WATER ENGINEERING

THIRD STAGE / ENVIRONMENTAT ENG. DEPARTMENT

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My darlings , welcome in you in of Third Stage of Environmental Eng.

With my best wishes in this coarse .

Prof. Dr. Jabbar H. Al-Baidhani

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Sedimentation is a physical treatment process that utilizes gravity to separate suspended solids from water. The process is widely used as the first stage in surface water treatment to remove turbidity causing particles after coagulation and flooculation. Sedimentation is also (2) to increase sludge solids concentration in sludge thickening . Presedimentation is also used in some cases to remove settleable solids such as gravel, grit, and sand from river water before it pumped to the drinking water treatment plant.

In this lecture, the theory and design procedures for sedimentation basins are discussed. Examples design calculations for presedimentation , and also examples calculation for the determination of both Newton's law , and Stoke's law are presented through these calculations examples. The design of a sedimentation basin is dependent upon the concentration, size. and behavior of the solid suspension. In general, there are four types or classes of sedimentation.

Gravity Separation Theory

The removal of suspended and colloidal materials from water by gravity separation is one of the most widely used unit operations in water treatment. Sedimentation is the term applied to the separation of suspended particle that are heavier than water, by gravitational settling. The terms sedimentation and settling are used interchangeably. A sedimentation basin may also be referred to as a sedimentation tank, clarifier, settling basin, or settling tank.

Classification of settling behavior

Settling particles can settle according to four different regimes (Figure 3.5), basically depending on the concentration and relative tendency of the particle to interact: 1) Type I discrete particle settling, 2) Type II flocculent particles settling, 3) Type III hindered or zone settling, and 4) Type IV compression settling .This review focuses on the equations that have been previously presented to model one of the four regimes.

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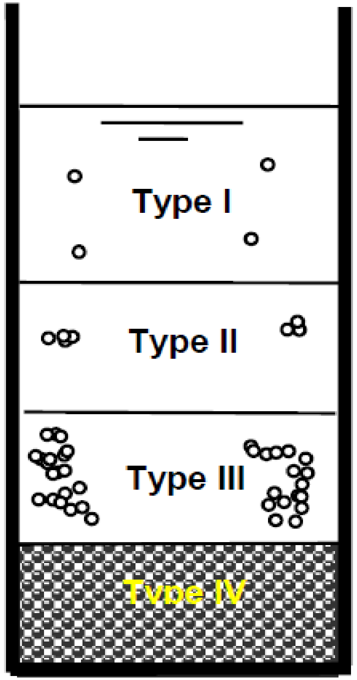

Figure 3.5 Types of Sedimentation

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Type I and Type II (discrete particles in dilute suspension) was simulated, as it is the applicable type for the operating conditions in rectangular sedimentation tanks for potable water treatment. The first two classes occur in sedimentation basins of water treatment plants. While the third and fourth classes occur in sedimentation basins of wastewater treatment plant, where, the concentration of suspended solids is too high. Settling of suspended particles in pre-sedimentation basins, which are not preceded by coagulation- flocculation process, is of class-I. During this class, there is no change in the shape, size or weight of discrete particles (do not form aggregates). [Duggal, K. N., 2008].

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

The settling of discrete, non-flocculating particles can be analyzed by means of the classic laws of sedimentation formed by Newton and Stokes. The balance of forces on an individual sand particle is formed by gravity, drag, and lift forces.

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

The force balance is written so that the direction of gravitational force is positive. Therefore, a positive settling velocity means that the particle settles and a negative settling velocity means the particle rises. The gravitational and buoyant forces are given,

by F=ma, as follows:

$$F_g = ma = \rho_p V_p g \quad \text{...........(3-1)}$$

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$$F_b = ma = \rho_w V_p g \qquad \ldots (3\text{-}2)$$

$$F_G = F_g - F_b = \rho_p V_p g - \rho_w V_p g = (\rho_p - \rho_w)\, g V_p \qquad \ldots (3\text{-}3)$$

Where :

m = mass, Kg.

a = acceleration, m/s^2

F_g = gravitational force, Kg.m/s^2

F_b = buoyant force, Kg.m/s^2

F_G =resultant gravitational force, Kg.m/s^2

ρ_p = density of particle, Kg/m^3

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ρw =density of water, Kg/m^3

g = acceleration due to gravity, 9.81 m/s^2

Vp = volume of particle, m^3

The frictional drag force depends on the particle velocity, fluid density, fluid viscosity, particle diameter, and the drag coefficient Cd (dimensionless), and is given by:

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Fd = (Cd Ap ρw u^2 p)/2 (ρp – ρw)g Vp …(3-4)

Where:

Fd = frictional drag force, Kg.m/s^2

Cd = drag coefficient, (unit less)

Ap = cross sectional or projected area of particle in direction of flow, (m)

up = particle settling velocity, (m/(s)).

A diagram for settling of an idealized spherical particle is shown below (Figure 3.6). The settling of discrete particles, assuming no interaction with the neighing particles, can be found by means of the classic laws of sedimentation of Newton and Stokes. Equating Newton's law for drag force to the gravitational force moving the particle, we get Equation

3.5

VsP=√(4g/3cd (sgP-1)dP) …(3-5)

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

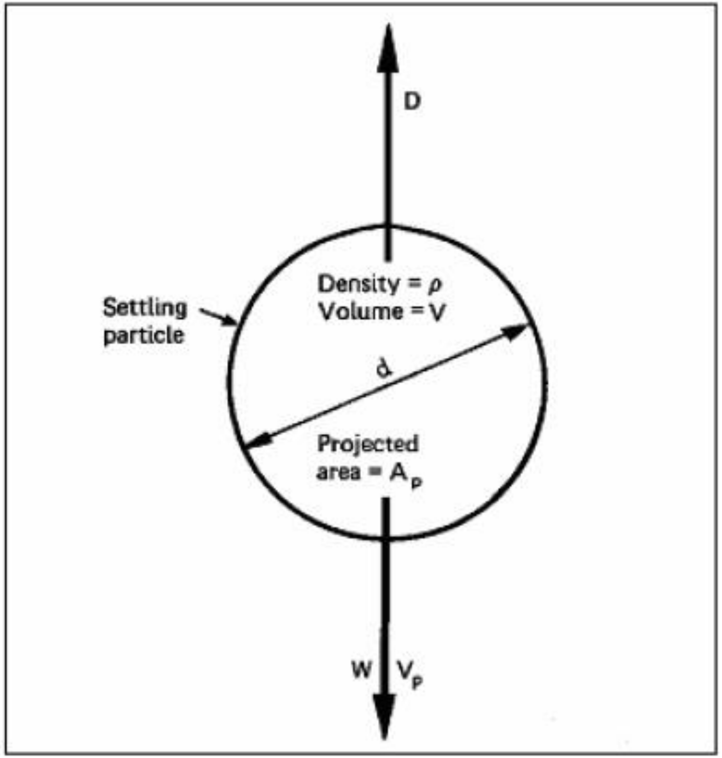

Figure 3.6 Definition diagram for particle terminal settling velocity

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Where VsP is the terminal settling velocity of the primary particle; Cd is the drag coefficient; g is the acceleration due to gravity; Sgp is the specific gravity of the particle; and dp is the diameter of the particle. The drag coefficient is a function of the Reynolds number (Re) and the particle shape.

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

The coefficient of drag Cd takes on different values depending on whether the flow regime surrounding the particle is laminar or turbulent. There are three distinct regions, depending on the Reynolds number Re:

1) laminar (Re <1),

2) transition<(Re=1 to 2000) and

3) turbulent (Re >2000).

For spherical particles, it can be represented by the following expressions:

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Re = (Vs . dp)/v …….(3-6)

Where v is kinematic viscosity of water,m^2/s, which is dependent on water temperature and it can be obtained from tables.

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For $Re < 1$ or $Re < 2$ or $Re \leq 0.5$, Cd is defined as;

$$CD = 24/Re \quad \ldots.(3\text{-}7)$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

While, for $1 < Re < 10$ or $0.5 < Re < 1000$,

Cd is defined as;

$$CD = 24/Re + 3/\sqrt{Re} + 0.34 \qquad \ldots (3\text{-}8)$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

For Reynolds numbers less than about 1.0, viscosity is the predominates. Assuming spherical particle, substitution of the first term of the drag coefficient equating into Newton's Equation yields Stokes low:

Vsp=g/18 ((Sgp-1))/v 〚dp〛^2 …(3-9)

For laminar-flow condition. Stoke found the drag force is to be:

Fd= 3 π μ vp dp

Settling in the Turbulent region:

In the turbulent region, inertial force are predominant, and the effect of the first two terms in the drag coefficient equation is reduced. For settling in the turbulent region, a value of 0.4 is used for the coefficient of drag. If a value of 0.4 is substituted into the coefficient of drag Cd equation the resulting settling equation is:

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

$$V_p = \sqrt{(3.33\, g\, (S_{gp}-1)\, d_p)} \qquad \ldots \text{(3-10)}$$

Where S is the particle specific gravity. Table (3-3) represents the physical properties of water. The general conclusion, that Vp depends on a particular diameter, particle density and, under some conditions, also on fluid viscosity and hence on temperature, is important in understanding sedimentation behavior.

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Furthermore, in practical sedimentation tanks, the terminal settling velocity is quickly reached, so, for non-flocculent particles and uniform fluid flow the settling velocity is constant throughout the settling time. This fact can be usefully applied to a study of settling in an ideal sedimentation tank to provide an important design principle for sedimentation process

Idealized Discrete Particle Settling

In the design of sedimentation basins, the usual procedure is to select a particle with a terminal velocity Vc (Surface Overflow SOR) and to design the basin so that all particles that have a terminal velocity equal to or greater than Vc will be removed. Thus the critical velocity to the overflow rate or surface loading rate. A common basis of design for discrete particle settling recognizes that the flow capacity is independent of the depth.

For continuous flow sedimentation, detention time should be such that all particles with the design velocity Vs will settle to the bottom of the tank. The design velocity, detention time, and basin depth are related as follows:

Vc (SOR) = (depth)/(detention time) … (3-17)

Idealized discrete particle settling in three different types of settling basins is illustrated on fig 3.7.

Particle that have a velocity of fall less than Vc will not all be removed during the time provided for settling. Assuming that the particles of various size are uniformly distributed over the entire depth of the basin at the inlet, it can be seen from an analysis of the panicle trajectory on fig.3.8 that particles with settling velocity less than Vc will be removed in the ratio:

Xr = Vp/Vc … (3-18)

Where:

Xr = the fraction of the particles with settling velocity Vp that are removed.

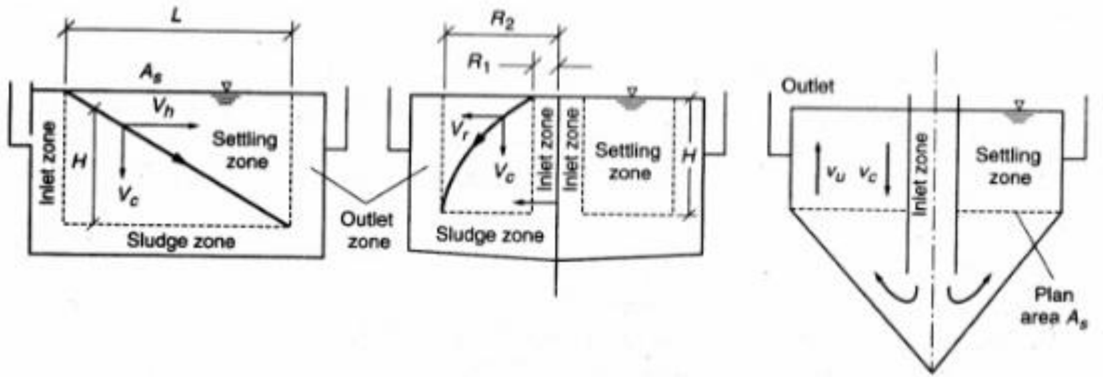

Figure 3.7 Definition sketch for the idealized settling of discrete particles in three different types of settling basins :(A) rectangular, (B) circular, (C) up-flow.

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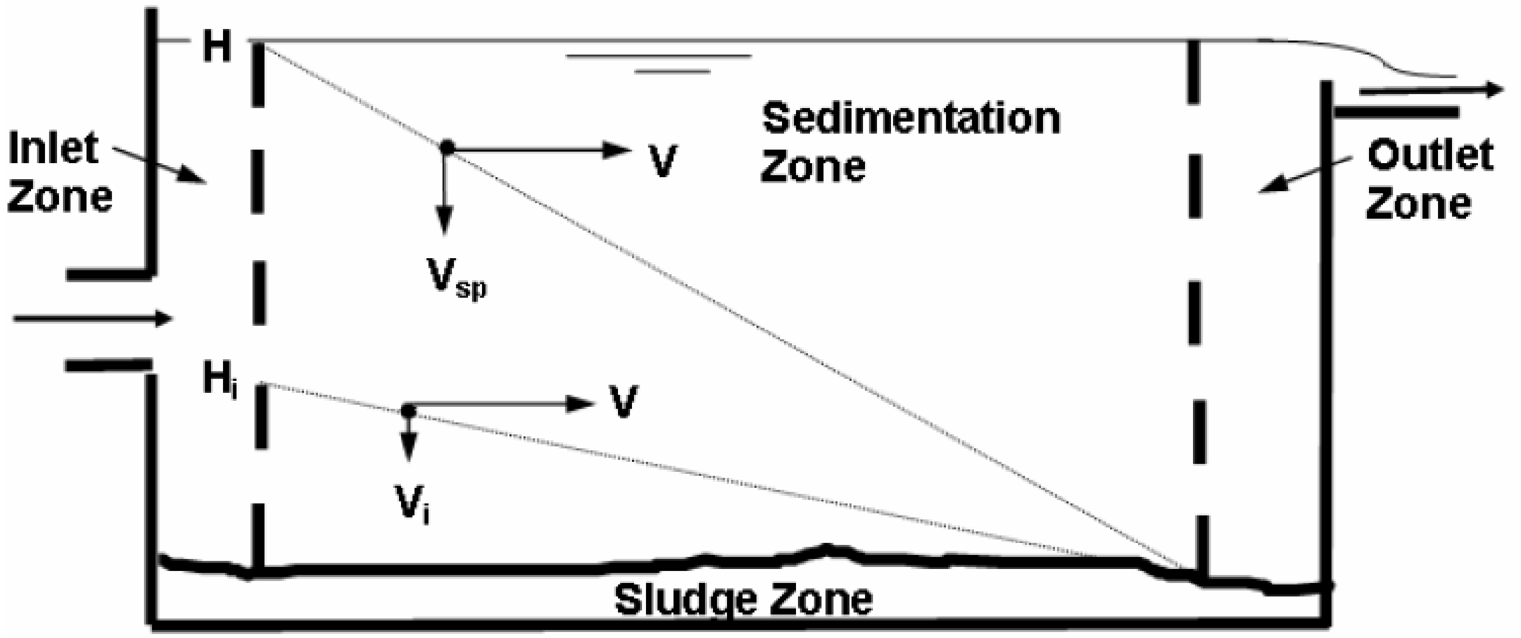

Figure 3.8 Sedimentation Basin Design (Ideal Basin)

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

The ideal rectangular horizontal flow sedimentation tank is considered divided into four zones (Figure 3.8)

1) Inlet zone - in which momentum is dissipated and flow is established in a uniform forward direction.

2) Settling zone - where quiescent settling is assumed to occur as the water flows towards the outlet.

3) Outlet zone - in which the flow converges upwards to the decanting weirs or launders.

4) Sludge zone - where settled material collects and is moved towards sludge hoppers for withdrawal. It is assumed that once a particle reaches the sludge zone it is effectively removed from the flow.

All particles with settling velocity equal or greater than SOR will be removed. Thus the fraction of all removed particles (theoretical efficiency) will be [McEwen, J. B., 1998];

$$\mathbf{F = (1\text{-}Xs) + \int_0^{Xs} \frac{vs}{SOR}\, dx \qquad \ldots(3\text{-}20)}$$

In Eq. (3-20), Xs represents the fraction of particles with settling velocity

less than SOR, (1-Xs) is the fraction of particles with Vs ≥ SOR and the integral is the fraction of particles with Vs < SOR which are removed in the settling tank.

Eq. (3-20) is approximated by:

$$\mathbf{F = (1\text{-}Xs) + \frac{1}{SOR} \sum_{i=1}^{i=n} Vsi \, \Delta xi} \qquad \dots \qquad \mathbf{(3\text{-}21)}$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Ex:

A settling basin is design to have surface over flow rate of 32.6 m/day determine the overall removal obtained for suspension with the size distribution given . the specific gravity of the particles is 1.2 g/cm^3 .

particle size (mm)	0.1	0.08	0.07	0.06	0.04	0.02	0.01
%Weight fraction greater than size percent	10	15	40	70	93	99	100

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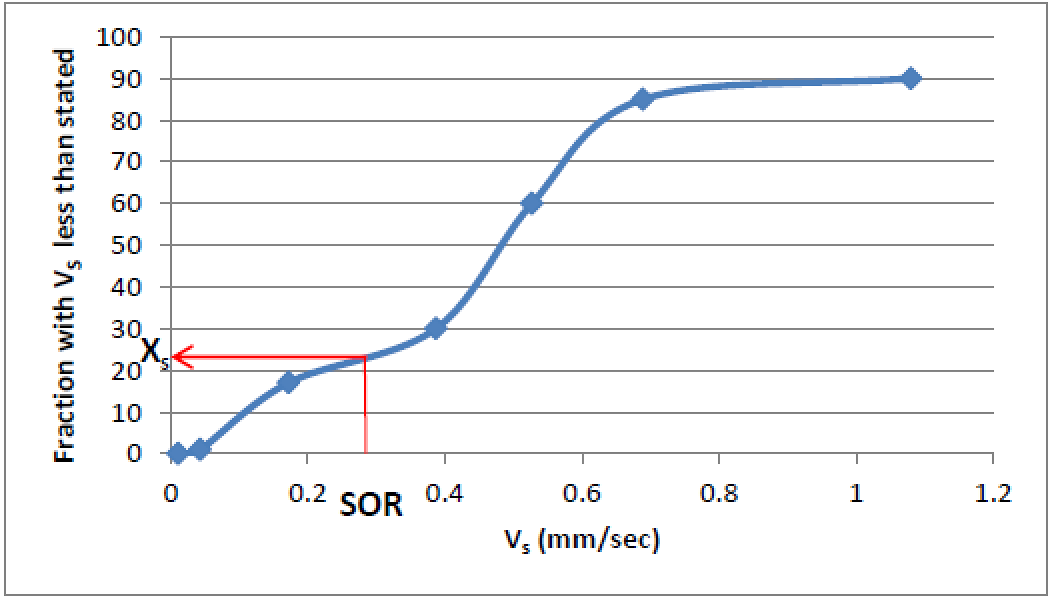


Figure 3.9 Cumulative distribution of particle settling velocity

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Solution::

At 20 C, μ_w= 1.027 cP

The settling velocities of the particles may be calculated from Soke,s law as follows :-

$$Vs = \frac{g}{18\mu}(\rho_p - \rho_w).dp^2 = \frac{9800 * 10^{-2}}{18\,(1.027\,) * 10^{-2}}\,(\,1.2 - 0.997\,)dp^2$$

$$= 107.62\,dp^2$$

V_t =SOR= 32.6 m/day = 0.37 mm/sec .

Wt fraction %	10	15	40	70	93	99	100
Vs.(mm/sec)	1.08	0.689	0.527	0.378	0.172	0.043	0.011
Re	0.1	0.05	0.04	0.02	0.01	0.001	0.0001

$$Re = \frac{Vs\,.dp\,.pw}{\mu} = \frac{1.08 * 0.1 * 0.997}{1.027} = 0.1$$

Since the calculated Reynolds numbers are all less 0.5, Stokes law is applicable and the calculation of velocity is valid.All particles with settling velocity greater than 0.37 mm/s will be removed.

Δx	0.04	0.04	0.04	0.04	0.04	0.04	0.027
V	0.06	0.16	0.22	0.26	0.30	0.34	0.37
V . ΔX	0.0024	0.0064	0.0088	0.0104	0.012	0.0136	0.0099

$$\therefore \; F = (1 - 0.267) + \frac{1}{0.37}(0.0635) \approx 90\%$$

Thus from the graph, the fraction (1-Xs) is equal to 0.73. The graphical determination of ΣvΔx is tabulated below:

Δx	0.04	0.04	0.04	0.04	0.04	0.04	0.027
V	0.06	0.16	0.22	0.26	0.30	0.34	0.37
V . ΔX	0.0024	0.0064	0.0088	0.0104	0.012	0.0136	0.0099

$$\therefore\ F = (1 - 0.267) + \frac{1}{0.37}(0.0635) \approx 90\%$$

The overall removal is thus:

$$F = (1\text{-}Xs) + \frac{1}{SOR} \sum_{i=1}^{i=n} Vsi\ \Delta xi \qquad \ldots (3\text{-}21)$$

$$\therefore\ F = (1 - 0.267) + \frac{1}{0.37}(0.0635) \approx 90\%$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Eample:

Find the followings :-

a)the settling velocity in water at 20 C of spherical particle $4.5*10^{-3}$cm in diameter and having a specific gravity of 2.65 g/cm^3

b)the rising velocity of the particle in (a) if its specific gravity is 0.8

$\mu = 1.009 * 10^{-2}$ g/cm .sec

c)the settling velocity of 20 c (d= 0.12 cm) $\rho_w = 1$ g/cm^3 =1000 kg/m^3

Solution:

$$a)V_s = 9/18\ (\rho p - \rho w)\ d^2 = \frac{981\ (2.65-1)(4.5*10^{-3})^2}{18*1.009*10^{-2}} = 0.18\ \frac{cm}{sec}$$

$$Re = \frac{Vs\ .dp\ .\rho w}{\mu} = \frac{0.18*4.5*10^{-3}*1}{1.009*10^{-2}} = 0.08 < 0.5\quad o.k$$

$$b)V_s = \frac{981\ (0.8-1)(4.5*10^{-3})^2}{18*1.009*10^{-2}} = -0.022\ cm/sec$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

GRAVITY SEPARATION THEORY

The removal of suspended and colloidal materials from water by gravity separation is one of the most widely used unit operations in water treatment. Sedimentation is the term applied to the separation of suspended particle that are heavier than water, by gravitational settling. The terms Sedimentation and settling are used interchangeably. A sedimentation basin may also be referred to as a sedimentation tank, clarifier, settling basin, or settling tank.

PARTICLE DISCRETE SETTLING THEORY (TYPE 1 SETTLING)

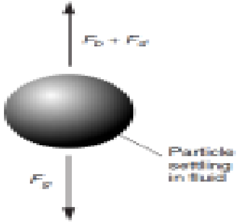
The settling of discrete, non flocculating particles can be analyzed by means of the classic laws of sedimentation formed by Newton and Stokes. Newton's law yields the terminal particle velocity by equating the gravitational force of the particle to the frictional resistance, or drag. The force balance is written so that the direction of gravitational force is positive. Therefore, a positive settling velocity means that the particle settles and a negative settling velocity means the particle rises. The gravitational and buoyant forces are given by F = ma, as follows:

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

$$F_g = ma = \rho_p V_p g$$

$$F_b = ma = \rho_w V_p g$$

$$F_G = F_g - F_b = \rho_p V_p g - \rho_w V_p g = (\rho_p - \rho_w) g V_p$$



Where:

m = mass, kg

a = acceleration, m/s^2

F_g = gravitational force, ($kg.m/s^2$) i.e. (N)

F_b = buoyant force, ($kg.m/s^2$) i.e. (N)

F_G = resultant gravitational force, ($kg.m/s^2$) i.e. (N)

ρ_p = density of particle, (kg/m^3)

ρ_w = density of water, (kg/m^3)

g = acceleration due to gravity, (9.81 m/s^2)

V_p = volume of particle, (m^3)

The frictional drag force depends on the particle velocity, fluid density, fluid viscosity, particle diameter, and the drag coefficient C_d (dimensionless), and is given by:

$$F_d = \frac{C_d A_p \rho_w v^2{}_p}{2}$$

Where:

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

F_d = frictional drag force, (kg. m/s^2)

C_d = drag coefficient, (unit less)

A_p = cross sectional or projected area of particles in direction of flow, (m^2)

v_p = particle settling velocity, (m/s)

Equating the resultant gravitational force to the frictional drag force for spherical particles yields Newton' law:

$$v_{p(t)} = \sqrt{\frac{4\,g}{3\,C_d}\left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} = \sqrt{\frac{4\,g}{3\,C_d}(Sg_p - 1)\, d_p}$$

Where:

$v_{p(t)}$ = terminal velocity of particle, (m/s)

d_p = diameter of particle, (m)

Sg_p = specific gravity of the particle

The coefficient of drag C_d takes on different values depending on whether the flow regime surrounding the particle is laminar or turbulent. There are three distinct regions, depending on the Reynolds number NR:

1. laminar ($N_R < 1$),
2. transition< (N_R = 1 to 2000), and
3. turbulent ($N_R > 2000$). Although

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

Although particle shape affects the value of the drag coefficient, for particles that are approximately spherical, the coefficient of drag C_d is approximated by the following equation:

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34$$

The Reynolds number N_R (or Re) for settling particles is defined as:

$$N_R = \frac{v_p\, d_p\, \rho_w}{\mu} = \frac{v_p\, d_p}{v}$$

where :

μ = dynamic viscosity, ($N.s/m^2$)

v = kinematic viscosity, (m^2/s)

Newton's Equation must be modified for non-spherical particles. An application that has been proposed is to rewrite the equation as follows :

$$v_{p(t)} = \sqrt{\frac{4\, g}{3\, C_d\, \phi}\left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} = \sqrt{\frac{4\, g}{3\, C_d\, \phi}(S\, g_p - 1)\, d_p}$$

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

where ϕ is a shape factor. The value of the shape factor is 1.0 for spheres, 2.0 for sand grains, and up to and greater than 20 for fractal floc. The shape factor ϕ especially important in wastewater treatment where few, if any, particles are spherical.

Settling in the Laminar Region.

For Reynolds numbers less than about 1.0, viscosity is the predominant force governing the settling process, and the first term in drag coefficient equation predominates. Assuming spherical particles, substitution of the first term of the drag coefficient equation into Newton's Equation yields Stokes' law:

$$v_p = \frac{g\,(\rho_p - \rho_w)d^2{}_p}{18\mu} = \frac{g\,(S\,g_p - 1)d^2{}_p}{18v}$$

For laminar-flow condition. Stoke found the drag force to be:

$$F_d = 3\,\pi\mu v_p\,d_p$$

Settling in the Transition Region

In the transition region, the complete form of the drag equation must be used to determine the settling velocity.

Settling in the Turbulent Region

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In the turbulent region, inertial forces are predominant, and the effect of the first two terms in the drag coefficient equation is reduced. For settling in the turbulent region, a value of 0.4 is used for the coefficient of drag. If a value of 0.4 is substituted into the coefficient of drag C_d equation the resulting settling equation is:

$$v_p = \sqrt{3.33\, g \left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} = \sqrt{3.33\, g\, (S\, g_p - 1)\, d_p}$$

Table S-1 represents the physical properties of water

TABLE S-1

PHYSICAL PROPERTIES OF WATER

Temperature T (°C)	Specific Weight γ (kN/m³)	Density[a] ρ (kg/m³)	Dynamic Viscosity[b] μ (× 10^{-3} kg/m·s)	Kinematic Viscosity ν (× 10^{-6} m²/s)	Surface Tension[c] σ (N/m)	Modulus of Elasticity[a] E (× 10^9 N/m²)	Vapor Pressure P_v (kN/m²)
0	9.805	999.8	1.781	1.785	0.0765	1.98	0.61
5	9.807	1000.0	1.518	1.519	0.0749	2.05	0.87
10	9.804	999.7	1.307	1.306	0.0742	2.10	1.23
15	9.798	999.1	1.139	1.139	0.0735	2.15	1.70
20	9.789	998.2	1.002	1.003	0.0728	2.17	2.34
25	9.777	997.0	0.890	0.893	0.0720	2.22	3.17
30	9.764	995.7	0.798	0.800	0.0712	2.25	4.24
40	9.730	992.2	0.653	0.658	0.0696	2.28	7.38
50	9.689	988.0	0.547	0.553	0.0679	2.29	12.33
60	9.642	983.2	0.466	0.474	0.0662	2.28	19.92
70	9.589	977.8	0.404	0.413	0.0644	2.25	31.16
80	9.530	971.8	0.354	0.364	0.0626	2.20	47.34
90	9.466	965.3	0.315	0.326	0.0608	2.14	70.10
100	9.399	958.4	0.282	0.294	0.0589	2.07	101.33

Principle of Sedimentation – Discrete Particles Settling (Type I Settling)

EXAMPLE

Determine the terminal settling velocity for a sand particle with an average diameter of 0.5 mm, a shape factor of 0.85, and a specific gravity of 2.65, settling in water at 20 ° C.

SOLUTION :

For temperature 20 ° C, from Table S-1:

The kinematic viscosity value given is 1.003 X 10^{-6} m^2/s .

1- Determine the terminal settling velocity for the particle using Stokes' law:

$$v_p = \frac{g\,(S\,g_p - 1)d^2{}_p}{18v}$$

$$v_p = \frac{(9.81\ m/s^2)(2.65 - 1)(0.5\ x\ 10^{-3}\ m)^2}{18\ (1.003\ x\ 10^{-6}\ m^2/s)} = 0.224\ m/s$$

2- Check the Reynolds number (include the shape factor Ø:

$$N_R = \frac{\emptyset\, v_p\, d_p}{v}$$

$$N_R = \frac{0.85\left(0.224\frac{m}{s}\right)(0.5\ x\ 10^{-3}\ m)}{(1.003\ x\ 10^{-6}\ m^2/s)} = 94.9$$

The use of Stokes' law is not appropriate for Reynolds number > 1.0. Therefore, Newton's law must be used to determine the settling velocity in the transition region.

3- For the first assumed settling velocity, use the Stokes' law settling velocity calculated above. Using the resulting Reynolds number, also determined previously, compute the drag coefficient.

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{94.9} + \frac{3}{\sqrt{94.9}} + 0.34 = 0.901$$

4- Use the drag coefficient in Newton's equation to determine the particle settling velocity.

$$v_{p(t)} = \sqrt{\frac{4\,g}{3\,C_d}(S\,g_p - 1)\,d_p}$$

$$= \sqrt{\frac{4\,(9.81\,m/s^2)(2.65 - 1)(0.5\,x\,10^{-3}\,m)}{3\,x\,0.901}}$$

$$= 0.109\,m/s$$

Because the initial assumed settling velocity (0.224 m/s) does not equal the settling velocity calculated by Newton's equation (0.109 m/s), a second iteration is necessary.

5- For the second iteration, assume a settling velocity value of 0.109 m/s, and calculate the Reynolds number. Use the Reynolds number to determine the drag coefficient, and use the drag coefficient in Newton's equation to find the settling velocity.

$$N_R = \frac{0.85\,\left(0.109\,\frac{m}{s}\right)(0.5\,x\,10^{-3}\,m)}{(1.003\,x\,10^{-6}\,m^2/s)} = 46.19$$

$$C_d = \frac{24}{46.19} + \frac{3}{\sqrt{46.19}} + 0.34 = 1.3$$

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$$v_{p(t)} = \sqrt{\frac{4\,g}{3\,C_d}(s\,g_p - 1)\,d_p}$$

$$= \sqrt{\frac{4\,(9.81\,m/s^2)(2.65 - 1)(0.5\,x\,10^{-3}\,m)}{3\,x\,1.3}}$$

$$= 0.091\,m/s$$

Because the settling velocity used to compute the Reynolds number agrees with the settling velocity value from Newton's equation, the solution approach has been confirmed.

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