
- flow pattern around the particle.

The flow pattern around the particle is incorporated in the drag coefficient. The value of the drag coefficient is not constant, but depends on the magnitude of the Reynolds number for settling.
For spherical particles the Reynolds number is given by:

$$Re = (Vs \cdot d_{pipe}) / \nu$$

in which:
ν = kinematic viscosity (m^2/s)
d_{pipe} = diameter of the pipe

In drinking water treatment practice, laminar settling is common. The Reynolds number for laminar settling of spheres is Re<1, resulting in the following relationship between the Reynolds number and the drag coefficient:

$$Re < 1 \quad c_D = \frac{24}{Re}$$

Substitution of this relationship in the equation for the settling velocity gives the Stokes' equation:

$$v_s = \frac{1}{18} \cdot \frac{g}{\nu} \cdot \frac{\rho_s - \rho_w}{\rho_w} \cdot d^2$$

The settling velocity is thus dependent on the viscosity of the fluid and also the temperature.

The relationship between kinematic viscosity and temperature is:

$$\nu = \frac{497 \cdot 10^{-6}}{(T + 42.5)^{1.5}}$$

in which:
T = temperature (°C)

When the Reynolds number Re > 1,600, settling is turbulent and when 1<Re<1,600, settling is in transition between laminar and turbulent.
In Figure 4 the relationship between the drag coefficient and the Reynolds number is represented.
In Figure 5 the settling velocity as a function of particle size and density is shown.

2.2 *Horizontal flow settling tanks*

In practice, settling occurs in flowing water. An ideal horizontal flow settling tank has the following characteristics:
- at the inlet the suspension has a uniform composition over the cross-section of the tank
- the horizontal velocity, vo is the same in all parts of the tank
- a particle that reaches the bottom is definitive-

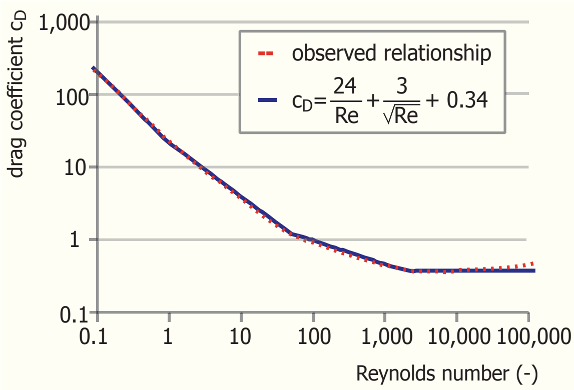


Figure 4 - Relationship between Reynolds number and drag coefficient

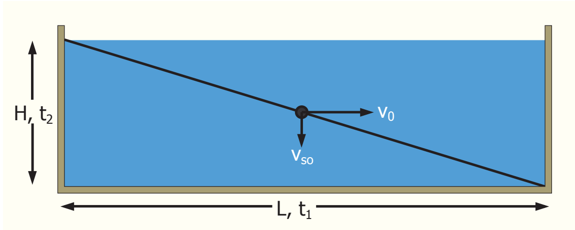


Figure 6 - Settling in a horizontal flow settling tank

ly removed from the process and is not re-suspended.

The flow velocity in a horizontal settling tank is:

$$v_o = \frac{Q}{B \cdot H}$$

in which:

V_0	=	horizontal flow velocity	(m/h)
Q	=	flow	(m^3/h)
B	=	width of the tank	(m)
H	=	height of the tank	(m)

The surface loading of a settling tank is determined by:

$$v_{so} = \frac{Q}{B \cdot L}$$

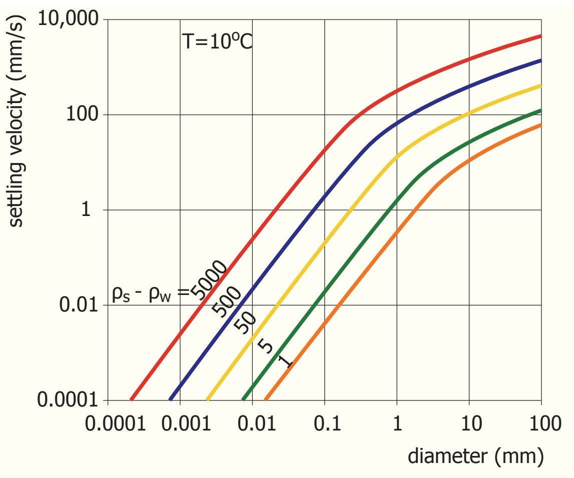


Figure 5 - Settling velocity of discrete spherical particles

in which:

V_{so}	=	surface loading	($m^3/(m^2.h)$)
L	=	length of the tank	(m)

In Figure 6 the trajectory of a particle is represented. At t_1 the water leaves the tank and after t_2 the particle has settled. The particles settle, therefore, when $t_2 < t_1$.

The velocity of the particle is divided into horizontal and vertical components and the settling times can be written as:

$$t_2 \leq t_1 \Rightarrow \frac{H}{v_s} \leq \frac{L}{v_0} \Rightarrow \frac{H}{v_s} \leq \frac{B \cdot H \cdot L}{Q}$$

$$\Rightarrow \frac{1}{v_s} \leq \frac{1}{v_{so}} \Rightarrow v_s \geq v_{so}$$

In special cases, when the settling velocity equals the surface loading, the particle reaches the end of the tank. This settling velocity is called the critical velocity vso and is also equivalent to the surface loading.

It can be concluded that a particle will only be removed if the settling velocity is greater than or equal to the critical settling velocity (Figure 7). After determining the settling velocity of a particle during a settling test, the surface loading and thus the dimensions of an ideal tank can be determined. It is remarkable that, in theory, settling in a horizontal flow settling tank is only determined by the flow and the surface area of the tank and is independent on the height of the tank.

The fraction of the particles that settle in the case vs < vso is (Figure 7):

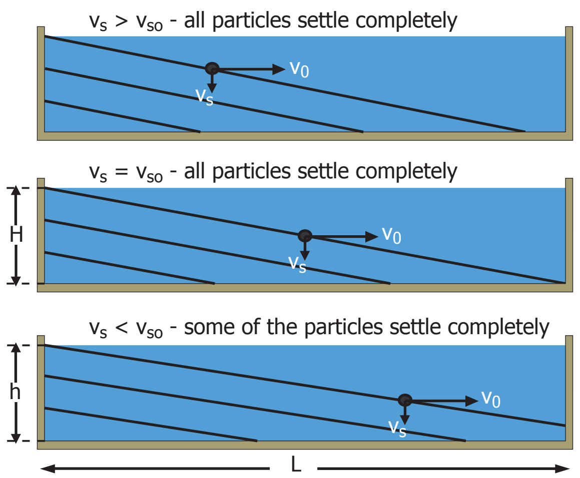


Figure 7 - Settling of a suspension in a horizontal flow settling tank

$$\frac{h}{H} = \frac{v_s \cdot T}{v_{so} \cdot T} = \frac{v_s}{v_{so}}$$

in which:
T = residence time of water in the settling tank(s)

The residence time of water in the settling tank is expressed as T and equals t_1 from Figure 6.

2.3 Settling efficiency of a suspension

In a suspension, the fraction of particles with a settling velocity higher than the surface loading settle completely. The fraction with a lower settling velocity settles partly. The efficiency is determined from the cumulative frequency distribution of settling velocities obtained from a settling test.

The settling test is executed in a cylindrical container (column) filled with a homogeneous sample of the suspension to be tested (Figure 8). At different time intervals samples are taken at different depths and analysed for suspended solids, turbidity or any other index that can be reduced by settling. The depth is measured using the water surface level as reference. In Table 1 the analyses of a settling column test at depth h=1.0 m are listed and this situation is represented in Figure 8.

In Figure 9 the cumulative frequency distribution of the settling velocities is represented. The ratio of sampling depth and time is given as a function of the relative solids concentration. The solids with the lowest settling velocity determine the residence time of a settling system.

The particles with a settling velocity higher than the critical settling velocity vso are removed completely. This is represented in Figure 9 by the red arrow. , the part of the settling efficiency that is

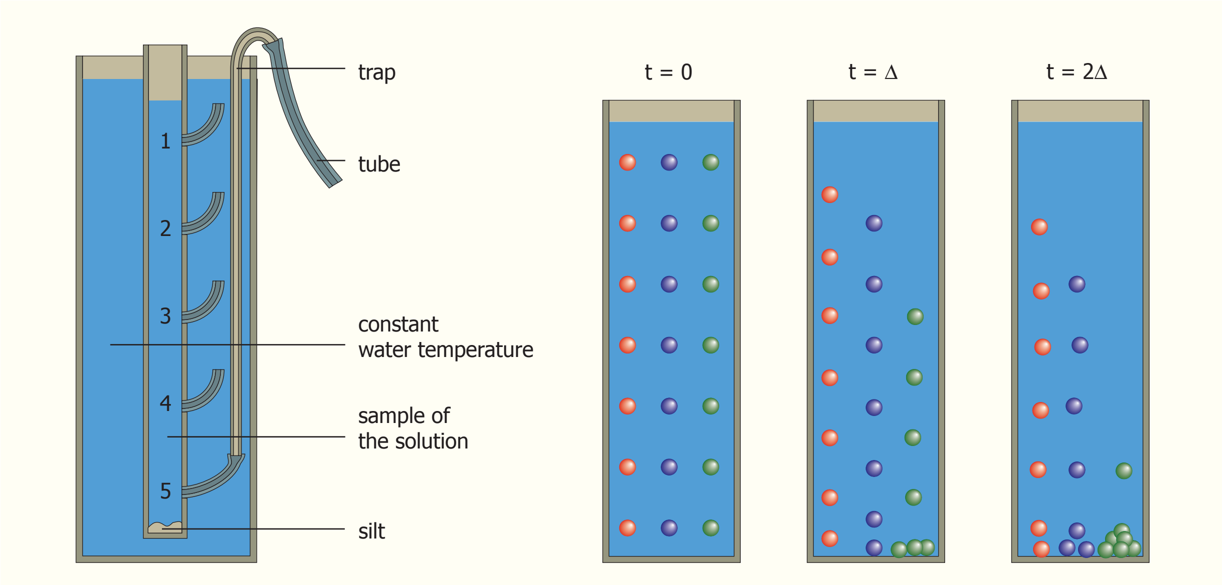


Figure 8 - Settling column and representation of different settling velocities

Table 1 - Particle concentration and relative particle concentration from a settling test at a depth of h = 1.0 m

t (s)	0	600	900	1,800	2,700	3,600	5,400	7,200
c (ppm)	86	84	79	57	41	29	7	3
$p=c/c_o$ (%)	100	98	92	66	48	34	8	4

caused by complete settling, for a relative solids concentration p0, at a settling velocity of Vs0 is

$$r_1 = 1 - p_o$$

in which:

r_1 = the portion of the overall efficiency of a settling tank caused by complete settling (-)

po = relative solids concentration at surface loading V_{so} (%)

From the particles with a lower settling velocity than vso, only the particles that enter the tank at a reduced height will be removed.

From the fraction of particles, dp, with settling velocity vs, only the fraction h/H or vs/vso will be removed. (Section 2.2) This part of the efficiency (partial removal) can be described by:

$$r_2 = \int_0^{p_o} \frac{v_s}{v_{so}} dp = \frac{1}{v_{so}} \int_0^{p_o} v_s dp$$

in which:

r_2 = the portion of the overall efficiency of a settling tank caused by partial settling (-)

The efficiency caused by partial settling is represented by the blue surface in Figure 9 divided by the critical settling velocity. Graphically, this part of the total efficiency can be determined as shown in Figure 10.

The equation of the total settling efficiency becomes:

$$r = (1 - p_o) + \frac{1}{v_{so}} \int_0^{p_o} v_s dp$$

For different values of vso the efficiency is calcu-

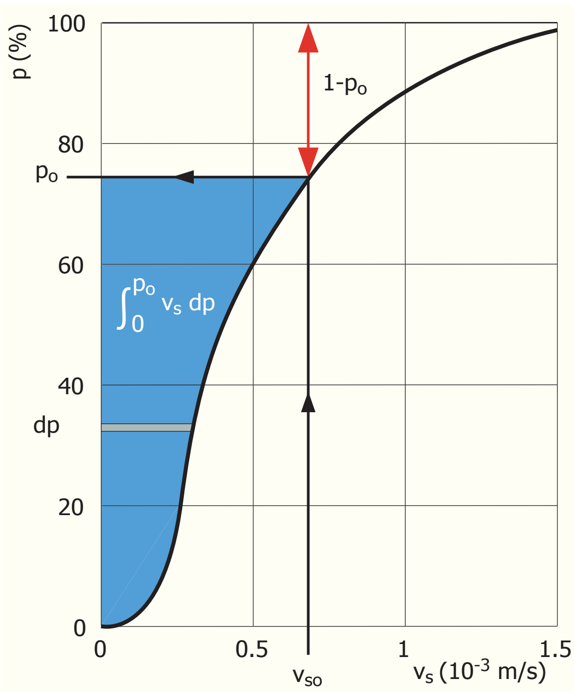


Figure 9 - Cumulative frequency distribution of settling velocities

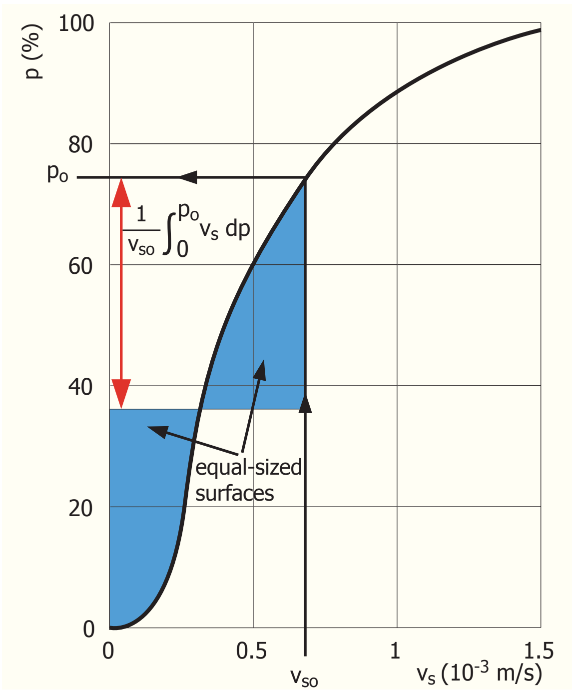


Figure 10 - Efficiency of partial settling

lated and the results are represented in Figure 11. It is concluded that the increase of the surface loading in a settling tank, decreases the settling efficiency.

2.4 Factors that affect settling

In the preceding paragraphs an ideal flow and discrete settling were assumed. In practice, however, the ideal situation does not exist and efficiency is influenced by density, size, temperature, turbulence, stability, bottom scour and flocculation

Regarding the density and the size of the particles, the bigger these are, the faster is the settling, whereas the lower is the temperature, the higher is the viscosity and the slower is the settling. Other factors that affect settling are discussed in more detail in the further paragraphs.

2.4.1 Turbulence

When the flow in a horizontal flow tank is laminar, the trajectory of a particle is straight . In turbulent flow, however, particles are transported by eddies in random directions., influencing the settling of particles (some settle faster and others slower) (Figure 12). In general, the more turbulent the flow, the slower is the settling.

The flow characteristics can be determined, based on the Reynolds number

- laminar flow: Re < 2000

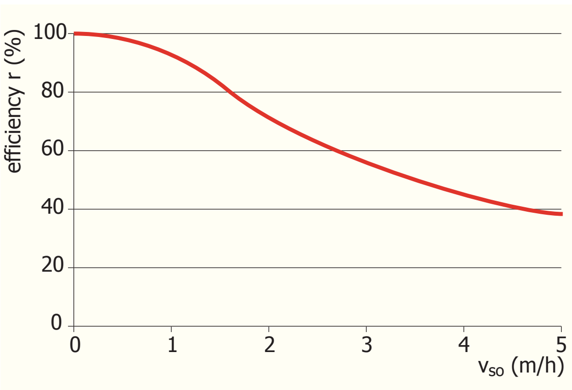


Figure 11 - Removal efficiency in a horizontal flow settling tank

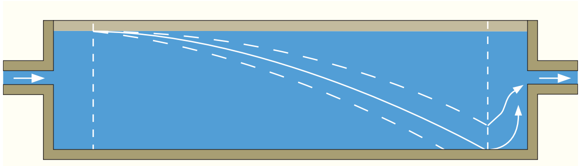


Figure 12 - Influence of turbulence on settling in a horizontal flow settling tank

- turbulent flow: Re > 2000.

In Figure 13 the settling efficiency for turbulent flow is represented as a function of vs/vso and vs/vo.

In practice, turbulence is not always a disadvantage since it increases the collision frequency of particles , thus increasing the efficiency of flocculant settling (section 3.4).

2.4.2 Stability

Flow is called stable when short circuiting does not occur. In Figure 14 an example of a short-circuit flow caused by wind effects is illustrated. The wind creates a dead zone (or eddy) in the corner of the settling tank which can lead the water to flow, locally, in the opposite direction from the general flow through the tank.

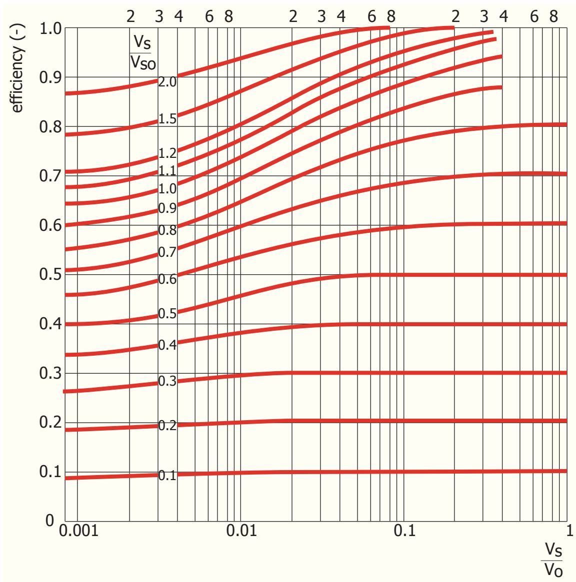


Figure 13 - Influence of turbulence on the efficiency of settling

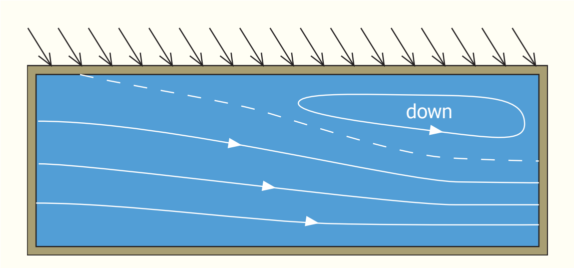


Figure 14 - Short-circuit flow caused by wind

Stability of flow is characterized by the Froude number Fr.

$Fr = V^2 / gR$

Substituting the equations for V and R for a rectangular tank, the Froude number becomes:

$Fr > 1.10^{-5}$ stable flow

$Fr < 1.10^{-5}$ unstable flow

2.4.3 Bottom scour

In theory, a particle is removed from the water when it reaches the bottom of the settling tank.

However, when bottom scour occurs, settled particles are re-suspended and washed out with the effluent.

In Figure 15 the forces on particles at the bottom of the tank are shown.

When the flow velocity in a settling tank is lower than the critical scour velocity, bottom scour doesnot occur:

2.4.4 Flocculation

Flocculation results in larger particles, increasing

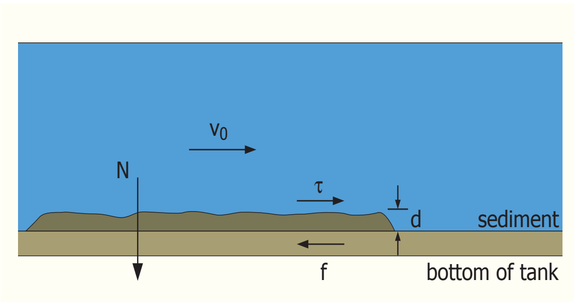


Figure 15 - Bottom scour

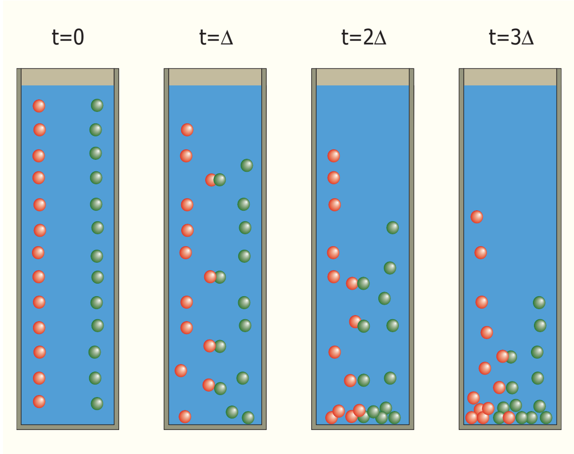


Figure 16 - Flocculant settling

the settling velocity.

During settling, the formation of aggregates as a result of collisions between particles, leads to the increase of settling velocity. This phenomenon is called flocculant settling (Figure 16).

Table 2 shows the results of a settling test for a flocculant suspension. Figure 17 presents the cumulative frequency distribution of settling velocities at different tank depths. Sincethe distributions differ over the height of the tank, it is concluded that flocculant settling occurs.

From Figure 18 it can also be concluded that the efficiency increases with the increasing depth. Contrary to discrete settling, the height of the tank is important for the efficiency of flocculant settling.

3. Design of an ideal settling tank

In ideal settling tanks the flow is stable ($Fr > 10^{-5}$) and not turbulent ($Re < 2,000$).

At a temperature of 10 °C these conditions are met with a horizontal flow velocity and a hydraulic radius of:

$V_0 = 6.4.10^{-3}$ m/s

$R < 0.41$ m

Table 2 - Relative particle concentration from a settling test

	h = 0.075 m	h = 1.5 m	h = 2.25m	h = 3.0 m
t = 0 s	100	100	100	100
t = 600 s	93	96	98	99
t = 1200 s	81	86	88.5	89.5
t = 1800 s	70.5	77.5	81	83
t = 2700 s	28	38	46.5	53
t = 3600 s	13.5	22	31	40
t = 5400 s	3	8	13.5	20
t = 7200 s	1.5	3	6	9.5

Tanks that meet these conditions are short, wide and shallow or long, narrow and deep (Figure 19). Such configurations are expensive to build due to the amount of space they require.

In practice, the structure of sedimentation tanks considers not only the Reynolds and Froude numbers but also the construction costs , thus leading to a compromise between the length, width and depth ratios.

3.1 Inlet constructions

In the preceding paragraphs it was assumed that the water is uniformly distributed over the tank cross-section, but in practice this does not occur.

For an even distribution of the water over the width (and depth) of the tank, inlet constructions are introduced. Figure 20 shows an example of an inlet construction.. The inlet velocity is reduced by several inlet channels, followed by a diffuser wall (Figure 21) that distributes the water through openings, over the entire cross-section (width and depth) of the tank.

At the end of the wall, the flow velocity and the velocity head in the inlet channel are zero. The head loss caused by friction, however, is lower than the decrease in velocity head, resulting in apiezometric level increase.

The water level at the end of the inlet channel is, thus, higher than the level at the beginning and, therefore,there is more water entering the tank at the end of the inlet than at the beginning.. To avoid this uneven distribution, the head loss over the openings in the diffuser wall must be larger than the difference in piezometric level induced by the decrease in flow velocity.

In practice, alternative inlet constructions include the Clifford and the Stuttgarter inlet (Figure 22).

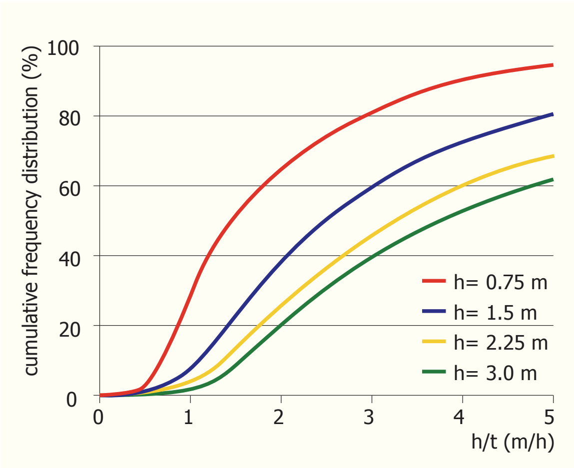


Figure 17 - Cumulative frequency distribution of settling velocities at different tank depths

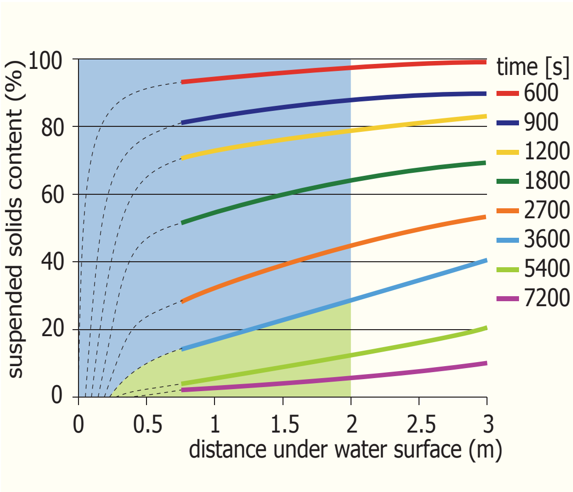


Figure 18 - The relative particle concentration

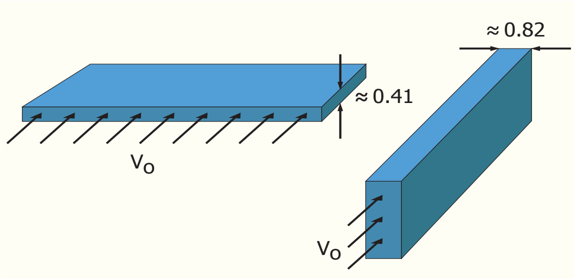


Figure 19 - Settling tanks with laminar and stable flows

3.2 Outlet constructions

The outlet construction is situated at the end of the settling tank and generally consists of an overflow weir. At the outlet, re-suspension of settled solids must be prevented so the flow velocity in an upward direction must be limited (Figure 23).

The flow velocity in an upward direction is:

$$v_H = \frac{1}{5} \cdot \frac{Q}{B \cdot H} < v_{so}$$

in which:
vH =outflow velocity in an upward direction [m/s]

Resulting in:

$$\frac{L}{H} < 5$$

Most of the horizontal flow settling tanks have an L/H>5 and thus:

$$\frac{Q}{n \cdot B} < 5 \cdot H \cdot v_{so}$$

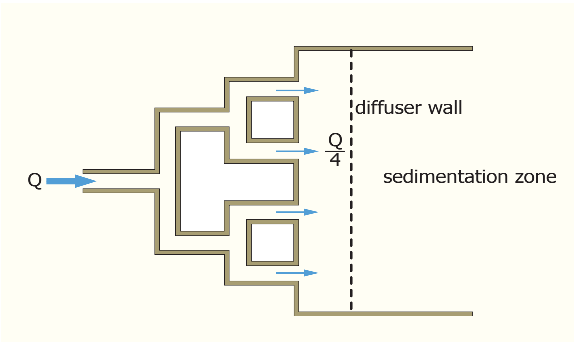


Figure 20 - Inlet construction

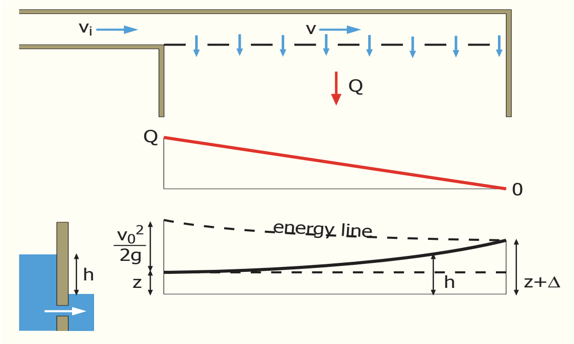


Figure 21 - Diffuser wall

Therefore, the length of the overflow weir must be several times the width of the tank.
To create sufficient length for the overflow weir, several troughs are placed parallel to each other (Figure 24).

3.3 Sludge zone and removal

In the sludge zone the solids accumulate and their removal is done hydraulically or mechanically.

Hydraulic sludge removal is done at regular intervals by dewatering the tank and flushing the sludge with pressured water (from hydrants) to a hopper at the bottom of the tank from where it is removed by gravity or by pumping.

Mechanical sludge removal is frequently applied when sludge volumes are large or the sludge is unstable, resulting in anaerobic decomposition during storage in the sludge zone. This type of removal consists of scrapers that transport the sludge to a hopper in the middle of a round settling tank or near the inlet of a rectangular tank,

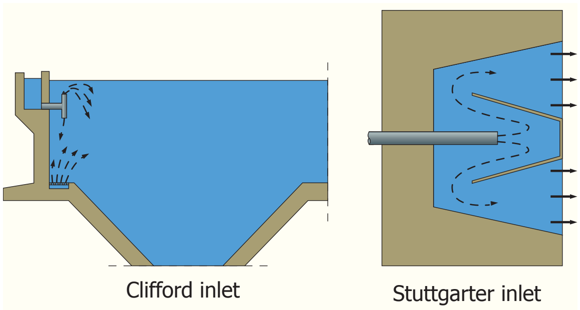


Figure 22 - Clifford and Stuttgarter inlet

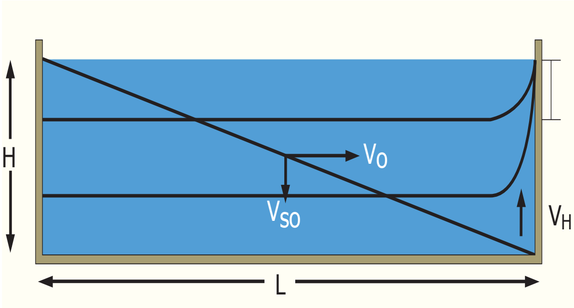


Figure 23 - Upward velocity to overflow weir

from where the sludge is finally removed.

4. Settling tank alternatives

4.1 Vertical flow settling tank

In vertical flow settling tanks the inlet of the water is situated at the bottom of the tank and the water flows in an upward direction (Figure 25).
The flow velocity, in this case, equals the surface loading:

$$v_0 = \frac{Q}{B \cdot L} = v_{so}$$

Therefore only particles with a settling velocity greater than the upflow velocity settle, whereasother particles are washed out:

$V_s >= V_{so}$ settles completely
$V_s < V_{so}$ does not settle

The settling efficiency is entirely determined by the particles that settle completely (see Figure 9):

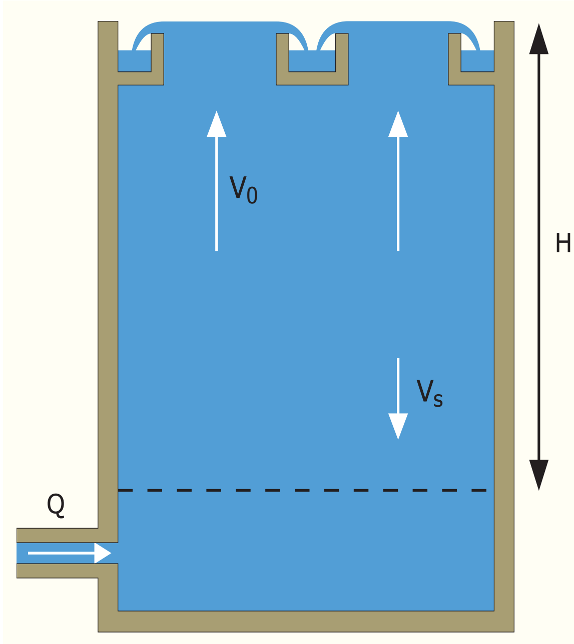


Figure 25 - Vertical flow settling

$$r = 1 - p_o$$

Vertical flow tanks are used for flocculant settling (e.g., in the form of floc blanket clarifiers) but not for discrete settling, since in this case, the efficiency is higher when horizontal tanks are used.

4.2 Floc blanket clarifier

The floc blanket clarifier consists of a (conical) vertical flow tank (Figure 26). Coagulant is dosed at the inlet of the clarifier to promotefloc formation.. Small, light flocs with a settling velocity lower than the upflow velocity are transported with the water flow in an upward direction and collide with larger, heavier flocs. Due to collision,

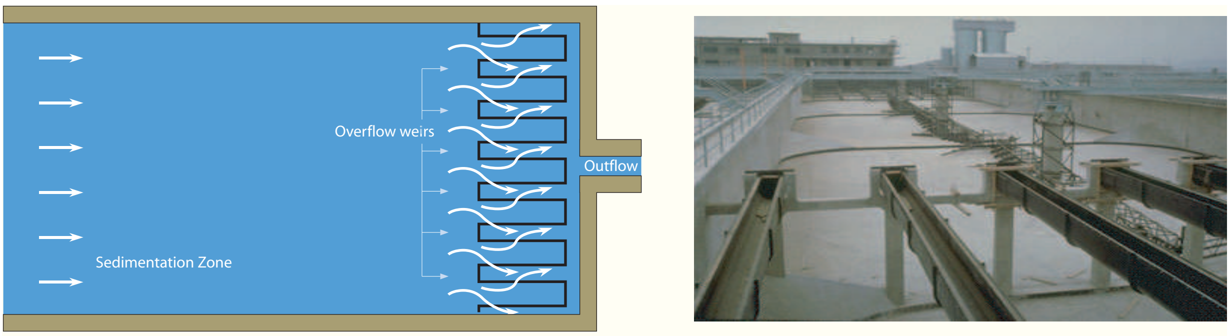


Figure 24 - Outlet construction: overflow weir for effluent discharge

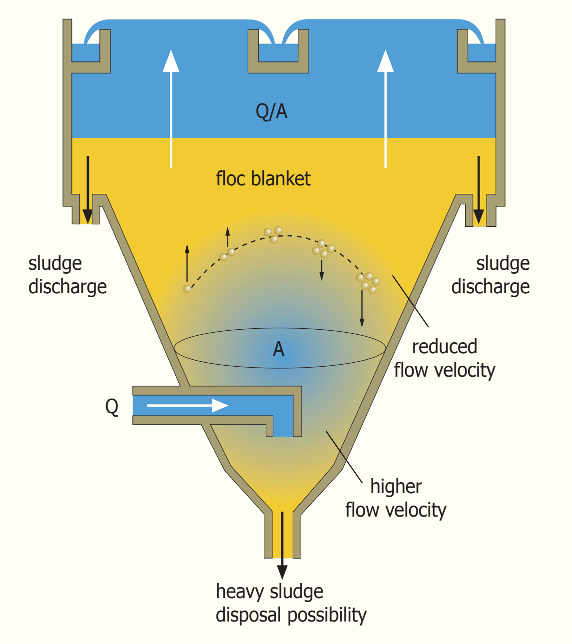


Figure 26 - Floc blanket installation

there isattachment of particles and consequent increase of the settling velocityuntil they reach the bottom of the tank, where a sludge removal device is installed.

Flocs that do not form aggregates are transported to the top of the installation where the surface area is the largest and the upflow velocity the lowest, and a floc blanket is formed. The floc blanket has a filtering effect for small flocs. Therefore, high efficiencies can be achieved with relatively short residence times.

In The Netherlands, the Berenplaat plant in Rotterdam uses floc blanket clarifiers (Figure 27). The inlet of the water is at the top of the installation. A stirring device creates turbulence in the floc formation chamber to increase the collision frequency. After leaving the mixing chamber, the flocs form a blanket and the effluent water is drained by troughs.

4.3 Tray settling tanks

The efficiency of discrete settling can be increased by applying horizontal baffles (false floors or trays) (Figure 28).

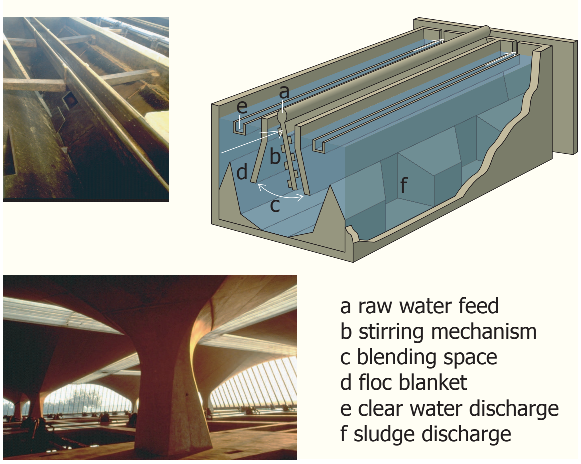


Figure 27 - Floc blanket installation at Berenplaat

In section 2.2 it is shown that the settling efficiency for discrete particles is independent of the height of the settling tank. The application of horizontal baffles gives a double surface area and half of the surface loading, resulting in an increase of efficiency. Horizontal baffles also improve the flow pattern, decreasingthe Reynolds number andincreasing the Fourde number, which results in aless turbulent and more stable flow.

4.4 Tilted plate settling

In tilted plate settling tanks, water passes baffles that are placed at a steep angle.

In Figure 29, an example is given of a counter-current tilted plate settling tank. The water flows in an upward direction while the sludge settles on the plates and slides down. The angle of the plates must be about 55o to 60o to guarantee sludge removal.

In Figure 30, the flow in a counter-current tilted plate settling tank is pictured.

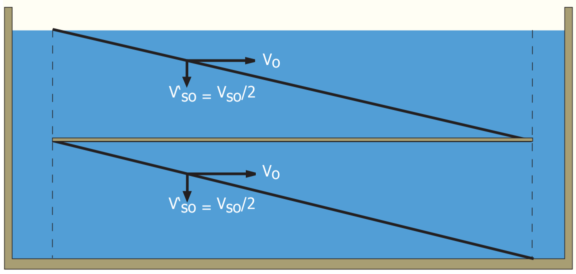


Figure 28 - Tray settling

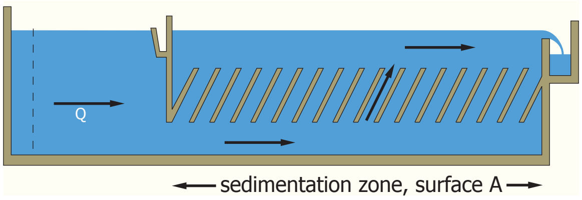


Figure 29 - Counter-current tilted plate settling

the space occupied by tilted plate settling tanks is smaller by a factor of 20 than what is needed for horizontal flow tanks.

4.5 Optimal hydraulic conditions

Both the Froude number and the Reynolds number depend on the hydraulic radius and the horizontal flow velocity.

In Figure 31 the stability boundary, Fr > 10^{-5}, and the turbulence boundary, Re < 2,000, are given. In addition, the combinations of hydraulic radius and horizontal flow velocity of horizontal flow and tilted plate tanks applied in practice are shown. From the graph it can be derived that the flow in horizontal flow tanks is turbulent and in some cases unstable (and short-circuit flow can occur). The flow in tilted plate tanks, however, is favorable. The Reynolds number is always smaller than 2,000, resulting in laminar flow; and the Froude number is always higher than 10^{-5}, resulting in a stable flow without short-circuiting.

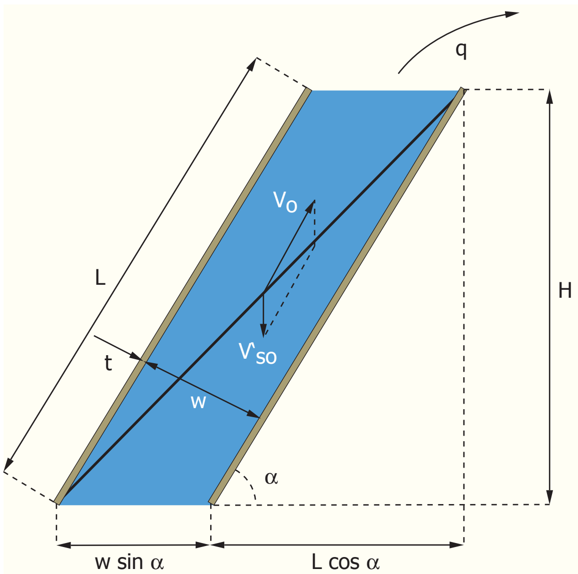


Figure 30 - Flow through a tilted plate settler

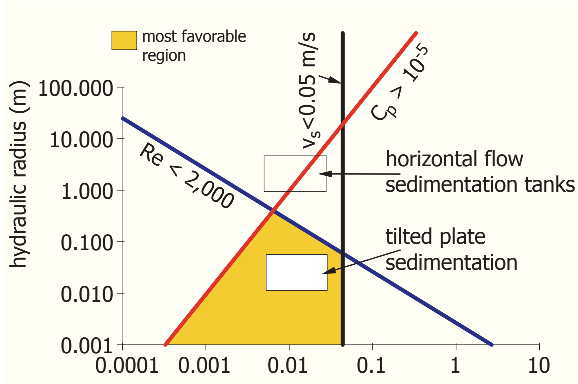


Figure 31 - Hydraulic conditions for optimal settling