

CHAPTER 1

SEDIMENTATION

SEDIMENTATION PROCESSES

Sedimentation is used to remove suspended solids from waste water. The settling tank has three main functions:

- (1) It must provide for effective removal of suspended solids so that its effluent is clear.
- (2) It must collect and discharge the supernatant stream of sludge.
- (3) It must thicken the sludge to a certain concentration of solid.

Three distinct types of sedimentation may be considered:

- (1) Discrete settling. This is the settling of a dilute suspension of particles which have little or no tendency to flocculate.
- (2) Flocculent settling, which occurs when the settling velocity of the particles increases as they fall to the bottom of the tank, due to coalescence with other particles.
- (3) Zone settling, which happens when interparticle forces are able to hold the particles in a fixed position relative to each other. In this case the particles sink as a large mass rather than as discrete particles.

Mathematical descriptions of the three cases must be treated separately.

Discrete settling

The settling of a discrete non-flocculating particle in a dilute suspension can be described by means of classical mechanics. Such a particle is not affected by the presence of other particles, and settling is therefore a function only of the properties of the fluid and the characteristics of the particles. As shown in Fig. 1.1, the particle is affected by three forces:

- (1) Gravity, F_g ,
- (2) the buoyant force, F_b and
- (3) the frictional force, F_f .

In accordance with Newton's second law of motion, we can set up the following equation:

$$m \frac{dv_s}{dt} = F_g - F_b - F_f \quad (1.1)$$

where v_s = the linear settling velocity of the particles,
 m = the mass of the particles and t = time.

Gravity is given by:

$$F_g = \rho \cdot V \cdot g \quad (1.2)$$

where ρ = the particle density, V = the particle volume and g = the acceleration due to gravity.

The buoyant force is:

$$F_b = \rho_e \cdot V \cdot g \quad (1.3)$$

where ρ_e = the fluid density.

The frictional force is a function of different particle parameters, such as roughness, size, shape and velocity of the particle, and of the density and viscosity of the fluid. It can be described by the following relationship:

$$F_f = \frac{C_d \cdot A \cdot \rho_e \cdot v_s^2}{2} \quad (1.4)$$

where C_d = Newton's dimensionless drag coefficient and A = the projected particle area in the direction of the flow. C_d varies with Reynolds number.

By substituting the equations (1.2), (1.3) and (1.4) in equation (1.1), an expression for the dynamic behaviour of the particles is obtained:

$$m \cdot \frac{dv_s}{dt} = g(\rho - \rho_e)V - \frac{C_d \cdot A \cdot \rho_e \cdot v_s^2}{2} \quad (1.5)$$

After an initial transient period the acceleration becomes zero and the velocity is constant. This velocity can be obtained from equation (1.5):

$$v_s = \left(\frac{2g(\rho - \rho_e) \cdot V}{C_d \cdot \rho_e \cdot A} \right)^{1/2} \quad (1.6)$$

If the particles are spherical and the diameter is d , the V/A is equal to $2/3 \cdot d$ and equation (1.6) becomes:

$$v_s = \left(\frac{4g(\rho - \rho_e)d}{3C_d \cdot \rho_e} \right)^{1/2} \quad (1.7)$$

Newton's drag coefficient C_d is, as mentioned, a function of Reynolds number and of the shape of the particle. The relationship between C_d and Reynolds number for spheres and cylinders is given in Fig. 1.2.

When Reynolds number is below 1, the relationship between C_d and Re can be approximated by $C_d = \frac{24}{Re}$, where $Re = \text{Reynolds number}$ defined as:

$$\frac{d \cdot \rho_e \cdot v_s}{\mu}, \text{ where } \mu = \text{the viscosity.}$$

In this case (1.7) conforms with Stokes law:

$$v_s = \frac{g}{18\mu}(\rho - \rho_e) \cdot d^2 \quad (1.8)$$

From Fig. 1.2 it can be seen that C_d is approximately constant for turbulent flow in the range for Reynolds number between 1000 and 250,000. For this region the velocity v_s is given by:

$$v_s = 1.82 \left(\frac{(\rho - \rho_e) \cdot d \cdot g}{\rho_e} \right)^{1/2} \quad (\text{for spheres only}) \quad (1.9)$$

If we consider a section of an ideal settling tank, the particles and velocity vectors are equally distributed, the liquid moves as an ideal slug and all particles reaching the bottom are effectively removed. We can then set up the following equation (Camp, 1945):

$$v_s = \frac{Q}{A} \quad (1.10)$$

where $Q = \text{the rate of flow through the tank}$ and $A = \text{the tank surface area}$. All particles with settling velocities greater than v_s will be completely removed, and particles with settling velocities v less than v_s , will be removed in the ratio v/v_s .

If clear water is drawn off at a surface rate Q/A , the particles should settle at a velocity just opposed by the velocity of the rising liquid. Under such circumstances the top particles will of course be stationary and never reach the bottom, so the overflow rate in equation (1.10) must be considered as a critical minimum value for clarification.

Example 1.1

100 m³/h of waste water must be treated. Discrete settling can be considered of spherical particles with a diameter of approximately 0.1 mm and specific gravity of 1.01 g/ml. Calculate the necessary surface area.

Solution

Assuming that $Re < 1$, then

$$v_s = \frac{10}{18 \cdot 10^{-3}} (1010 - 1000) \cdot (10^{-4})^2 = 5.56 \cdot 10^{-5} \text{ m/s, as } \mu = 10^{-3} \text{ Pa/s.}$$

For water:

$$Re = \frac{10^{-4} \cdot 1000 \cdot 5.56 \cdot 10^{-5}}{10^{-3}} = \ll 1$$

The assumption was right, and:

$$A = \frac{Q}{v_s} = \frac{100/3600}{5.56 \cdot 10^{-5}} \cong 500 \text{ m}^2.$$

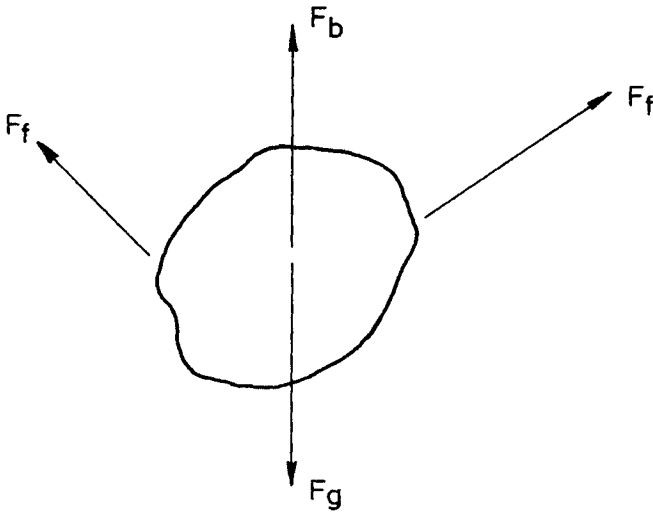


Fig. 1.1. The settling particle is affected by three forces: The gravity, F_g , the buoyant force, F_b and the frictional force, F_f .

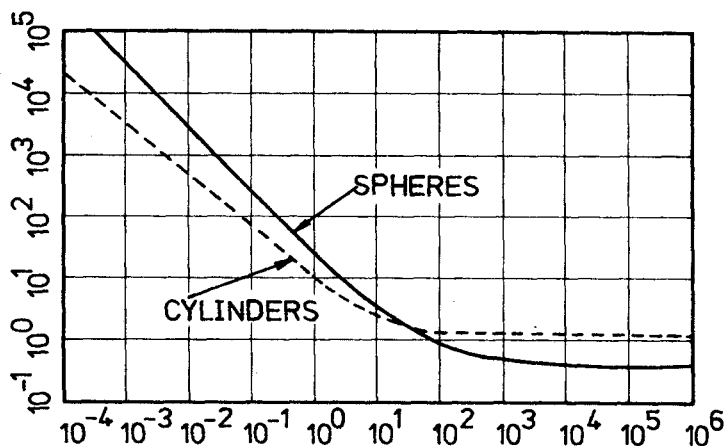


Fig. 1.2. Experimental variation of the drag coefficient with Reynolds number. After Fair et al. (1968).

Flocculent settling

Suspended solid in industrial waters cannot usually be described as discrete particles. If any of the interacting particles have characteristics which might cause agglomeration, growth of individual particles to larger sizes is a natural consequence. Hence, the greater the tank depth, the greater is the opportunity for contact among particles and so sedimentation depends on the depth as well as on the properties of the fluid and the particles.

As yet, there is no satisfactory formulation for predicting the effect of flocculation on the settling rate. Thus flocculent settling requires extensive testing to define the characteristics of the waste water.

Evaluation of the sedimentation characteristics of flocculent settling can be accomplished by placing a quantity of the waste water in a column similar to the one shown in Fig. 1.3. The suspension is settled and the concentration of the particles is determined on samples withdrawn at the different sampling points. The fraction of the particles removed at each step is used to construct lines showing equal fraction or equal per cent removal as illustrated in Fig. 1.4. The lines are called isoconcentration lines: The per cent maximum settling path for the indicated per cent removal.

If the tank has an overflow rate of $v_1 = H_4/t_2$ all particles having a settling velocity $\geq v_1$ will be removed from the tank and particles with a velocity $v < v_1$ will be removed in proportion to v/v_1 .

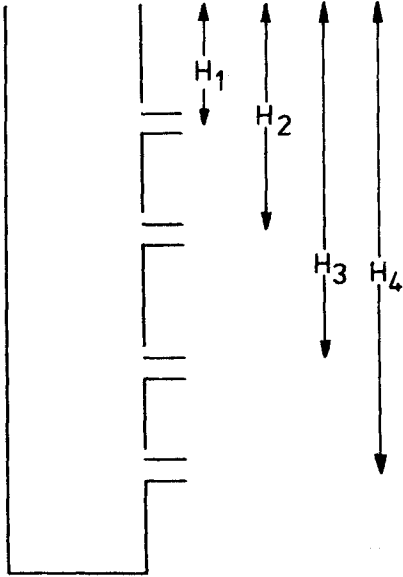


Fig. 1.3. Column with four sampling points for settling tests.

Fig. 1.4 shows that the remaining solid between R_a and R_b has settled with an average velocity of $v = H'/t_2$ and the solid between R_c and R_d has settled with an average velocity of H''/t_2 . An approximation for the total overall removal, R , by the chosen overflow is given by:

$$R = R_c + \frac{H'}{t_2 \cdot v_1} (R_b - R_c) + \frac{H''}{t_2 \cdot v_1} (R_a - R_b) \quad (1.10)$$

This approximation can be improved by adding more terms and increasing the interval between the isoconcentration lines.

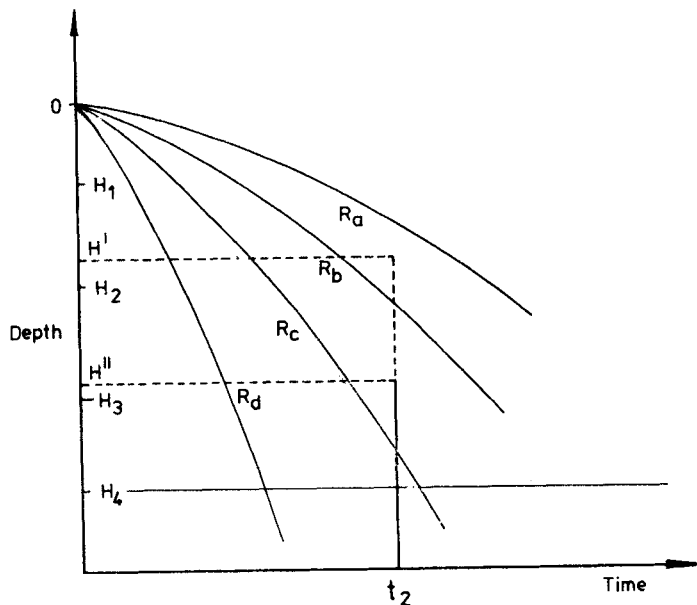


Fig. 1.4. The result of a settling test illustrated with isoconcentration lines: R_a , R_b , R_c and R_d .

Zone settling

Zone settling of activated sludge and flocculated chemical suspension occurs when the concentration of solids exceeds approximately 0.5 g/l. The particles form a mass, which settles as a blanket with a distinct interface between the settling sludge and the clarified effluent. The interface can be observed in a batch settling test. Initially all the suspension is at a uniform concentration and the height of the interface as Z_0 (see Fig. 1.5 which shows the height of the interface plotted against time). In the region A-B, settling is hindered, but proceeds at a constant rate. The region B-C shows a transition into the compression zone, represented by C-D. The zones are further illustrated in Fig. 1.6.

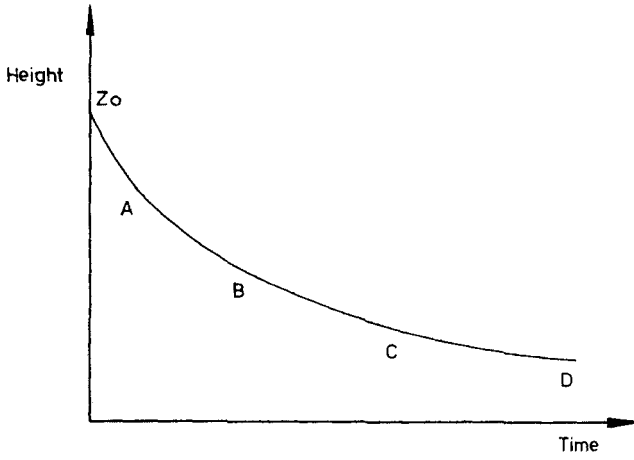


Fig. 1.5. Height of interface in zone settling as function of the time.

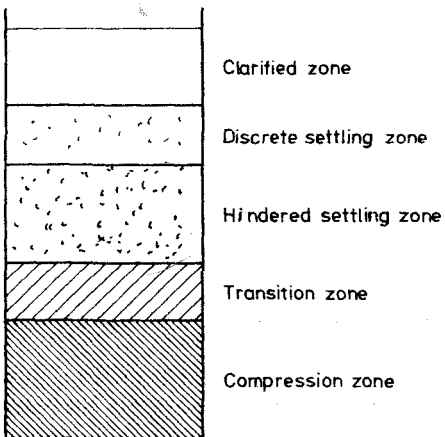


Fig. 1.6. Illustration of the zones in zone settling.

It is possible to design a continuous clarifier based on the batch settling test. Two areas must be calculated; A_1 , the area required for clarification, and A_2 , the area required for thickening. A_1 can be calculated from:

$$A_1 = \frac{Q}{v_s} \quad (1.11)$$

where v_s now = the subsidence velocity for hindered settling and Q = as previously defined.

To find A_2 it is necessary to find the relationship between settling rate and the concentration in the sludge. The tangent is drawn at different points of the settling curve and the slope of the tangent indicates the settling rate, v (see Fig. 1.7). The corresponding concentration in the sludge is calculated from the following equation:

$$C = \frac{C_o \cdot Z_o}{Z} \quad (1.12)$$

where C_o = the slurry concentration at the start of the settling, Z_o (as mentioned above) = the total height and Z is as shown in Fig. 1.7. By use of this equation it is possible to calculate C , the concentration of suspended solid in the sludge layer, as a function of the settling rate. It is now possible to calculate W_s , defined as the weight of solid in sludge produced per minute per m^2 (Badger and Banchemo, 1955):

$$W_s = \frac{v}{\frac{1}{C} - \frac{1}{C_s}} \quad (1.13)$$

where C_s is equal to the required concentration of suspended solid in the layer.

W_s is calculated for different values of C , and the minimum value for W_s is used to determine the area necessary for thickening. The area per m^3/h , A , is found by dividing the sludge concentration C_o by W_s , where C_o is defined above:

$$A = \frac{C_o}{W_s} \quad (1.14)$$

Example 1.2

In Fig. 1.8 the results are shown of six different batch settling tests (Jørgensen, 1971). On the basis of a sludge concentration of

20 g/l, find the area per m^3 of waste water treated for the six different precipitations. $C_o = 1.1$ g/l for precipitation with sulphuric acid and 1.4 g/l for precipitation with the other precipitants.

Solution

Based on Fig. 1.8 we construct Fig. 1.9, using equation (1.12), and Fig. 1.10 using equation (1.13).

Finally the area A is found, based on equation (1.14).

The results are summarized in Table 1.1.

TABLE 1.1

$C_s = 20$ g/l

Precipitation with	W_s -min kg/h·m ²	C_o (g/l)	Area (m ³)	C_s by additional settling(g/l)	Chemical (g/l)
Sulphuric acid	0.06	1.1	18.2	48	0.02
Aluminium sulphate	0.15	1.4	9.3	72	0.1
Glucose trisulphate	0.15	1.4	9.3	90	0.1
Sulphite liquor	0.83	1.4	1.7	78	0.1
Lignin sulphonic acid	0.83	1.4	1.7	78	0.1
Glucose trisulphate + azoprotein (ratio 10:1)	1.32	1.4	1.1	102	0.1

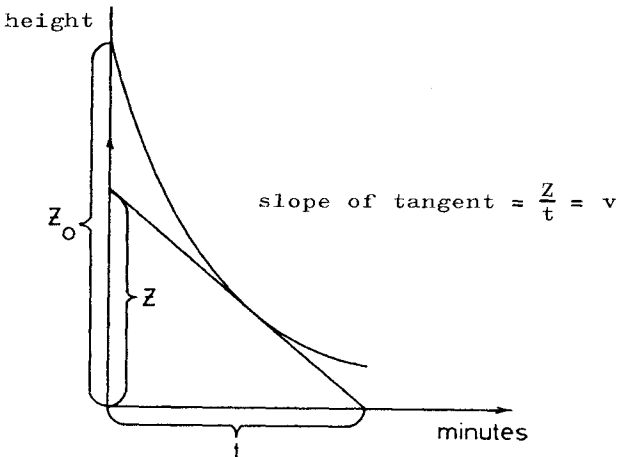


Fig. 1.7. Sedimentation. Z_o is total height. Slope of tangent (settling rate) is found as Z_o/t .

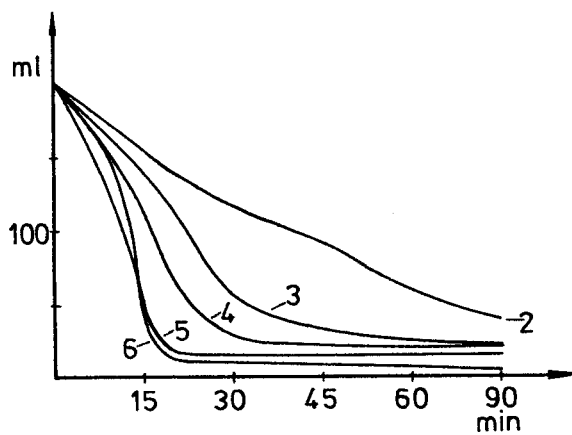
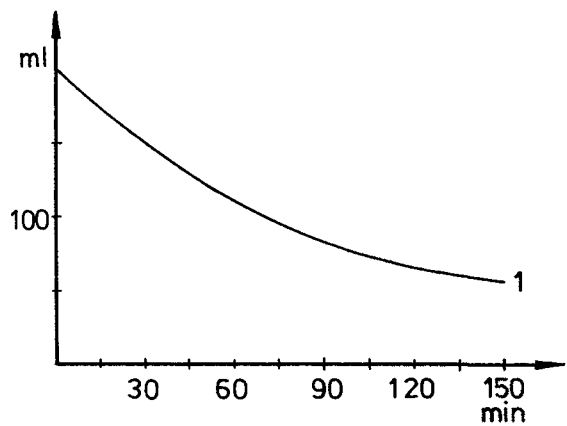


Fig. 1.8. Settling plotted against time for precipitation with:
 1. sulphuric acid 0.03 g/l, 2. glucose trisulphate 0.1 g/l,
 3. aluminium sulphate 0.1 g/l, 4. sulphite liquor 0.2 g/l,
 5. lignin sulphonic acid 0.1 g/l, 6. glucose trisulphate +
 10% azoprotein (total 0.1 g/l). pH for all samples 4.3.

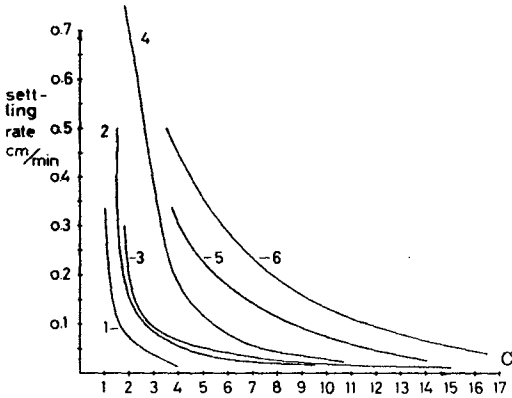


Fig. 1.9. Settling rate in cm/min is plotted against the slurry concentration at the transition layer for precipitation with - 1. sulphuric acid 0.03 g/l, 2. glucose trisulphate 0.1 g/l, 3. aluminium sulphate 0.1 g/l, 4. sulphite liquor 0.2 g/l, 5. lignin sulphonic acid 0.1 g/l, 6. glucose trisulphate + 10% azoprotein (total 0.1 g/l). pH for all samples 4.3.

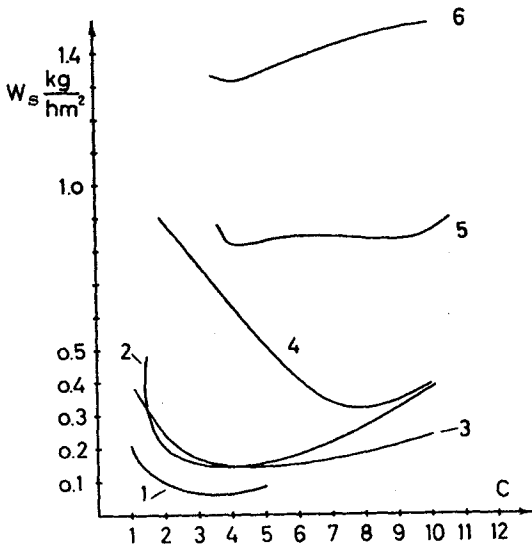


Fig. 1.10. Weight of solid produced kg/h m², W_s , for different values of C = concentrations of solid in the transition layer. 1. sulphuric acid 0.03 g/l, 2. glucose trisulphate 0.1 g/l, 3. aluminium sulphate 0.1 g/l, 4. sulphite liquor 0.2 g/l, 5. lignin sulphonic acid 0.1 g/l, 6. glucose trisulphate + 10% azoprotein (total 0.1 g/l). pH for all samples 4.3.

Dispersion patterns and short circuiting

Plug flow is never achieved in practice. Some of the particles will be short circuited and will therefore be held in the tank for a time less than V/Q , where V = the tank volume and Q = the flow rate (m^3/h).

Wind effects, hydraulic disturbances and density and temperature effects will all result in a deviation from the ideal plug flow. Short circuiting in a tank can be characterized by tracer techniques. Dye, salt or radioactive materials are introduced into the inlet and the concentration distribution in the effluent stream indicates the flow patterns. Some typical curves for effluent concentration versus time are shown in Fig. 1.11.

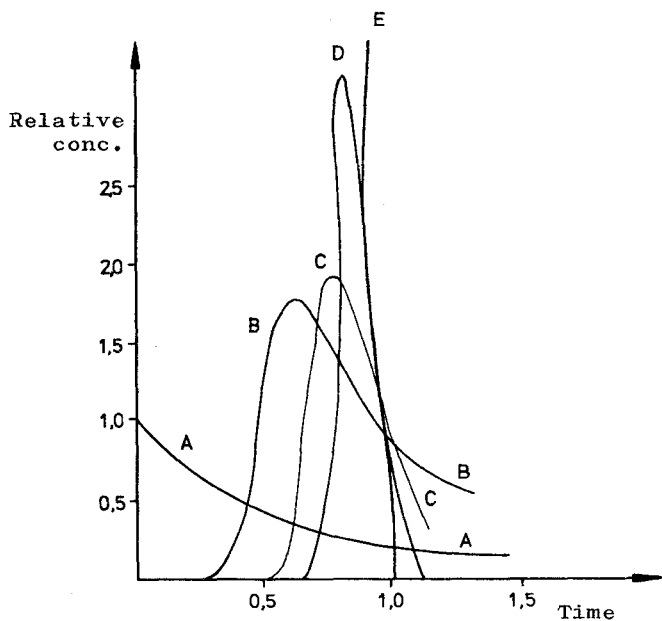


Fig. 1.11. Effluent concentration versus time.

The relative concentration 1.0 corresponds to the concentration achieved by complete mixing, and curve A shows the results of such an experiment, where the tank content was completely mixed. Curve B is typical of a wide shallow regular tank, while curve C represents the situation in a long narrow tank. Curve C represents the situation in a long narrow regular tank. Curve D represents a baffled tank and is, as shown, close to the ideal case for plug flow E.

The studies by Dague and Baumann (1961) are shown in Fig. 1.12.

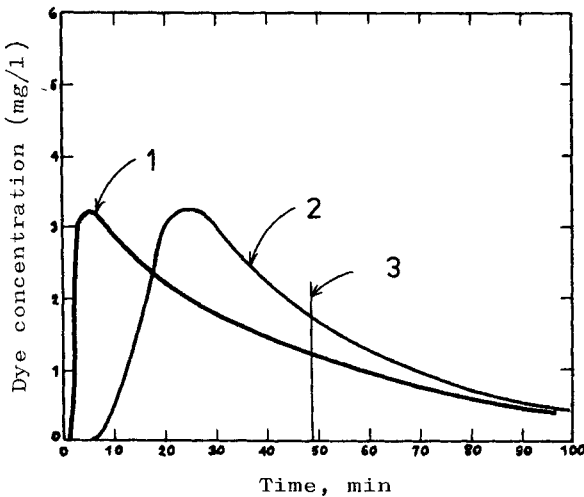


Fig. 1.12. 1) Feed in center, 2) Feed in periphery, 3) Theoretical retention time.

Centre and peripheral feed circular clarifiers were examined by means of dye dispersion. As can be seen, the difference between the two feeding methods is significant.

It is frequently possible to improve the performance in an existing settling tank by making modifications based on the results of a dispersion test. The addition of stream-deflecting baffles, inflow dividing mechanism and velocity dispersion feed wells may decrease short circuiting and increase efficiency.

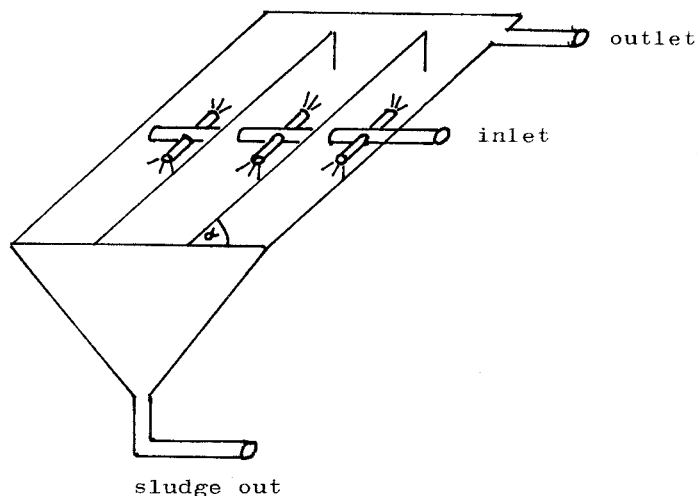


Fig. 1.13. Steeply inclined tube settler. Shows the principle of the tube settler.

Tube settlers

Fig. 1.13 shows the principle of tube settlers. The design incorporate the use of very small diameter tubes in an attempt to apply the shallow depth principle as suggested by Camp (1946). Flow through tubes with a diameter of 5-10 cm offers optimum hydraulic conditions and maximum hydraulic stability. Culp et al.(1968) have reported excellent results using tube settlers with a detention time of less than 10 minutes. The detention time can be calculated in accordance with the following equation:

$$Y_A = v_s \left(\frac{L}{S} \cos \alpha + 1 \right) \quad (1.15)$$

where $Y_A = \frac{Q}{A}$, L = the length of the tube, S = the distance between the tubes (the diameter of the tubes) and α = the angle of the tube to the horizontal (see Fig. 1.13).

As can be seen from this equation, $\frac{Q}{A}$ will increase as α decreases. It should therefore be an advantage to place the tubes as near as possible to horizontal. However, the horizontal settler is not self-cleaning and must be back-washed. Therefore the steeply inclined 60° tube settler is more commonly used. Continuous gravity draining of settled solid might be achieved from tubes inclined of angles between 45° and 60° .

The clarifier

The clarifier may be designed as a rectangular or circular tank, and may utilize either centre or peripheral feed. The tank can be designed for centre sludge withdrawal or for withdrawal over the entire tank bottom. Two different types of tank are shown in Figs. 1.14 and 1.15. The first one is designed for small flows, where the height of the tank is only moderate in spite of the angle of the cone. The second clarifier is made of concrete and is able to deal with a considerably larger flow rate. An inlet device is designed to distribute the flow across the width and the depth of the settling tank, and correspondingly an outlet device is designed to collect the effluent uniformly at the outlet end of the tank.

It is very difficult to design a full-scale sedimentation tank based on settling experiments, as several important factors influencing particle behaviour in a full-scale operation are neglected in settling experiments. Tanks are subject to eddies, currents, wind action, resuspension of sludge, etc. This implies that a full-scale clarifier will show a slightly reduced efficiency compared to settling experiments, which, however, can be taken into consideration if a safety factor is used. The choice of an acceptable safety factor requires experience. The practical factor might vary from 1.5 when the tank is very small, baffled and protected from wind, to 3.0 in case of a large tank, unbaffled and unprotected from wind. Even with the use of the safety factor, however, perfect performance should not be expected.

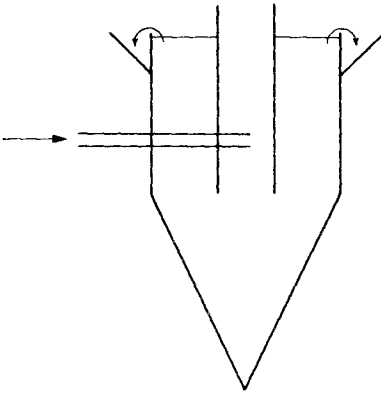


Fig. 1.14. Settling tank for small flow rates.

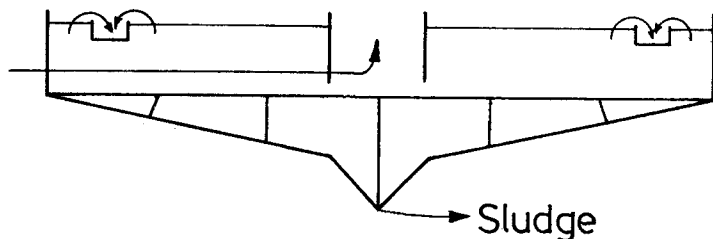


Fig. 1.15. Settling tank for large flow rates.

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