The Ideal Sedimentation Basin

An ideal sedimentation basin is divided into four distinct zones: the inlet, settling, sludge, and outlet zones as shown in Figure 10-4.

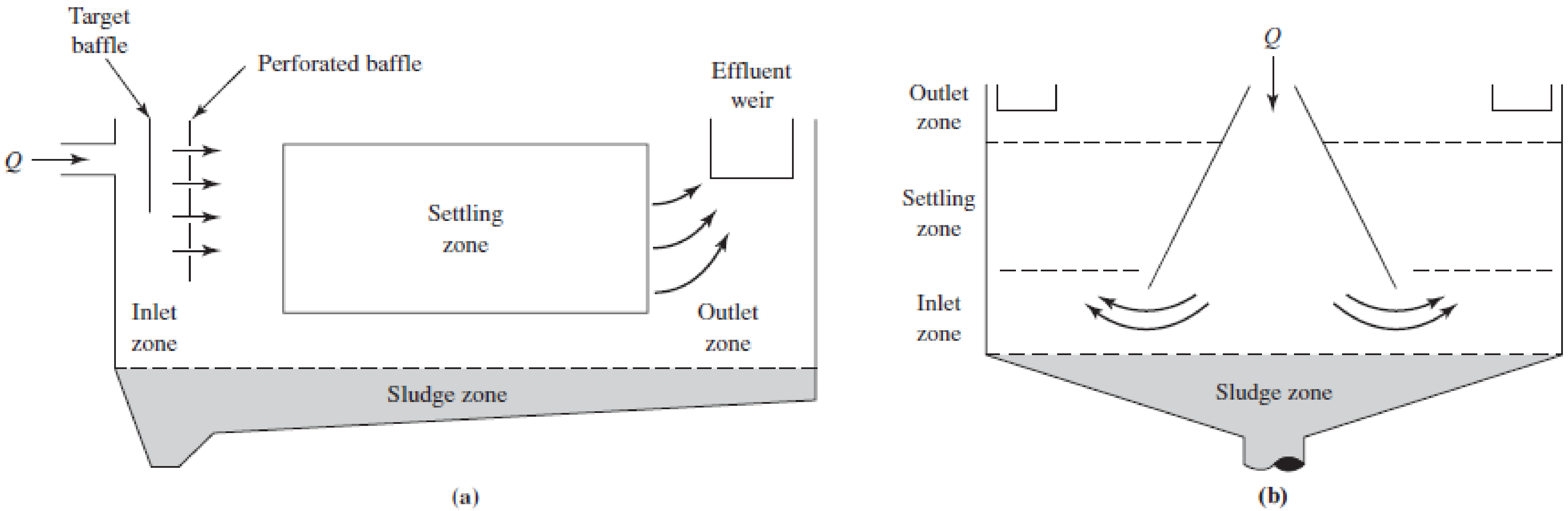


FIGURE 10-4
Zones of sedimentation: (*a*) horizontal flow clarifier; (*b*) upflow clarifier.

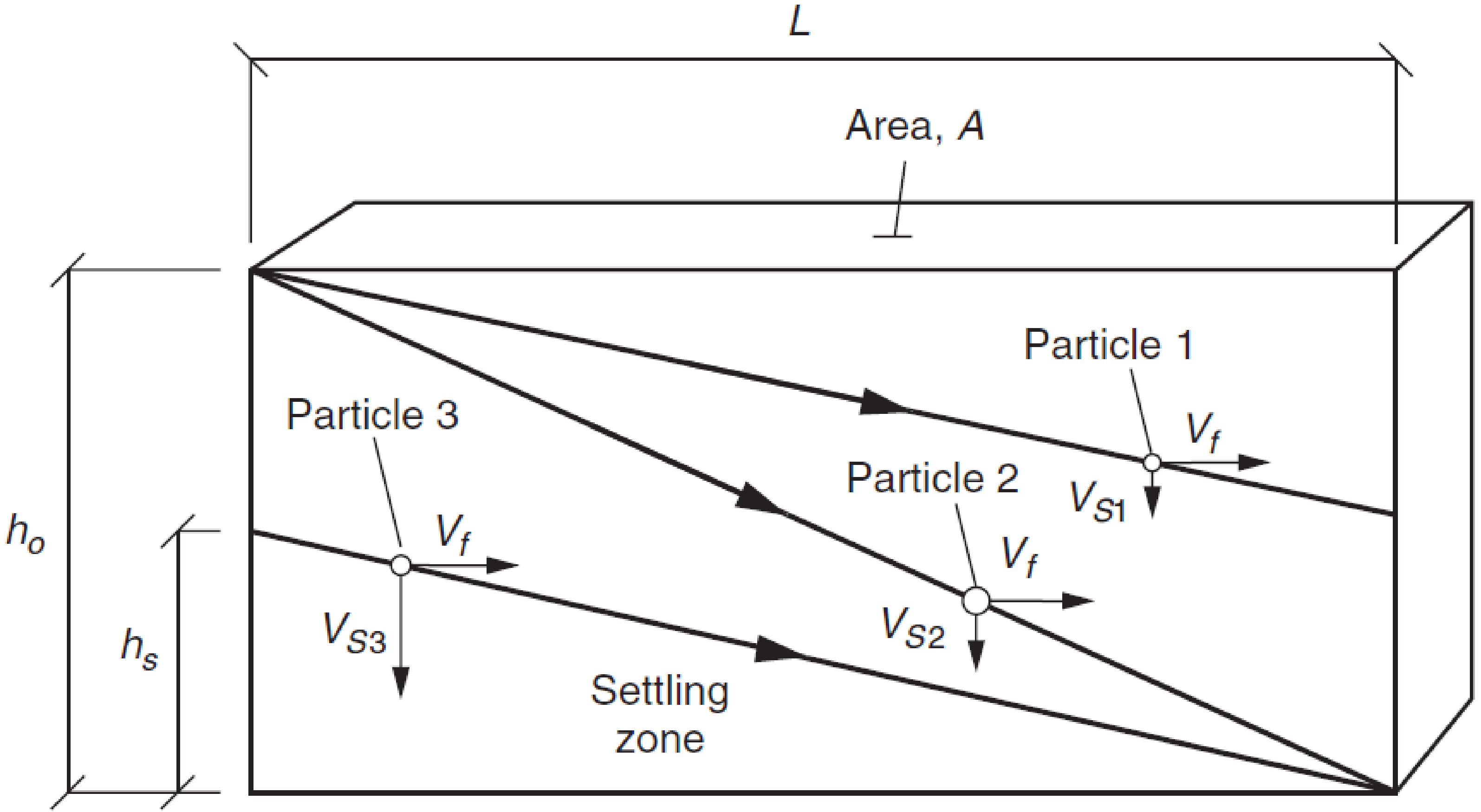
The ideal settling basin theory for removal of discretely settling particles in an ideal settling basin assumes the following:

- Type I settling.
- Four zones in the basin: inlet, outlet, sludge, and settling.
- Even distribution of flow (uniform horizontal velocity) entering the settling zone.
- Even distribution of flow leaving the settling zone.
- Uniform distribution of particles through the depth of the inlet zone end of the settling zone.
- Particles that enter the sludge zone are captured and remain in the sludge zone.
- Particles that enter the outlet zone are not removed from the water.

Rectangular Sedimentation Basins

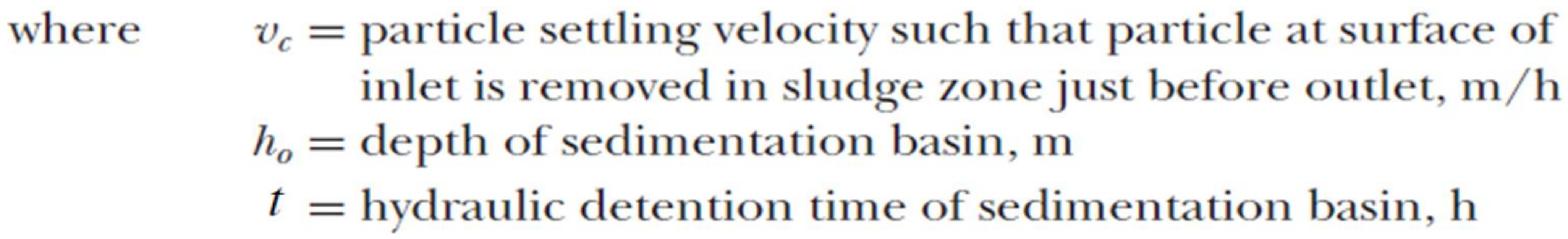
- Particle trajectories have two components in the settling zone: the *settling velocity* (v_s) and the *fluid velocity* (v_f), as shown on Fig. 10-5.

Figure 10-5
Discrete particle trajectories in settling zone of a rectangular clarifier.



- For a rectangular sedimentation basin the fluid velocity is constant.
- The settling velocity for discrete particles is also constant because the particles do not flocculate or interfere with one another.
- Since both horizontal and vertical components of the velocity are constant, the particle trajectories are linear.
- As noted above, every particle that enters the sludge zone is removed.
- A particle from the inlet zone that enters at the top of the basin and settles in the sludge zone just before the outlet is assigned a *critical settling velocity* (v_c), (particle 2 in Fig. 10-5).
- The critical particle settling velocity is given by the equation:

$$v_c = \frac{h_o}{t}$$

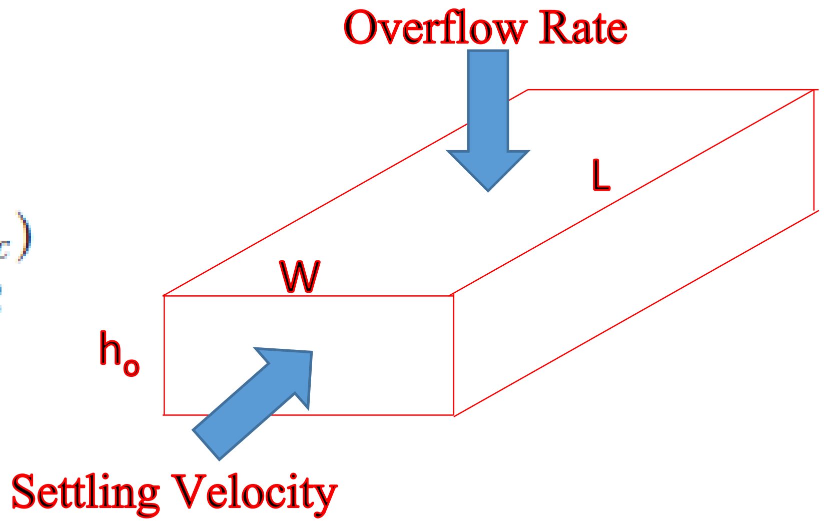


where v_c = particle settling velocity such that particle at surface of inlet is removed in sludge zone just before outlet, m/h
h_o = depth of sedimentation basin, m
t = hydraulic detention time of sedimentation basin, h

- The critical settling velocity may be defined as the overflow rate using the relationships

$$\boxed{v_c = \frac{h_o}{t} = \frac{h_o Q}{h_o A} = \frac{Q}{A} = \mathrm{OR}} \qquad t = \frac{V}{Q}$$

where OR = overflow rate, $\mathrm{m^3/m^2 \cdot h}$ (equal to v_c)
A = area of top of basin settling zone, $\mathrm{m^2}$
Q = process flow rate, $\mathrm{m^3/h}$



- The critical design parameter (overflow rate) for rectangular and circular sedimentation basins is identical (the same equations for the v_c).
- Any particles in the inlet zone with a settling velocity v_s greater than or equal to the critical settling velocity v_c will be removed regardless of the starting position because their trajectories will take them into the sludge zone before they exit the basin.

- The percentage of particles removed, ***P***, with a settling velocity of (v_s) in a horizontal flow sedimentation tank designed with an overflow rate of (***OR***) or (v_c) is

$$P = \left(\frac{v_s}{v_c}\right)100\%$$

Example 10-3.

An existing horizontal-flow sedimentation tank has an overflow rate of 17 $m^3/d.m^2$. What percentage removal should be expected for each of the following particle settling velocities in an ideal sedimentation tank: 0.1 mm/s, 0.2 mm/s, and 1 mm/s?

Solution:

a. Begin by computing the overflow rate in compatible units.

$$(17\ \mathrm{m^3/d \cdot m^2})\left(\frac{1{,}000\ \mathrm{mm/m}}{86{,}400\ \mathrm{s/d}}\right) = 0.197 \text{ or } 0.2\ \mathrm{mm/s}$$

b. For the 0.1 mm/s particles

$$P = \frac{0.1\ \text{mm/s}}{0.2\ \text{mm/s}}(100\%) = 50\%$$

c. For the 0.2 mm/s particles

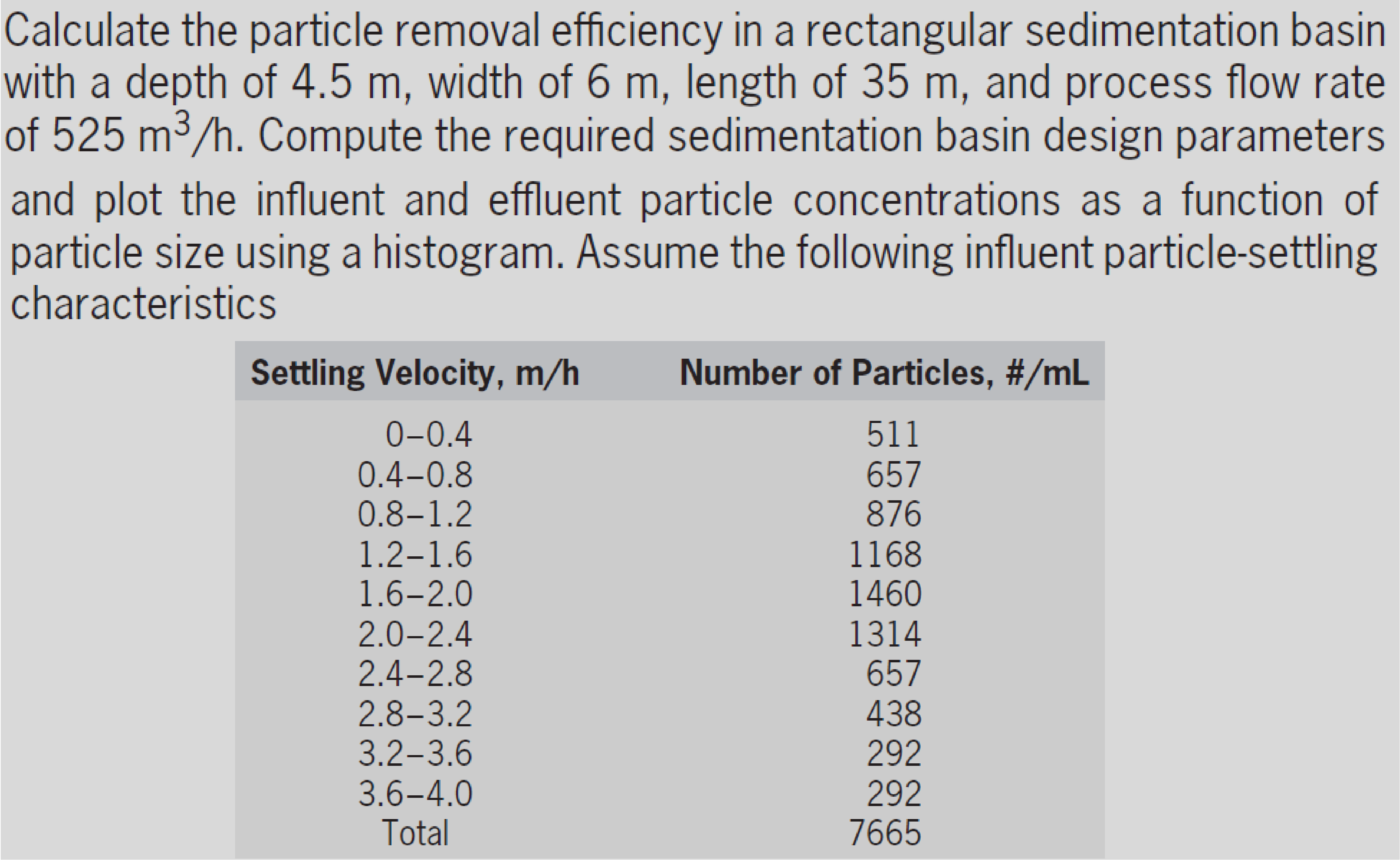
$$P = \frac{0.2\ \text{mm/s}}{0.2\ \text{mm/s}}(100\%) = 100\%$$

d. For the 1 mm/s particles

$$P = \frac{1\ \text{mm/s}}{0.2\ \text{mm/s}}(100\%) = 500\%$$

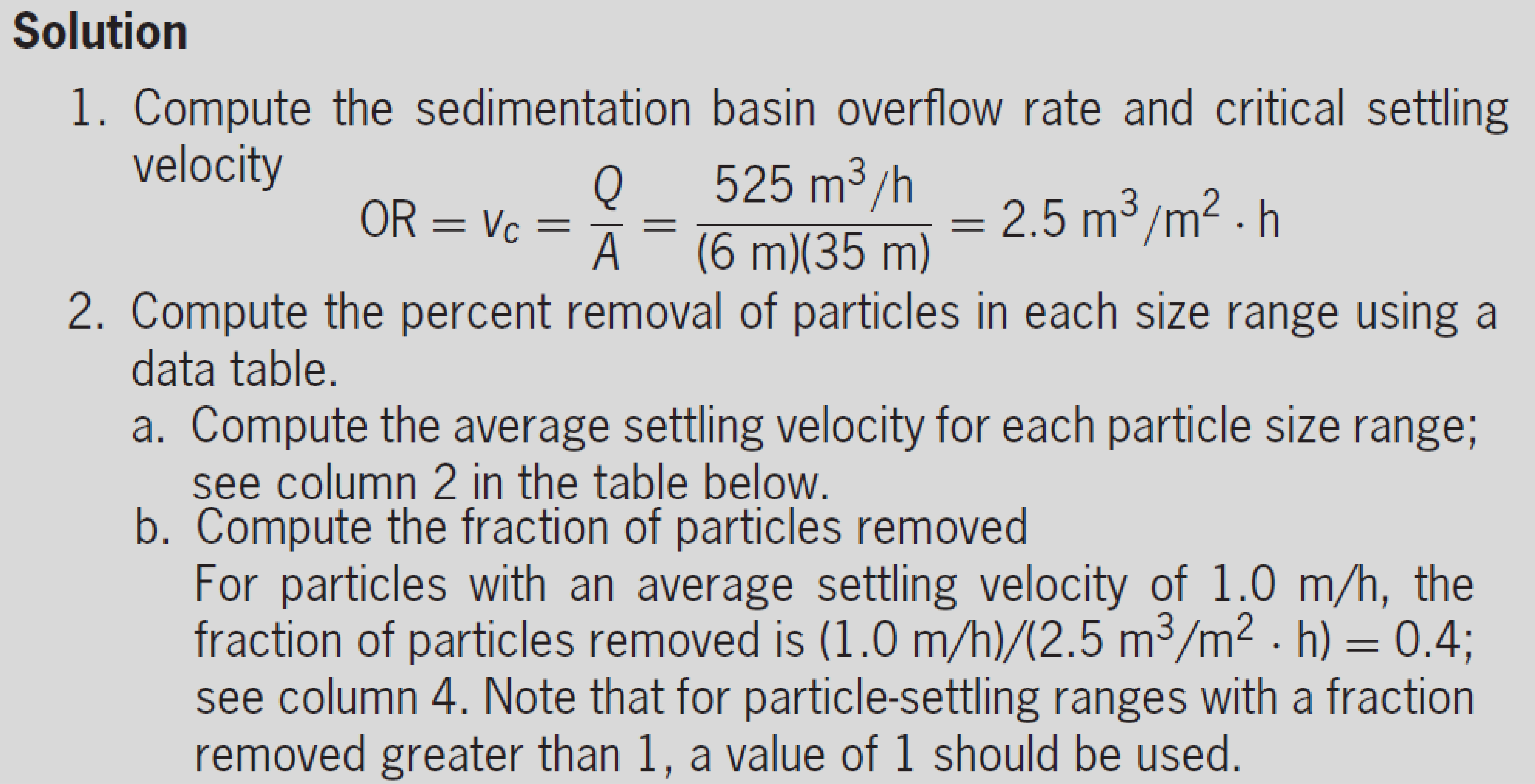
But the particle removal cannot be greater than 100%, so the particle removal is 100% for the particles settling at 1 mm/s.

Example 10-4.



Calculate the particle removal efficiency in a rectangular sedimentation basin with a depth of 4.5 m, width of 6 m, length of 35 m, and process flow rate of 525 m^3/h. Compute the required sedimentation basin design parameters and plot the influent and effluent particle concentrations as a function of particle size using a histogram. Assume the following influent particle-settling characteristics

Settling Velocity, m/h	Number of Particles, #/mL
0–0.4	511
0.4–0.8	657
0.8–1.2	876
1.2–1.6	1168
1.6–2.0	1460
2.0–2.4	1314
2.4–2.8	657
2.8–3.2	438
3.2–3.6	292
3.6–4.0	292
Total	7665

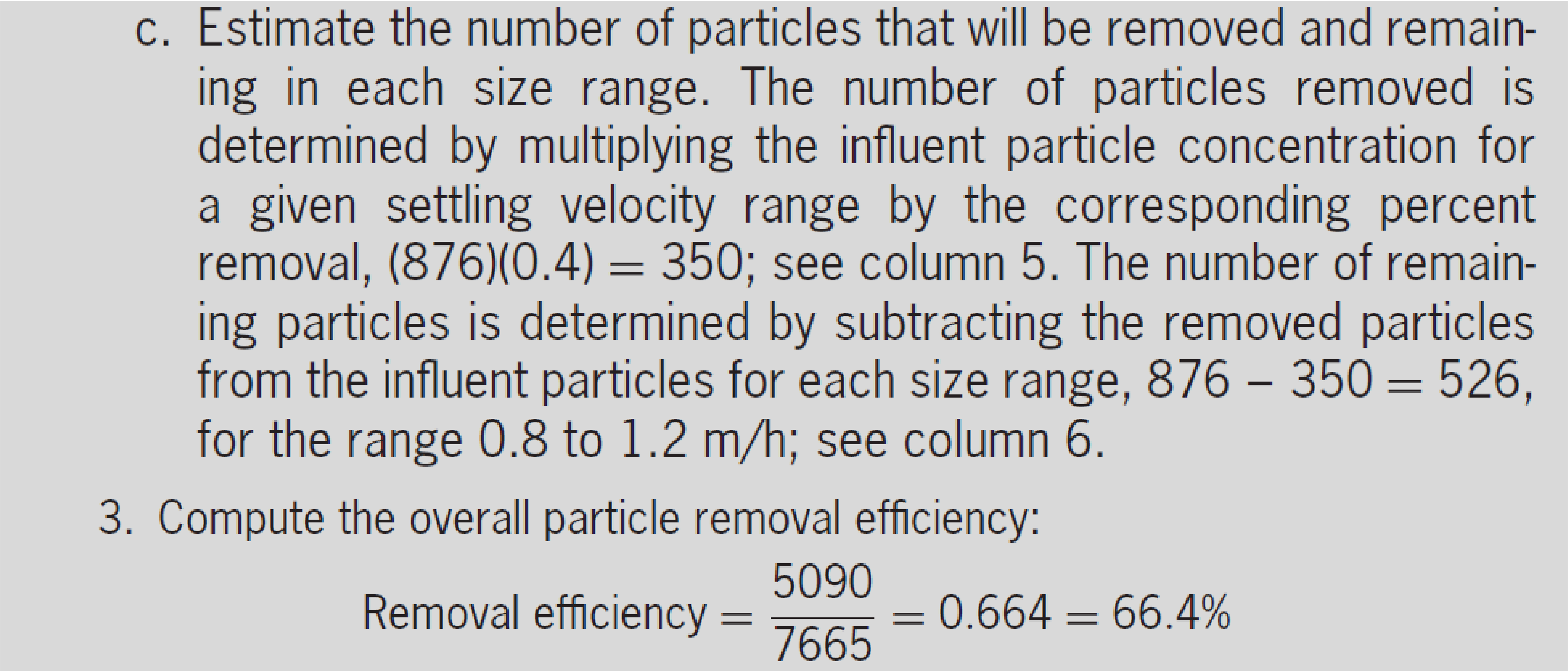


Solution

1. Compute the sedimentation basin overflow rate and critical settling velocity

$$\mathrm{OR} = v_c = \frac{Q}{A} = \frac{525\ \mathrm{m^3/h}}{(6\ \mathrm{m})(35\ \mathrm{m})} = 2.5\ \mathrm{m^3/m^2 \cdot h}$$

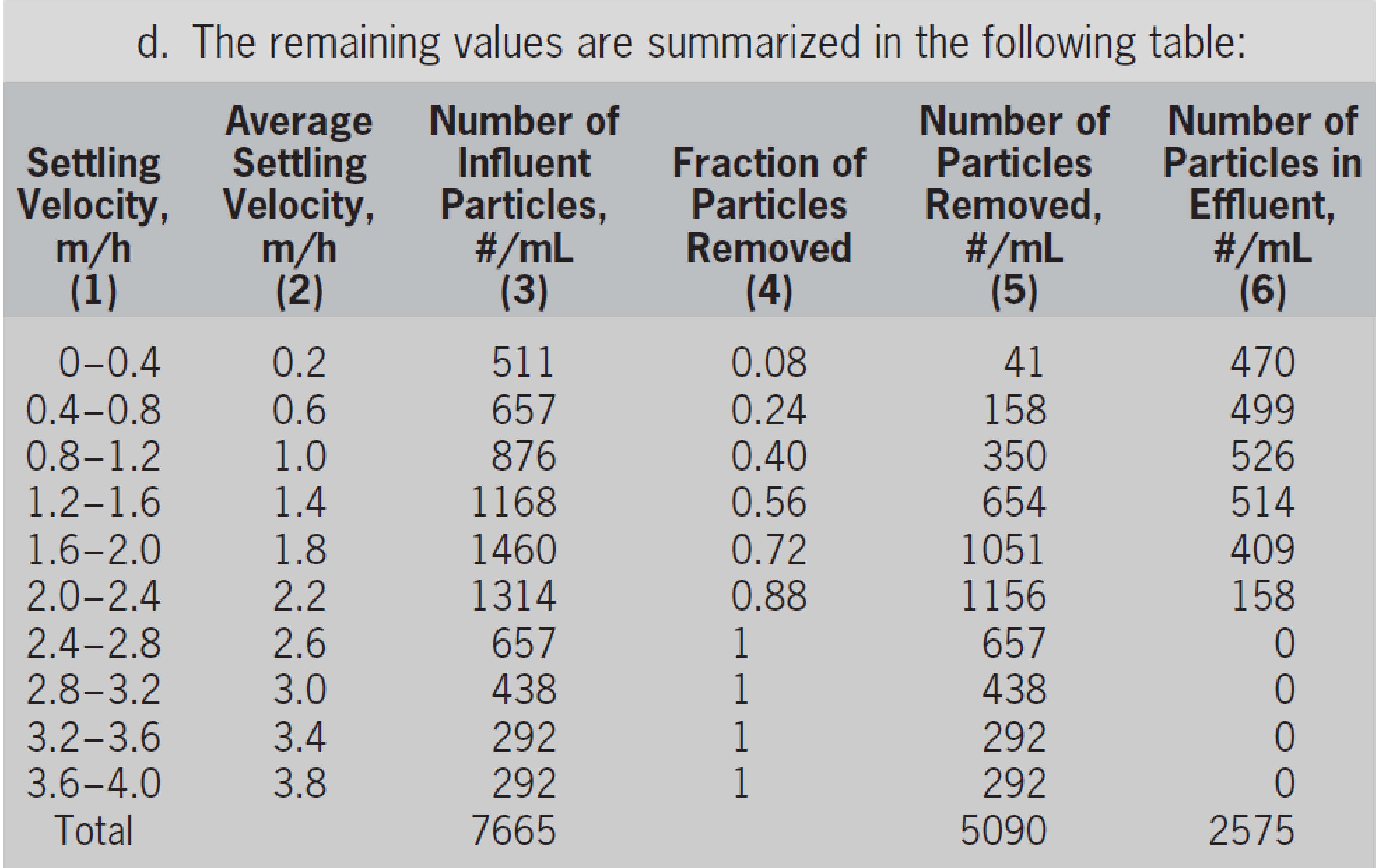
2. Compute the percent removal of particles in each size range using a data table.
   a. Compute the average settling velocity for each particle size range; see column 2 in the table below.
   b. Compute the fraction of particles removed
   For particles with an average settling velocity of 1.0 m/h, the fraction of particles removed is $(1.0\ \mathrm{m/h})/(2.5\ \mathrm{m^3/m^2 \cdot h}) = 0.4$; see column 4. Note that for particle-settling ranges with a fraction removed greater than 1, a value of 1 should be used.



c. Estimate the number of particles that will be removed and remaining in each size range. The number of particles removed is determined by multiplying the influent particle concentration for a given settling velocity range by the corresponding percent removal, (876)(0.4) = 350; see column 5. The number of remaining particles is determined by subtracting the removed particles from the influent particles for each size range, 876 – 350 = 526, for the range 0.8 to 1.2 m/h; see column 6.

3. Compute the overall particle removal efficiency:

$$\text{Removal efficiency} = \frac{5090}{7665} = 0.664 = 66.4\%$$

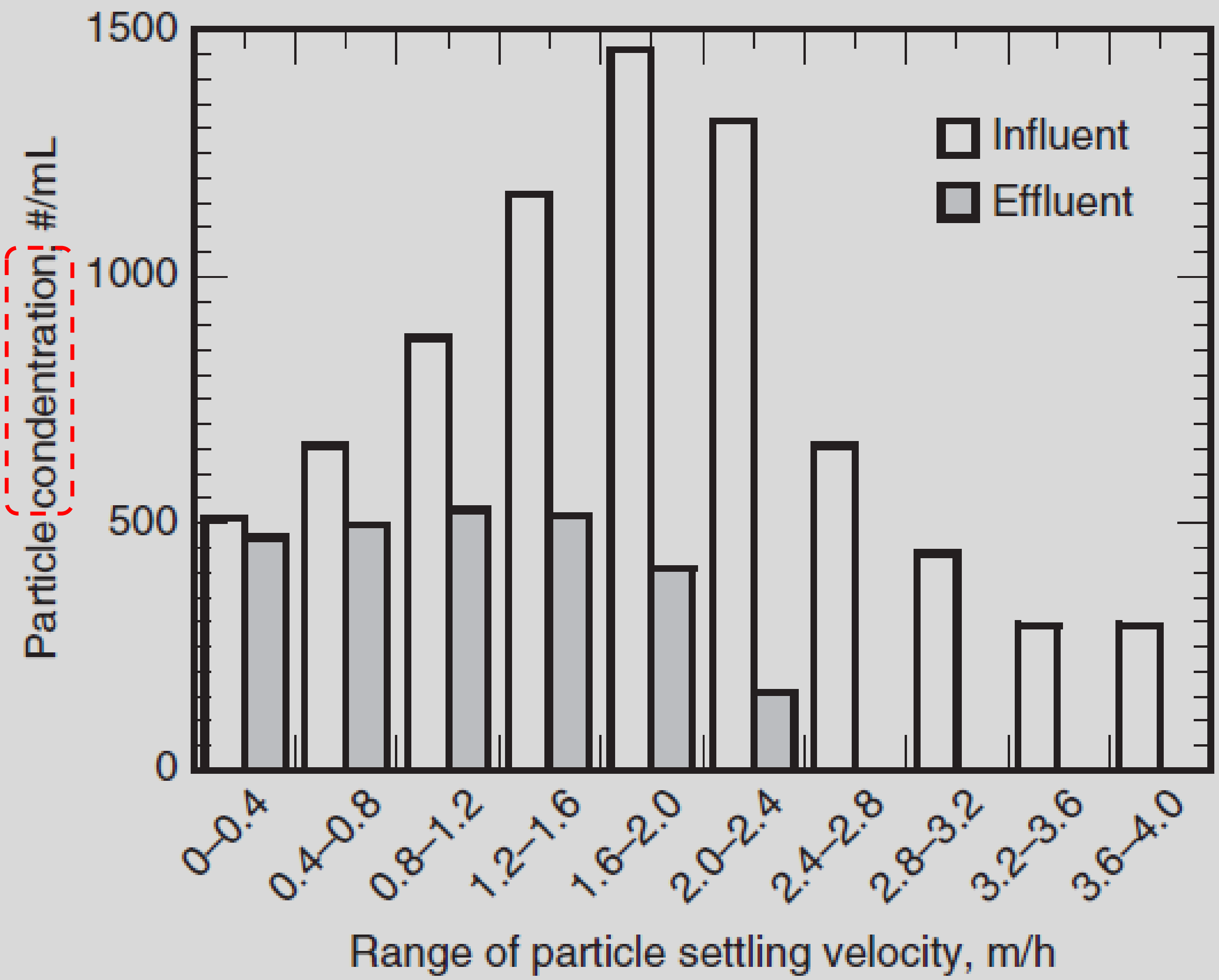


d. The remaining values are summarized in the following table:

Settling Velocity, m/h (1)	Average Settling Velocity, m/h (2)	Number of Influent Particles, #/mL (3)	Fraction of Particles Removed (4)	Number of Particles Removed, #/mL (5)	Number of Particles in Effluent, #/mL (6)
0–0.4	0.2	511	0.08	41	470
0.4–0.8	0.6	657	0.24	158	499
0.8–1.2	1.0	876	0.40	350	526
1.2–1.6	1.4	1168	0.56	654	514
1.6–2.0	1.8	1460	0.72	1051	409
2.0–2.4	2.2	1314	0.88	1156	158
2.4–2.8	2.6	657	1	657	0
2.8–3.2	3.0	438	1	438	0
3.2–3.6	3.4	292	1	292	0
3.6–4.0	3.8	292	1	292	0
Total		7665		5090	2575

4. Plot the influent and effluent particle concentrations for each settling velocity range using a histogram.

concentration



Scour Velocity

To avoid the resuspension (scouring) of settled particles, horizontal velocities through the tank should be kept sufficiently low.

$$v_{\text{scour}} = \left[\frac{8\beta(s-1)gd}{f}\right]^{1/2}$$

where v_{scour} = horizontal velocity, m/s
β = constant for the type of scoured particles
= 0.04 for unigranular material
= 0.06 for sticky interlocking material
s = specific gravity of particle
g = acceleration due to gravity, 9.81 m/s^2
d = diameter of particle, m
f = Darcy–Weisbach friction factor, 0.02 to 0.03

- In most sedimentation tanks the horizontal velocity is well below the required to produce scour.

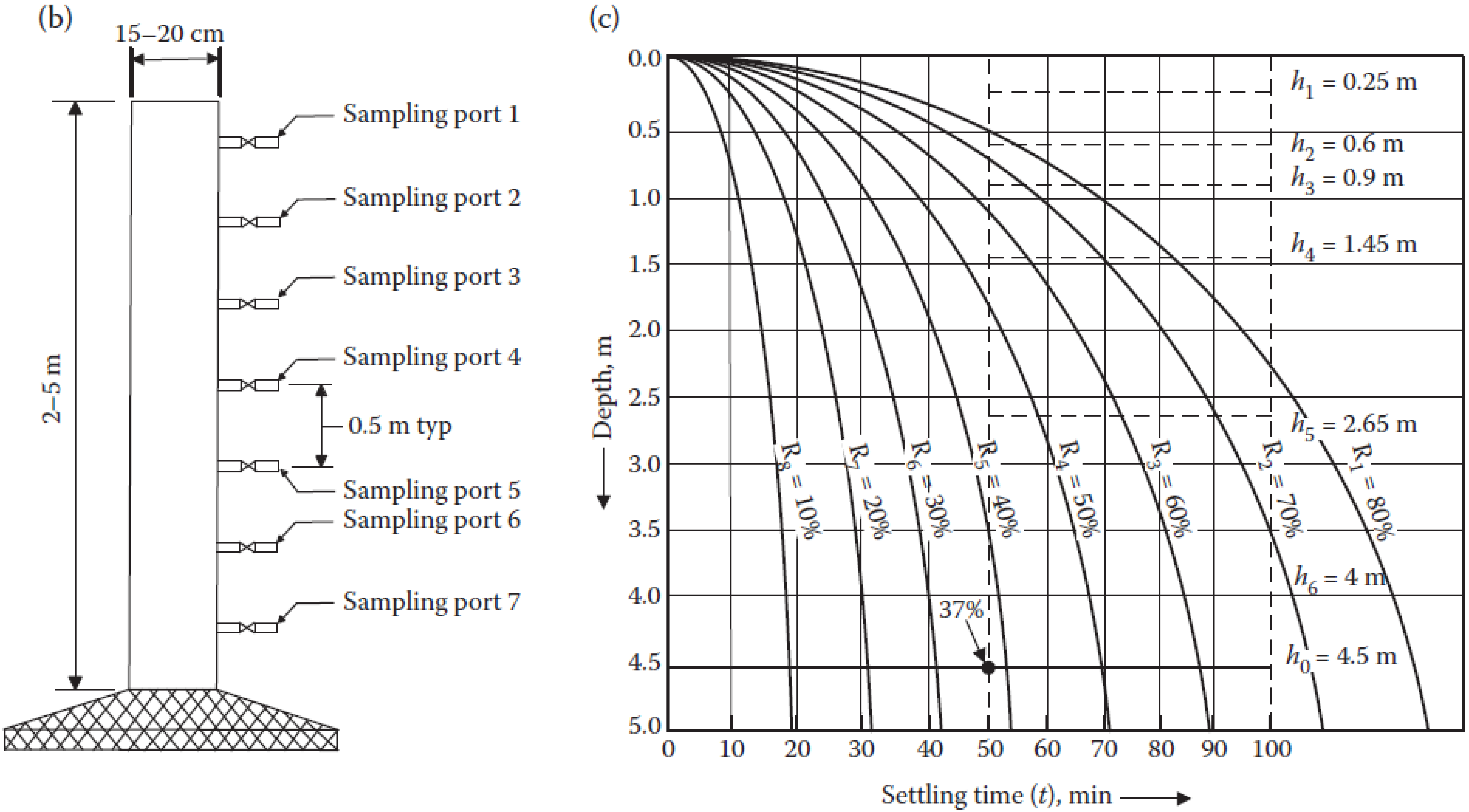
2. Type II Sedimentation (Flocculant Settling)

- ❑ Settling of flocculent particles results in coalescence (coherence) during sedimentation, with the particles growing into larger flocs as they descend.
- ❑ Flocculation is caused by differences in settling velocities of particles, resulting in heavy particles overtaking and coalescing with slower ones. Additionally, velocity gradients within the water produce collisions among particles. Hence, the path of the particles is not linear, and the settling velocity of the particles changes with time.
- ❑ The beneficial results are smaller particles growing into faster-settling floc and flocculation sweeping smaller and slower particles from suspension.
- ❑ The opportunity for contact among settling solids increases with depth.
- ❑ As a result, removal of suspended solids depends on water depth as well as overflow rate and detention time.

- ❑ Flocculent settling is common in clarifying both chemical and biological suspensions.
- ❑ The Stokes equation cannot be used because the flocculating particles are continually changing in size and shape.
- ❑ Laboratory tests with settling columns serve as a model of the behavior of flocculant settling.

Settling Column Model.

- ❑ Laboratory tests with settling columns can be used to:
  - Model the behavior of flocculant settling
  - Evaluate an existing settling tank
  - Develop data for plant expansion or modification of existing plants
- ❑ A settling column is filled with the suspension to be analyzed.
- ❑ The suspension is allowed to settle.
- ❑ Samples are withdrawn from sample ports at different elevations at selected time intervals.
- ❑ The settling column is 15–20 cm (6–8 in) in diameter and 2–5m (6.5–16 ft) tall.
- ❑ Ideally, the height should be equal to the proposed side water depth of the basin.



(b) flocculant column for batch settling test

(c) graph showing results of percent removal and isoremoval lines.

FIGURE 9.1 Flocculant settling

Source: Wastewater Treatment and Reuse Theory and Design Examples Volume 1: Principles and Basic Treatment

- The suspension is thoroughly mixed, then placed into the column to the desired depth.
- Samples are withdrawn usually at initial intervals of 5–10 min simultaneously from all ports.
- Later the frequency of sampling is increased.
- A test with duration of 1–3 h should yield sufficient data to develop the design parameters.
- The total suspended solids (TSS) concentration is determined for each sample.
- The percent removal is calculated:

$$R\% = \left(1 - \frac{C_t}{C_0}\right)(100\%)$$

where $R\%$ = percent removal at one depth and time, %
C_t = concentration at time, t, and given depth, mg/L
C_0 = initial concentration, mg/L

- A summary table with reduced results is generated, and a grid showing percent hypothetical removal of TSS at each port and at different time intervals is plotted.
- Lines or contours of equal percentage removal are drawn.
- These lines also trace the maximum trajectories of particles’ settling paths for specific concentrations in a flocculent suspension.

- The overall percent removal of solids at a given detention time and depth of the column is calculated from the following

$$\text{Overall percent removal} = \frac{h_1}{h_0}(100 - R_1) + \frac{h_2}{h_0}(R_1 - R_2) + \cdots + \frac{h_{n-1}}{h_0}(R_{n-1} - R_n) + R_n \qquad (9.1a)$$

OR

$$\text{Overall Percent removal} = \frac{\Delta h_1}{h_0}\left(\frac{100 + R_1}{2}\right) + \frac{\Delta h_2}{h_0}\left(\frac{R_1 + R_2}{2}\right) + \cdots + \frac{\Delta h_n}{h_0}\left(\frac{R_{n-1} + R_n}{2}\right) \qquad (9.1b)$$

where

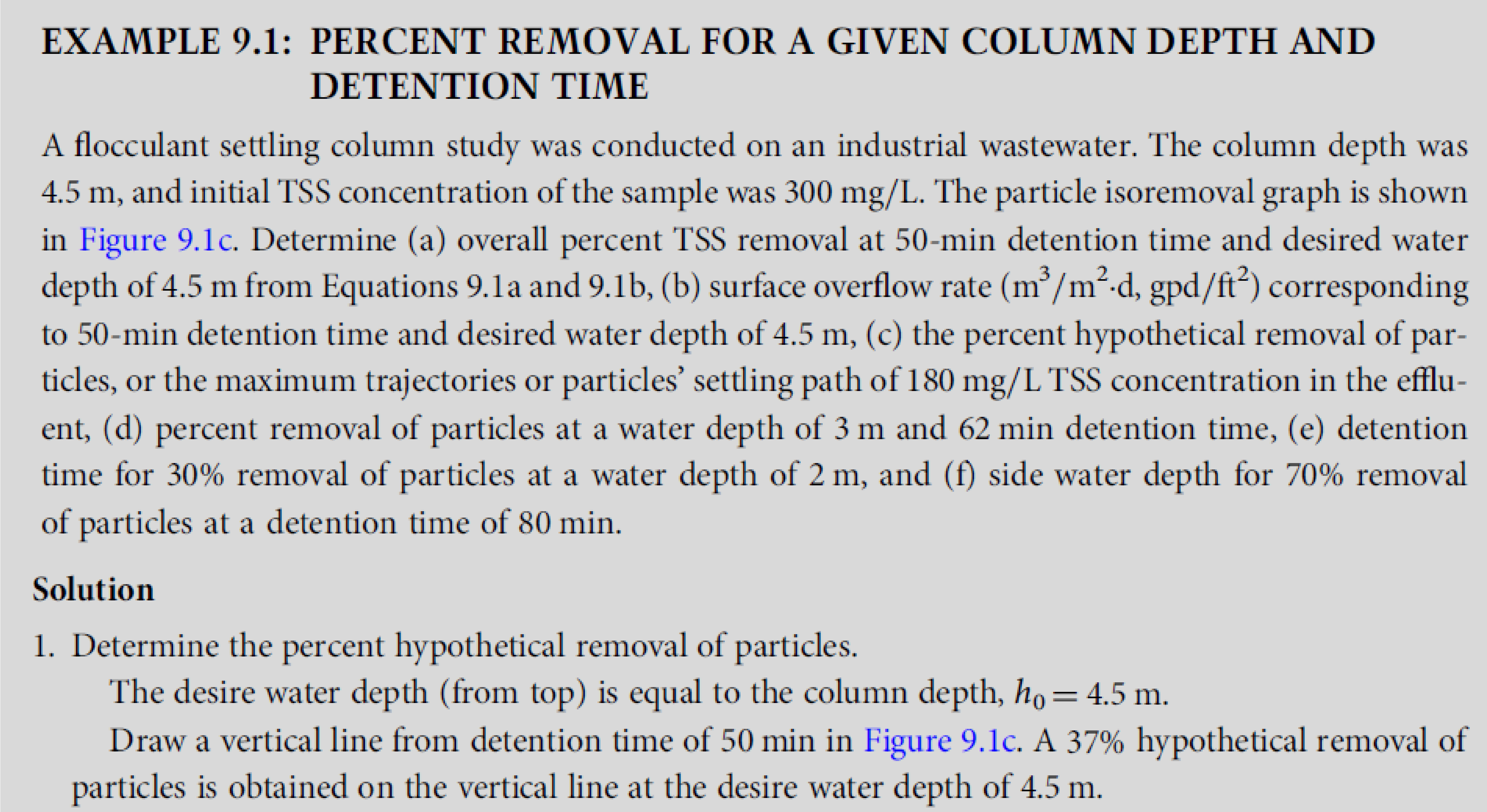
$h_1, h_2, \ldots, h_n$ = vertical distance from the top of the settling column to the midpoint between two consecutive particle isoremoval curves at the desired detention time (Figure 9.1c), m (ft)

h_0 = desired side water depth that is less than or equal to the depth of settling column (Figure 9.1c), m (ft)

$R_1, R_2, \ldots, R_n$ = consecutive particle isoremoval curves, percent removal

$\Delta h_1, \Delta h_2, \ldots, \Delta h_n$ = vertical distance between two consecutive particle isoremoval curves at the desired detention time (Figure 9.1c), m (ft)

- The theoretical detention time and surface overflow rate are obtained from the percent particle removal efficiency curves.



EXAMPLE 9.1: PERCENT REMOVAL FOR A GIVEN COLUMN DEPTH AND DETENTION TIME

A flocculant settling column study was conducted on an industrial wastewater. The column depth was 4.5 m, and initial TSS concentration of the sample was 300 mg/L. The particle isoremoval graph is shown in Figure 9.1c. Determine (a) overall percent TSS removal at 50-min detention time and desired water depth of 4.5 m from Equations 9.1a and 9.1b, (b) surface overflow rate ($m^3/m^2{\cdot}d$, gpd/ft^2) corresponding to 50-min detention time and desired water depth of 4.5 m, (c) the percent hypothetical removal of particles, or the maximum trajectories or particles' settling path of 180 mg/L TSS concentration in the effluent, (d) percent removal of particles at a water depth of 3 m and 62 min detention time, (e) detention time for 30% removal of particles at a water depth of 2 m, and (f) side water depth for 70% removal of particles at a detention time of 80 min.

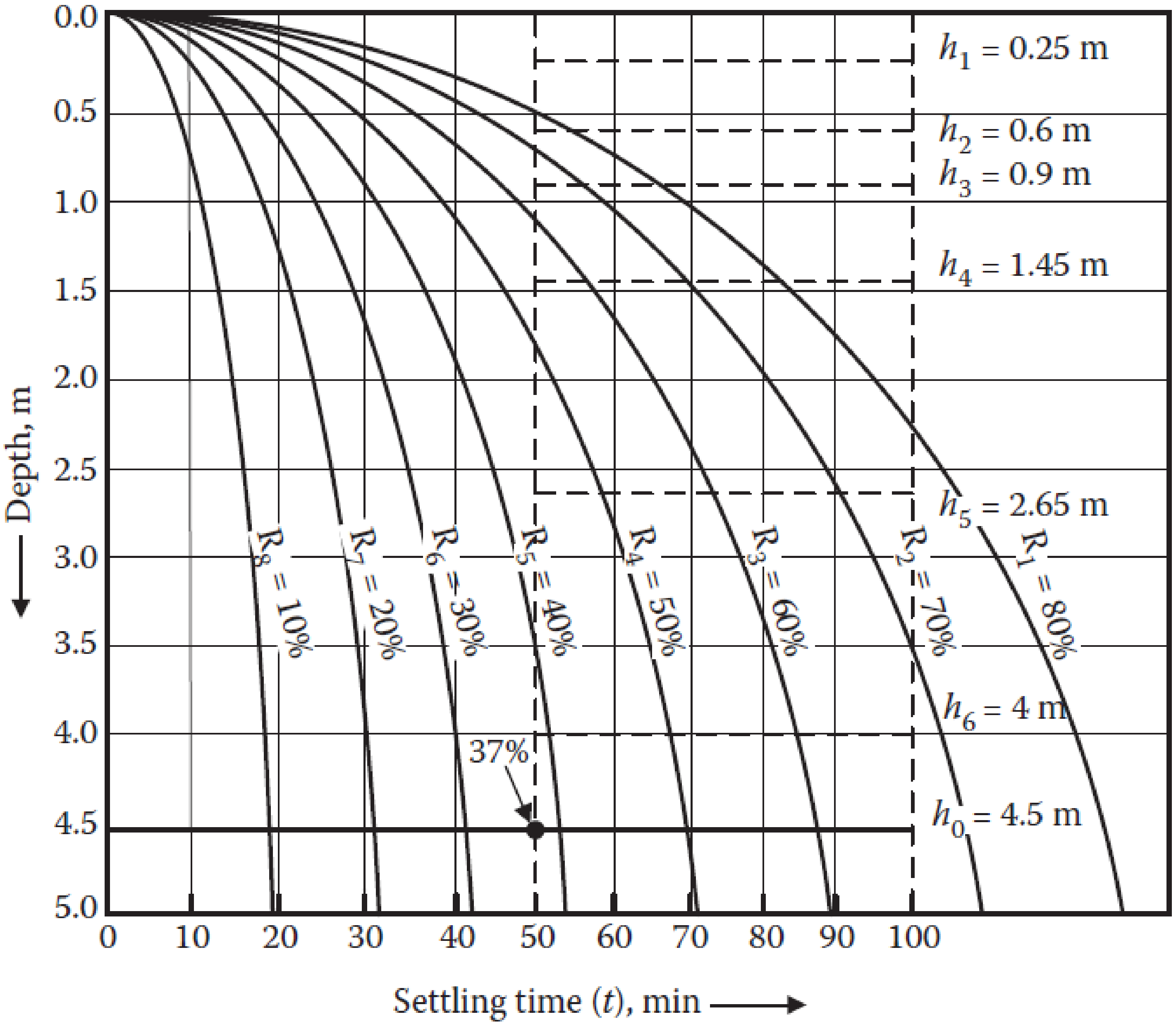
Solution

1. Determine the percent hypothetical removal of particles.

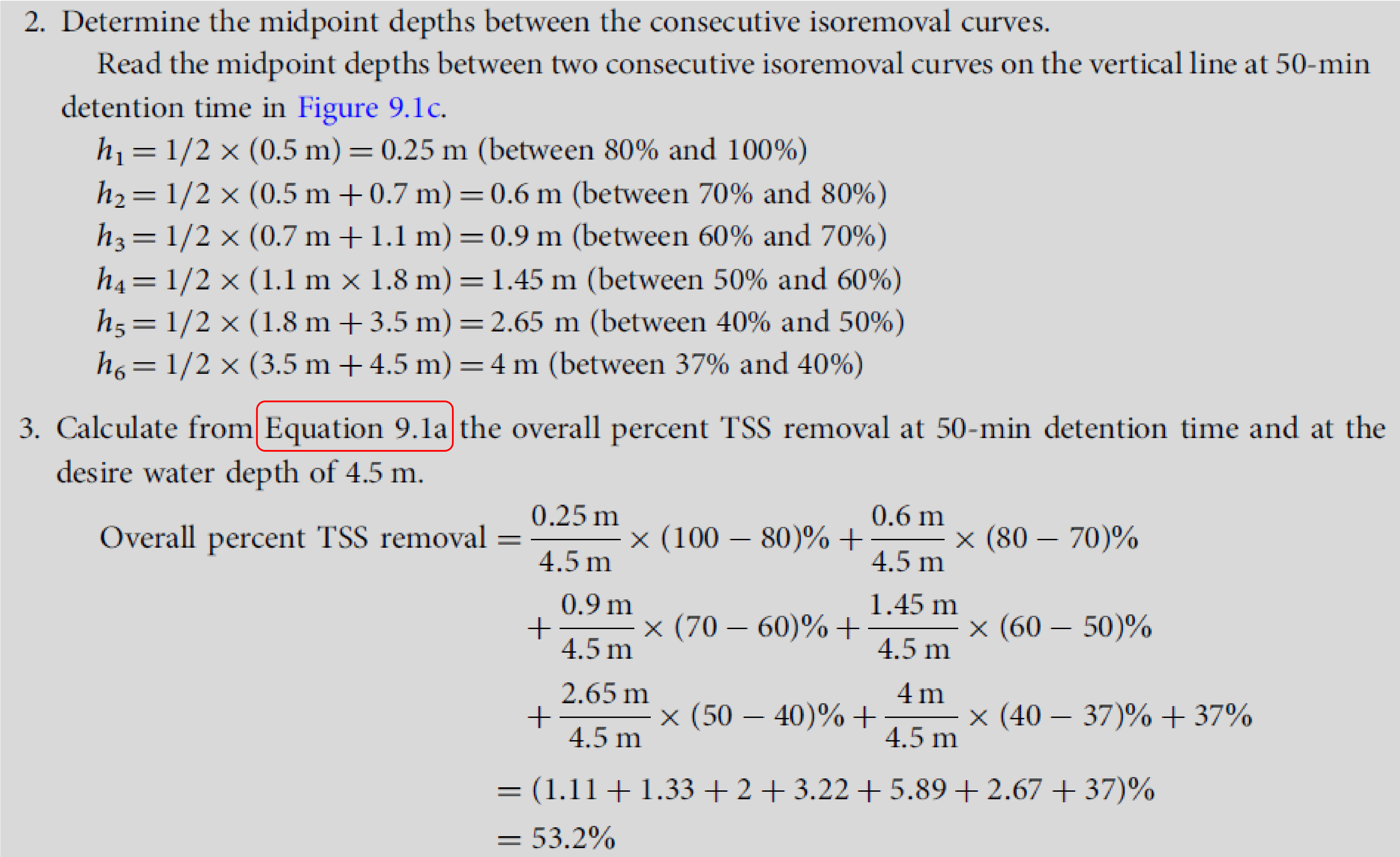
The desire water depth (from top) is equal to the column depth, $h_0 = 4.5$ m.

Draw a vertical line from detention time of 50 min in Figure 9.1c. A 37% hypothetical removal of particles is obtained on the vertical line at the desire water depth of 4.5 m.

(c)



0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Depth, m
0
10
20
30
40
50
60
70
80
90
100
Settling time (t), min
h_1 = 0.25 m
h_2 = 0.6 m
h_3 = 0.9 m
h_4 = 1.45 m
h_5 = 2.65 m
h_6 = 4 m
h_0 = 4.5 m
R_8 = 10%
R_7 = 20%
R_6 = 30%
R_5 = 40%
R_4 = 50%
R_3 = 60%
R_2 = 70%
R_1 = 80%
37%



2. Determine the midpoint depths between the consecutive isoremoval curves.

Read the midpoint depths between two consecutive isoremoval curves on the vertical line at 50-min detention time in Figure 9.1c.

$h_1 = 1/2 \times (0.5\ \text{m}) = 0.25\ \text{m}$ (between 80% and 100%)

$h_2 = 1/2 \times (0.5\ \text{m} + 0.7\ \text{m}) = 0.6\ \text{m}$ (between 70% and 80%)

$h_3 = 1/2 \times (0.7\ \text{m} + 1.1\ \text{m}) = 0.9\ \text{m}$ (between 60% and 70%)

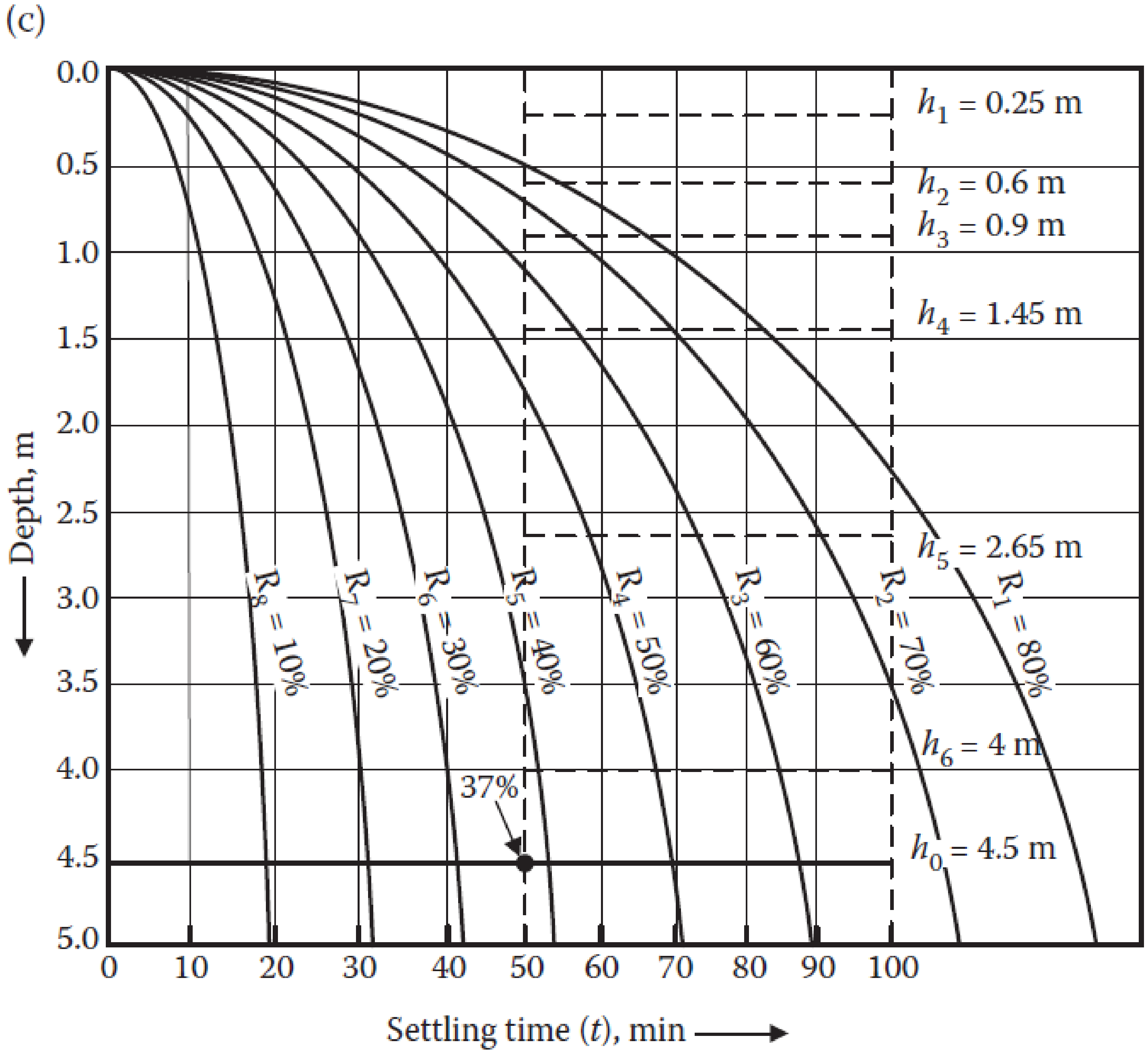
$h_4 = 1/2 \times (1.1\ \text{m} \times 1.8\ \text{m}) = 1.45\ \text{m}$ (between 50% and 60%)

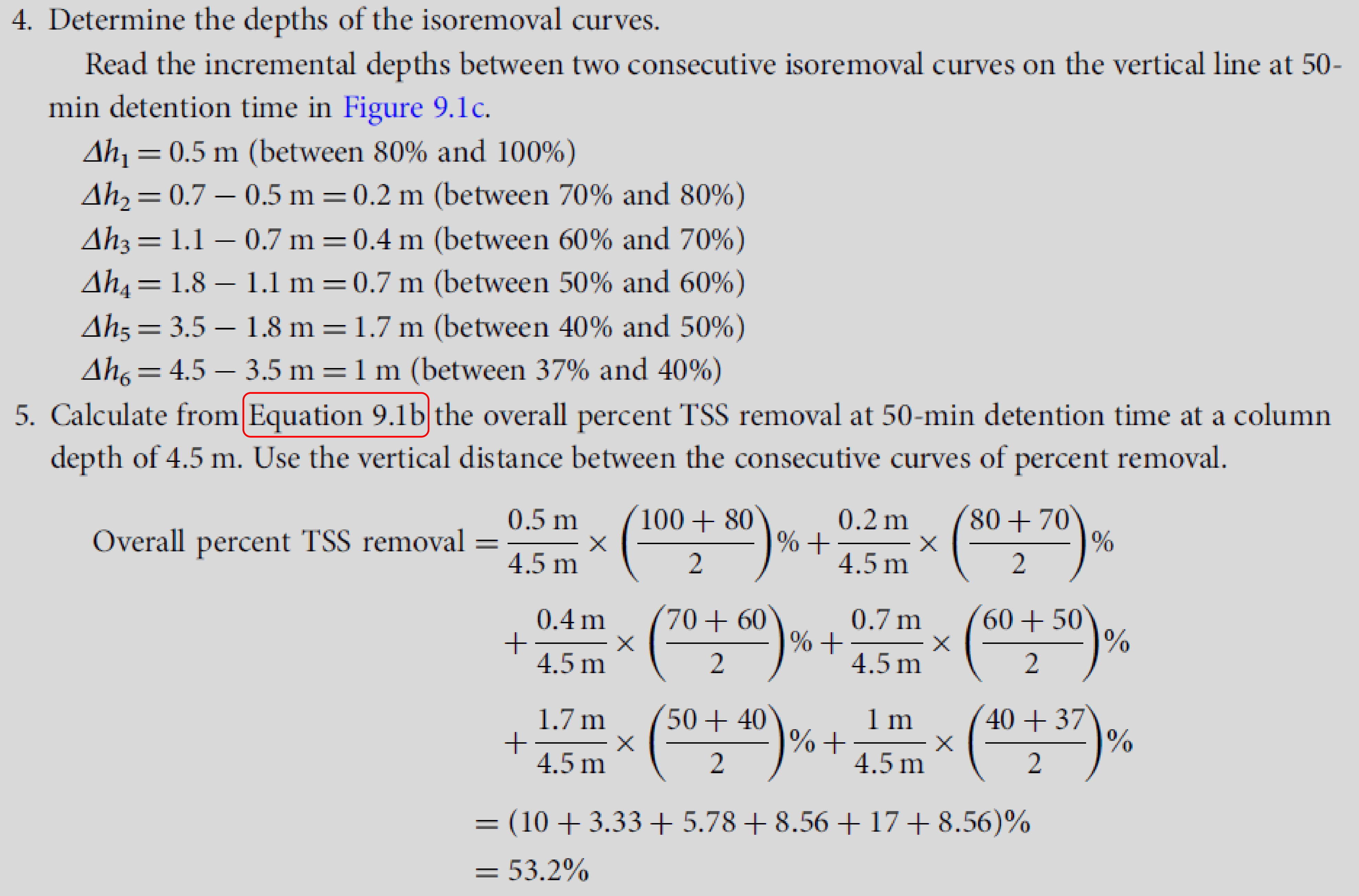
$h_5 = 1/2 \times (1.8\ \text{m} + 3.5\ \text{m}) = 2.65\ \text{m}$ (between 40% and 50%)

$h_6 = 1/2 \times (3.5\ \text{m} + 4.5\ \text{m}) = 4\ \text{m}$ (between 37% and 40%)

3. Calculate from Equation 9.1a the overall percent TSS removal at 50-min detention time and at the desire water depth of 4.5 m.

$$\begin{aligned}
\text{Overall percent TSS removal} &= \frac{0.25\ \text{m}}{4.5\ \text{m}} \times (100 - 80)\% + \frac{0.6\ \text{m}}{4.5\ \text{m}} \times (80 - 70)\% \\
&\quad + \frac{0.9\ \text{m}}{4.5\ \text{m}} \times (70 - 60)\% + \frac{1.45\ \text{m}}{4.5\ \text{m}} \times (60 - 50)\% \\
&\quad + \frac{2.65\ \text{m}}{4.5\ \text{m}} \times (50 - 40)\% + \frac{4\ \text{m}}{4.5\ \text{m}} \times (40 - 37)\% + 37\% \\
&= (1.11 + 1.33 + 2 + 3.22 + 5.89 + 2.67 + 37)\% \\
&= 53.2\%
\end{aligned}$$


(c)
Depth, m
Settling time (t), min
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
10
20
30
40
50
60
70
80
90
100
h_1 = 0.25 m
h_2 = 0.6 m
h_3 = 0.9 m
h_4 = 1.45 m
h_5 = 2.65 m
h_6 = 4 m
h_0 = 4.5 m
R_8 = 10%
R_7 = 20%
R_6 = 30%
R_5 = 40%
R_4 = 50%
R_3 = 60%
R_2 = 70%
R_1 = 80%
37%



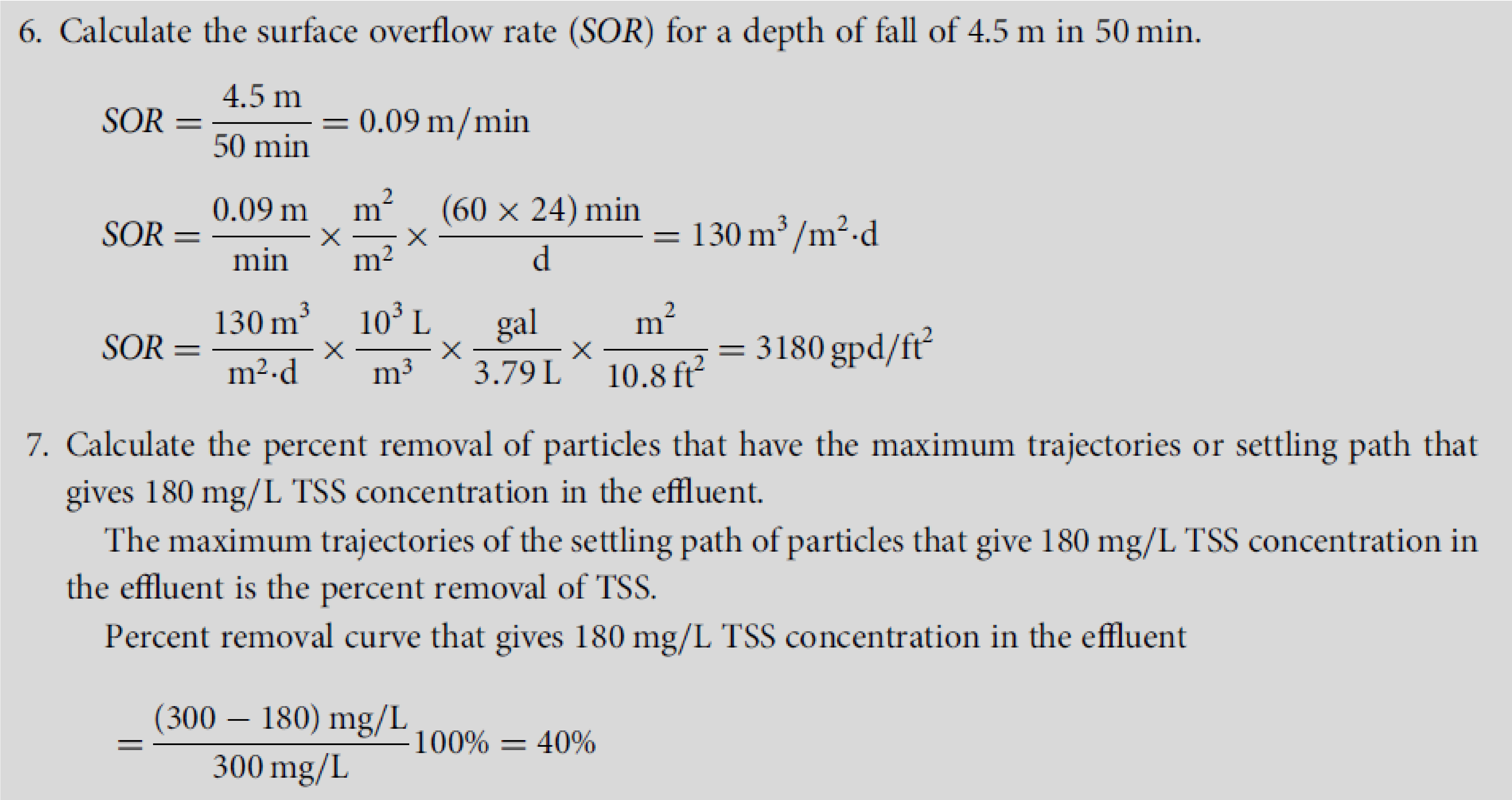
4. Determine the depths of the isoremoval curves.

   Read the incremental depths between two consecutive isoremoval curves on the vertical line at 50-min detention time in Figure 9.1c.

   $\Delta h_1 = 0.5$ m (between 80% and 100%)
   $\Delta h_2 = 0.7 - 0.5$ m $= 0.2$ m (between 70% and 80%)
   $\Delta h_3 = 1.1 - 0.7$ m $= 0.4$ m (between 60% and 70%)
   $\Delta h_4 = 1.8 - 1.1$ m $= 0.7$ m (between 50% and 60%)
   $\Delta h_5 = 3.5 - 1.8$ m $= 1.7$ m (between 40% and 50%)
   $\Delta h_6 = 4.5 - 3.5$ m $= 1$ m (between 37% and 40%)

5. Calculate from Equation 9.1b the overall percent TSS removal at 50-min detention time at a column depth of 4.5 m. Use the vertical distance between the consecutive curves of percent removal.

$$\begin{aligned}
\text{Overall percent TSS removal} &= \frac{0.5\text{ m}}{4.5\text{ m}} \times \left(\frac{100+80}{2}\right)\% + \frac{0.2\text{ m}}{4.5\text{ m}} \times \left(\frac{80+70}{2}\right)\% \\
&\quad + \frac{0.4\text{ m}}{4.5\text{ m}} \times \left(\frac{70+60}{2}\right)\% + \frac{0.7\text{ m}}{4.5\text{ m}} \times \left(\frac{60+50}{2}\right)\% \\
&\quad + \frac{1.7\text{ m}}{4.5\text{ m}} \times \left(\frac{50+40}{2}\right)\% + \frac{1\text{ m}}{4.5\text{ m}} \times \left(\frac{40+37}{2}\right)\% \\
&= (10 + 3.33 + 5.78 + 8.56 + 17 + 8.56)\% \\
&= 53.2\%
\end{aligned}$$



6. Calculate the surface overflow rate (*SOR*) for a depth of fall of 4.5 m in 50 min.

$$SOR = \frac{4.5\ \text{m}}{50\ \text{min}} = 0.09\ \text{m/min}$$

$$SOR = \frac{0.09\ \text{m}}{\text{min}} \times \frac{\text{m}^2}{\text{m}^2} \times \frac{(60 \times 24)\ \text{min}}{\text{d}} = 130\ \text{m}^3/\text{m}^2{\cdot}\text{d}$$

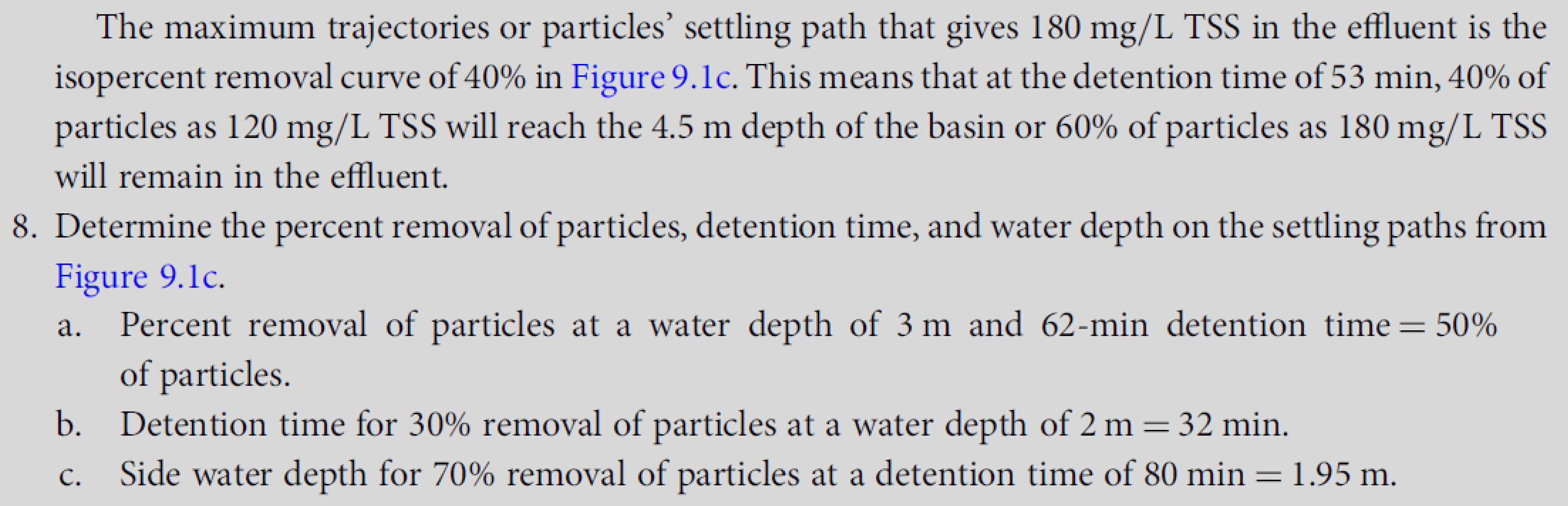
$$SOR = \frac{130\ \text{m}^3}{\text{m}^2{\cdot}\text{d}} \times \frac{10^3\ \text{L}}{\text{m}^3} \times \frac{\text{gal}}{3.79\ \text{L}} \times \frac{\text{m}^2}{10.8\ \text{ft}^2} = 3180\ \text{gpd/ft}^2$$

7. Calculate the percent removal of particles that have the maximum trajectories or settling path that gives 180 mg/L TSS concentration in the effluent.

The maximum trajectories of the settling path of particles that give 180 mg/L TSS concentration in the effluent is the percent removal of TSS.

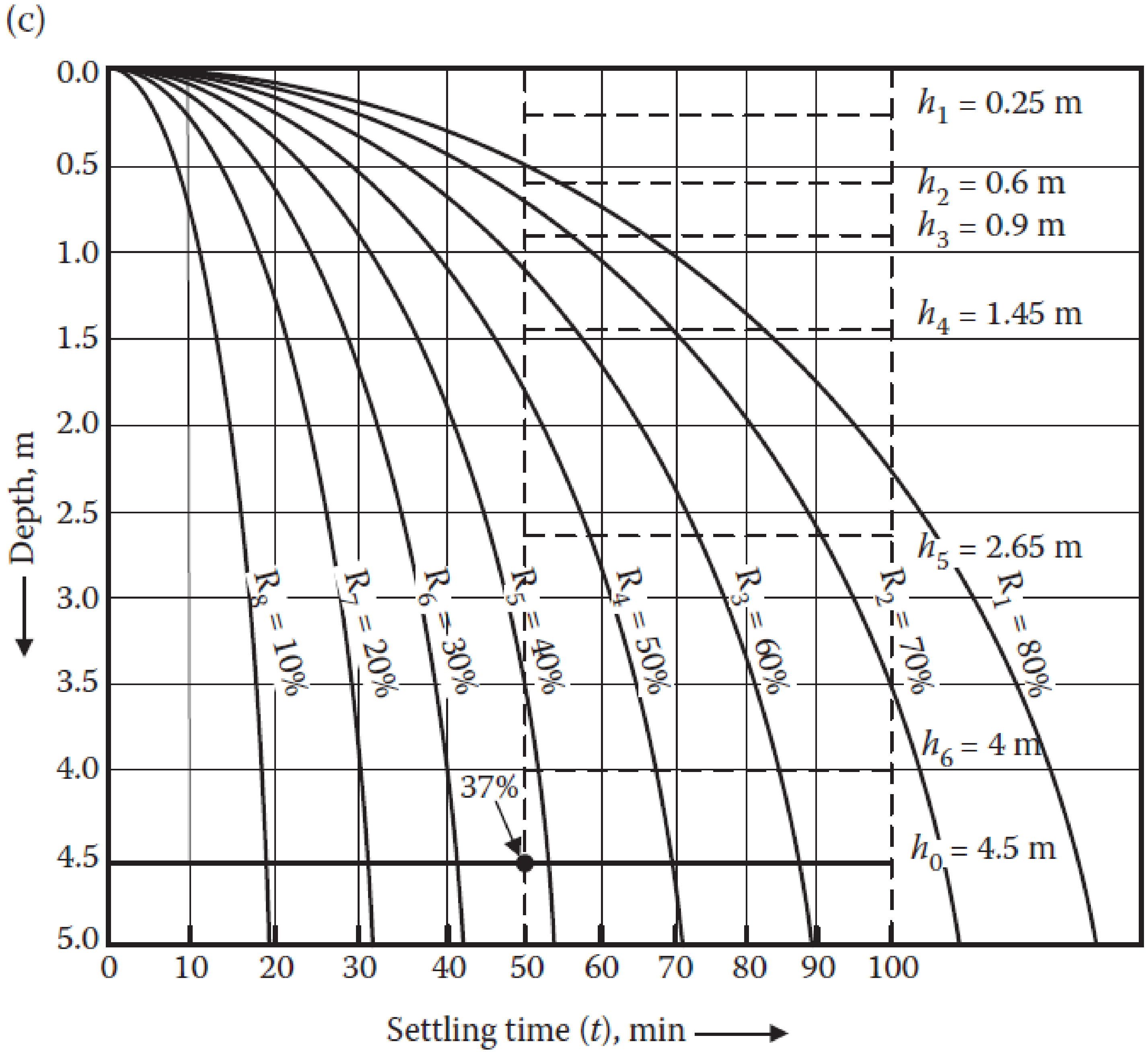
Percent removal curve that gives 180 mg/L TSS concentration in the effluent

$$= \frac{(300 - 180)\ \text{mg/L}}{300\ \text{mg/L}} 100\% = 40\%$$



The maximum trajectories or particles' settling path that gives 180 mg/L TSS in the effluent is the isopercent removal curve of 40% in Figure 9.1c. This means that at the detention time of 53 min, 40% of particles as 120 mg/L TSS will reach the 4.5 m depth of the basin or 60% of particles as 180 mg/L TSS will remain in the effluent.

8. Determine the percent removal of particles, detention time, and water depth on the settling paths from Figure 9.1c.
   a. Percent removal of particles at a water depth of 3 m and 62-min detention time = 50% of particles.
   b. Detention time for 30% removal of particles at a water depth of 2 m = 32 min.
   c. Side water depth for 70% removal of particles at a detention time of 80 min = 1.95 m.


(c)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Depth, m
0
10
20
30
40
50
60
70
80
90
100
Settling time (t), min
h_1 = 0.25 m
h_2 = 0.6 m
h_3 = 0.9 m
h_4 = 1.45 m
h_5 = 2.65 m
h_6 = 4 m
h_0 = 4.5 m
R_8 = 10%
R_7 = 20%
R_6 = 30%
R_5 = 40%
R_4 = 50%
R_3 = 60%
R_2 = 70%
R_1 = 80%
37%