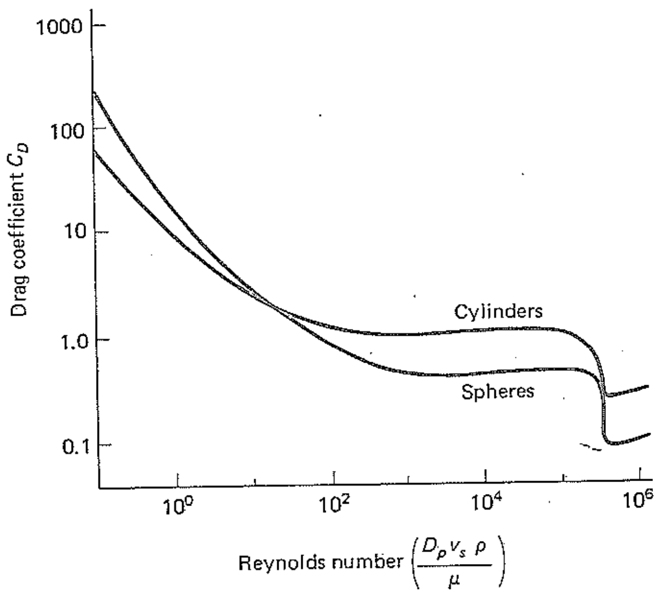

FIGURE 7-1 *Drag coefficients for settling of discrete particles.*

This equation is known as Stokes law and applies only to spherical particles settling under conditions where inertial drag forces are negligible.

7-3 IDEAL SETTLING BASINS

An ideal settling basin is defined as a tank in which settling occurs in the same manner as in a quiescent settling container of the same depth. A schematic diagram of a rectangular horizontal flow basin is shown in Fig. 7-2. This basin is comprised of four zones according to function. The inlet zone is a region where the incoming suspension is distributed uniformly over the cross-section of the tank. Thus, the concentration of suspended particles of each size is the same at all points in the vertical cross-section at the inlet end. In the settling zone, the particles settle at the same rate as they would in a quiescent fluid. The direction of fluid flow is horizontal and the fluid velocity is constant at all points in the settling region. At the outlet zone, the clarified liquid is collected uniformly over the cross-section of the basin. The solids collect in a sludge zone at the bottom of the tank. All particles reaching the sludge zone are permanently removed from the suspension.

Consider a suspension of discrete particles settling in an ideal basin.[1] The paths followed by the particles are straight lines determined by the vector sums of the two velocity components, as shown in Fig. 7-3. The horizontal

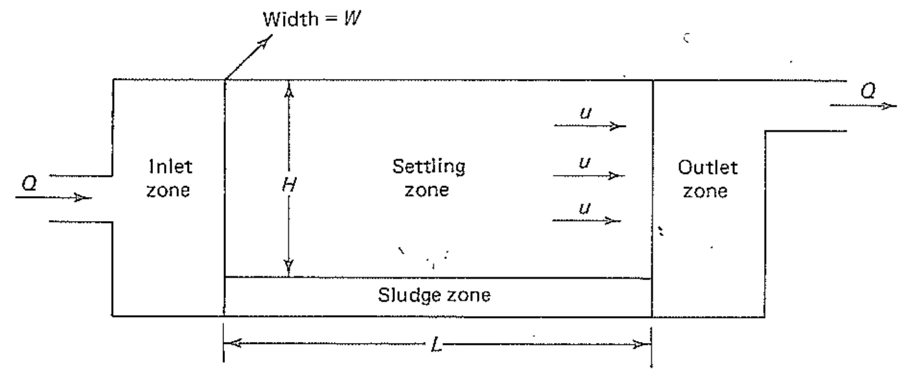

FIGURE 7-2 *Schematic diagram of a rectangular horizontal flow settling basin.*

velocity component of the particles due to fluid flow across the basin is equal to u. A particle with settling velocity v_0 starting at the top of the inlet zone will reach the bottom at the junction with the outlet zone. If this particle started at any lower point in the inlet zone, it will reach the bottom before the outlet zone. Thus, all particles with settling velocities equal to or greater than v_0 will be removed completely from the suspension.

Particles with settling velocities less than v_0 will be only partially removed. As shown in Fig. 7-3, a particle with settling velocity v_s will reach the bottom at the outlet if it enters the settling zone at height h. Particles initially at heights less than h will be removed whereas particles at heights above h will not touch the bottom before they flow into the outlet zone.

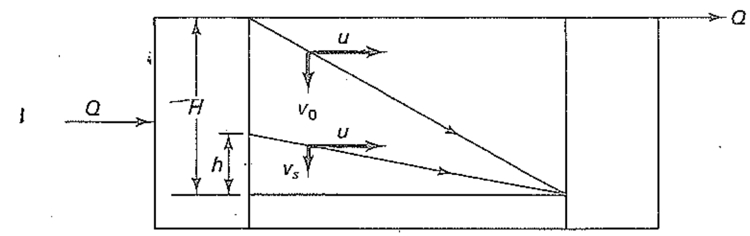

FIGURE 7-3 *Settling paths of discrete particles in a rectangular basin.*

From the geometry of Fig. 7-3, the fractional removal of particles with settling velocity v_s is

$$F_x = \frac{h}{H} \tag{7-7}$$

Since depth is the product of settling velocity and residence time,

$$F_x = \frac{v_s t_0}{v_0 t_0} = \frac{v_s}{v_0} \tag{7-8}$$

The residence time of any particle traversing the entire basin is

$$t_0 = \frac{L}{u} \tag{7-9}$$

The velocity v_0 can be related to flow rate and surface area

$$v_0 = \frac{H}{t_0} = \frac{Hu}{L} = \frac{HuW}{LW} = \frac{Q}{A} \tag{7-10}$$

where: Q = total volumetric flow rate of fluid

A = surface area of basin

Thus the fraction of particles with settling velocity v_s that are removed from an ideal basin is given by

$$F_x = \frac{v_s}{v_0} = \frac{v_s}{Q/A} \tag{7-11}$$

A similar relationship applies to the circular basin shown in Fig. 7-4. With a circular basin, the horizontal component of velocity varies with radius

$$u = \frac{Q}{2\pi r H} \tag{7-12}$$

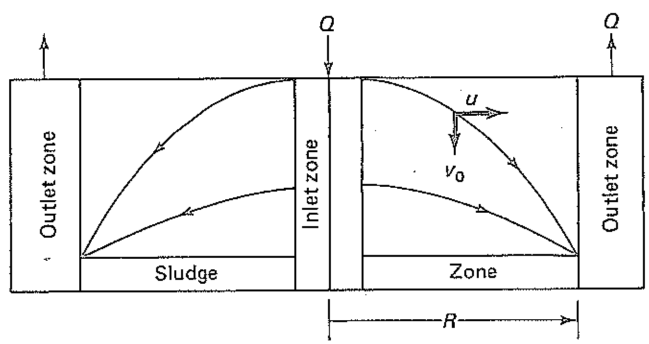

FIGURE 7-4 Settling paths of discrete particles in a circular basin.

Since u decreases with increasing radius and the settling velocity is constant, the paths of the particles are curved instead of straight. The slope of the settling curve at any radius is

$$\frac{dh}{dr} = \frac{v_s}{u} = \frac{2\pi r H v_s}{Q} \tag{7-13}$$

Integrating between the inside radius R_i and outside radius R_o, the fractional removal is found to be

$$F_x = \frac{h}{H} = \frac{v_s}{Q}(\pi R_o^2 - \pi R_i^2) = \frac{v_s}{Q/A} \tag{7-14}$$

Thus, the fractional removal of a circular basin is also a function of settling velocity, flow rate, and surface area only.

The quantity Q/A is generally called the overflow rate of the settling tank. Since Q/A has the units of velocity, it is sometimes erroneously considered as an upflow fluid velocity in the tank. Actually, Q is the horizontal flow rate in the tank and A is the surface area parallel to this flow.

The fractional removal of particles is independent of tank depth. For example, if the depth of the rectangular basin were $H/2$ with the same total flow Q, the horizontal velocity component would be doubled. Since the particles only need to settle half as far, however, all particles with settling velocities equal to or greater than v_0 are still removed. The fractional removal of particles with settling velocity v_s is

$$F_x = \frac{h/2}{H/2} = \frac{v_s}{v_0} = \frac{v_s}{Q/A} \tag{7-15}$$

The overall efficiency of an ideal sedimentation basin can be evaluated from the distribution of particle sizes as a function of settling velocity. In the cumulative distribution curve of Fig. 7-5, the ordinate f is the fraction of particles in the initial suspension with settling velocities less than the corresponding settling velocity on the abscissa. As discussed above, all particles with settling velocities $\geq v_0$ are removed completely. On the cumulative distribution curve, f_0 is the fraction of particles with settling velocities $\leq v_0$. Of the total number of particles in the suspension, then, the fraction removed completely is $1 - f_0$. For each particle size with settling velocity below v_0, Eq. (7-8) shows the fraction removed is v_s/v_0. To evaluate the removal of particles with settling velocities less than v_0, the cumulative distribution curve is integrated graphically from $f = 0$ to $f = f_0$

$$\int_0^{f_0} \frac{v_s}{v_0}\, df$$

The overall removal for all particle sizes is the sum of the terms for velocities above and below v_0

$$F = (1 - f_0) + \frac{1}{v_0}\int_0^{f_0} v_s\, df \tag{7-16}$$

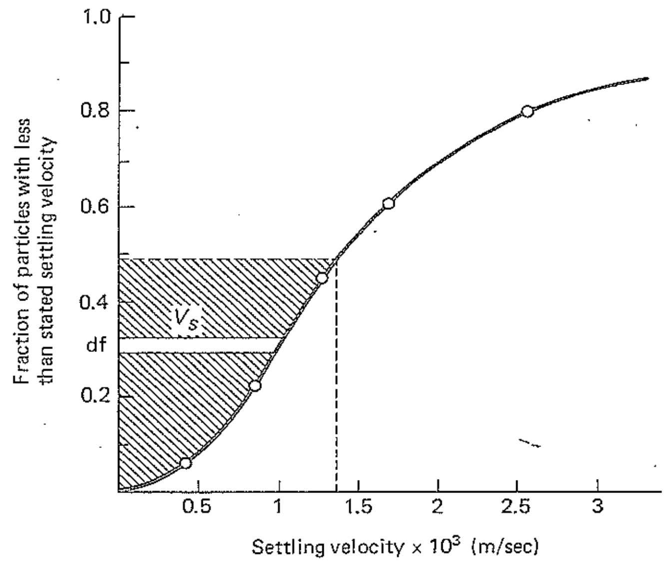

FIGURE 7-5 Cumulative distribution curve for particle settling velocities.

The evaluation of overall removal in an ideal basin from batch settling data is illustrated in Example 7-1.

EXAMPLE 7-1

A suspension of nonflocculating particles is allowed to settle in a column, under quiescent conditions. Samples are collected at a point 1.5 m below the surface of the liquid at intervals of time and the weight fraction of particles remaining is measured. The weight fraction remaining is the ratio of the measured concentration to the initial uniform concentration in the cylinder.

Settling Time (min)	*Weight Fraction Remaining*
5	0.96
10	0.81
15	0.62
20	0.46
30	0.23
60	0.06

Estimate the overall removal of particles from an ideal rectangular basin for an overflow rate of 1.36 $\ell/m^2 \cdot sec$ (2 gpm/ft^2).

SOLUTION

Calculate the settling velocities of the particles moving 1.5 m in the given time intervals. For example, for a settling time of 15 min, the settling velocity is

$$v_s = \frac{1.5}{15 \times 60} = 1.67 \times 10^{-3} \text{ m/sec}$$

The weight fraction remaining is plotted vs. settling velocity in Fig. 7-5.

The overflow rate can be converted to a velocity:

$$v_0 = \frac{Q}{A} = \frac{1.36\ \ell}{m^2 \cdot sec} \times \frac{m^3}{10^3\ \ell}$$
$$= 1.36 \times 10^{-3} \text{ m/sec}$$

From Fig. 7-5, a weight fraction of 0.49 corresponds to a settling velocity of 1.36×10^{-3} m/sec. All particles with settling velocities greater than v_0 are removed completely.

$$\text{Wt. fraction removed completely} = 1 - 0.49 = 0.51$$

A portion of the particles with settling velocity less than v_0 is removed. As explained in the text, this is found by integrating the shaded area of Fig. 7-5 graphically.

$$\frac{1}{v_0}\int_0^{0.49} v_s\, df = 0.30$$

$$\text{Overall removal} = 0.51 + 0.30 = 0.81$$

Our analysis of ideal basins showed that solids removal is related to overflow rate but is independent of fluid depth. From an economic viewpoint, this suggests the use of shallow basins to minimize size. For a given solids capacity, the fluid velocity through the basin is increased as the liquid depth is decreased. If the fluid velocity is increased, solids may be lifted from the bottom by shear forces and resuspended in the fluid. The resuspension of solids from the sludge layer is called scour. Fair[2] presents formulas for estimating fluid velocities which avoid scouring of particles.

7-4 TUBE SETTLERS

The analysis of settling of discrete particles in rectangular basins suggested that the liquid depth should be as shallow as practical. Another possible geometry for achieving shallow depths is bundles of tubes in parallel. If the tubes are horizontal or slightly inclined, the solids will accumulate on the bottom and must be removed by periodic draining. If the tubes are inclined at a steep angle, the solids will slide down the tubes countercurrent to the liquid flow and can be collected at the bottom. Yao[3] analyzed the performance of the tube settlers and found that they could be characterized by a dimensionless parameter

$$S = \frac{v_s}{u_b}\left(\sin\phi + \frac{L}{D_t}\cos\phi\right) \tag{7-17}$$

where: u_b = average fluid velocity
L = length of tube
D_t = diameter of tube
v_s = particle settling velocity
ϕ = angle of inclination of tubes

By analogy with rectangular basins, he defined a critical particle settling velocity v_0 for a given tube and flow rate. Any suspended particle with a settling velocity $\geq v_0$ will be completely removed. For a circular tube, he showed that any suspended particle with an S value $\geq \frac{4}{3}$ will be removed completely. Thus, the critical settling velocity for a tube is given by

$$v_0 = \frac{\frac{4}{3}u_b}{\sin\phi + (L/D_t)\cos\phi} \tag{7-18}$$

Yao examined the effect of geometry on the theoretical performance of a tube settler. He recommended that L/D_t be kept below 40 and preferably around 20 since higher values of L/D_t contribute only marginally to efficiency. He suggested that the angle of inclination be less than 40° since higher angles gave rapidly deteriorating performance. Culp[4] found that angles greater than 45° were needed to permit the sludge to slide back down the tube. Thus, the convenience of continuous sludge removal may involve some sacrifice in settler performance.

7-5 FLOCCULENT SUSPENSIONS

Many particles tend to coalesce during settling to form clusters of different size, shape, and weight. Since the larger particles that are formed have higher settling velocities, the paths of the particles are curved instead of straight. The overall settling process thus depends upon both the flocculating and settling characteristics of the particles.

The rate at which particles coalesce is related to the frequency of collisions between particles. In a quiescent settling cylinder or an ideal basin,

collisions occur as a result of heavier faster particles overtaking lighter slower particles. The collision frequency is proportional to the concentration of particles and the difference in settling velocities. Since the total number of collisions increases with time, the degree of flocculation also generally increases with residence time in the basin. The effect of flocculation on settling rate is more pronounced near the bottom of the tank after a period of settling. The fractional removal of flocculating particles is a function of both residence time and overflow rate. In contrast, the fractional removal of discrete particles depends upon overflow rate only.

The rate of flocculation cannot be predicted from collision frequency alone. The coalesence of particles depends upon many factors, such as the nature of the surface, the presence of charges, shape, and density. At present, there is no adequate theoretical model to predict the rate of flocculation in a suspension.

Laboratory settling tests are used to establish design parameters for flocculating suspensions. A uniform suspension is placed in a column of at least 5-inch diameter to reduce wall effects. Samples are withdrawn periodically from different depths and the solids concentrations are measured. The percent removal at each depth and time interval is calculated from the concentrations and plotted as shown in Fig. 7-6. Smooth curves are drawn between points of equal solids removal. For a given depth and residence time, the value read from the curve represents the percent of the initial suspended solids that would be removed completely in an ideal basin. Particles with lower settling velocities are removed partially as illustrated in Example 7-2.

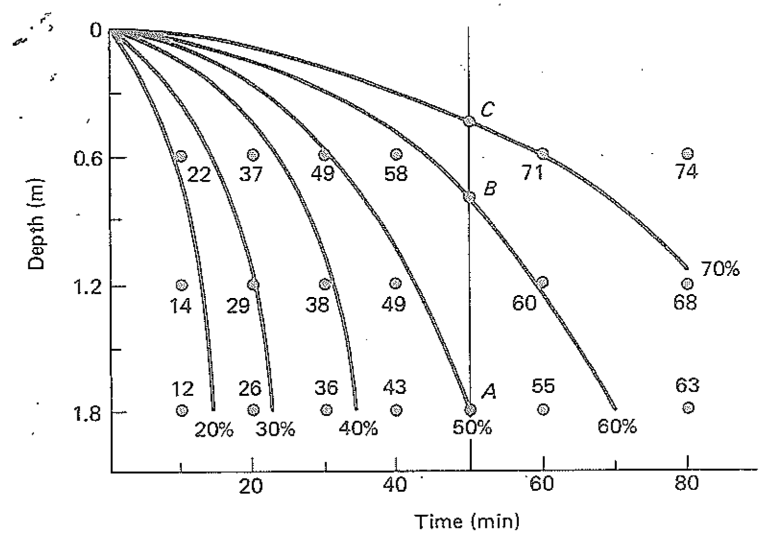

FIGURE 7-6 Percentage removal of flocculent particles as a function of depth and time.

If velocity gradients exist in the fluid, particles in a region of higher velocity can overtake and collide with particles in adjacent stream paths moving at slower velocities. The rate of flocculation is often increased by the presence of velocity gradients generated by gentle stirring. Since particles of flocculent suspensions are fragile, high velocity gradients will tend to disrupt them. Thus, there is an optimum range of velocity gradients or shear rates which promote the flocculation of particles.

EXAMPLE 7-2

A flocculating suspension is placed in a test column and allowed to settle under quiescent conditions. Samples are withdrawn periodically from different depths. The percentage of solids removed or settled out is determined for each sample.

Settling Time (min)	PERCENTAGE REMOVAL		
	0.6 *m*	1.2 *m*	1.8 *m*
10	22	14	12
20	37	29	26
30	49	38	36
40	58	49	43
60	71	60	55
80	74	68	63

Estimate the percentage removal of solids in an ideal basin with a depth of 1.8 m and a residence time of 50 min.

SOLUTION:

The percentage removals are plotted vs. time and depth in Fig. 7-6. Curves of constant percentage removal are drawn by interpolation between the data points. These curves trace the maximum settling paths for the various percentage removals. For example, the 60% curve means that 60% of the initial solids have a trajectory that takes them to or below the depth shown for any time. For any ideal settling basin that has a combination of depth and time falling on the 60% curve, 60% of the solids have a settling velocity equal to or greater than v_0 and are removed completely.

For a depth of 1.8 m and a time of 50 min,

$$v_0 = \frac{1.8}{50} = 0.037 \text{ m/min}$$

Point *A* on Fig. 7-6 shows that 50% of the solids reach 1.8 m in 50 min or less and are removed completely.

Particles with settling velocities less than v_0 are only partially removed in 50 min. If particles with a settling velocity v reach a depth h in 50 min, the fraction removed is

$$\frac{v}{v_0} = \frac{h/50}{1.8/50} = \frac{h}{1.8}$$

At 50 min settling time in Fig. 7-6, 50% settle 1.8 m and 60% settle 0.78 m (point *B*). The average depth settled for particles in the 50–60% range is $(1.8 + 0.78)/2 = 1.29$ m.

$$\therefore \quad \% \text{ removal in 50–60\% range} = \frac{1.29}{1.8}(60-50)$$
$$= 7.2\%$$

For the 60 to 70% range, 60% settle 0.78 m and 70% settle 0.42 m (point *C*) giving an average depth settled of 0.6 m.

$$\therefore \quad \% \text{ removal in 60–70\% range} = \frac{0.6}{1.8}(70-60)$$
$$= 3.3\%$$

Similarly, there will be additional removal in the 70 to 100% range of about 1.5%.

The overall removal is the sum of the removals at 50 min settling time:

$$\text{Overall removal} \simeq 50 + 7.2 + 3.3 + 1.5$$
$$= 62\%$$

7-6 GRAVITY THICKENING

In dilute suspensions, particles settle freely until they reach the sludge zone at the bottom of the basin. As concentration of the suspension is increased, there is a greater interaction between particles accompanied by a decrease in settling velocity. For certain types of suspensions, such as activated sludge, a concentration is reached where the particles settle collectively with a distinct interface between settling particles and clarified fluid. In this zone-settling regime, the cohesive forces between particles are sufficient to restrict the motion of the particles relative to each other. At a given cross-section, then, all particles settle at the same rate regardless of size. Since the settling rate depends upon concentration, however, the flux of solids through the basin may vary with depth.

A typical batch settling curve for a zone settling suspension is shown in Fig. 7-7. Starting with a uniform suspension, the position of the interface between settling particles and clear fluid is measured as a function of time.

WASTEWATER TREATMENT

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