Sedimentation

Most wastewaters and waters contain solids, and in many treatment processes solids are generated e.g., phosphate precipitation, coagulation and activated sludge bioxidation. Particles in water and wastewater that will settle by gravity within a reasonable period of time can be removed by "sedimentation" in sedimentation basins (also known as "clarifiers").

“Settleable” doesn’t necessarily mean that these particles will settle easily by gravity. In many cases they must be coaxed out of suspension or “solution” by the addition of chemicals or increased gravity (centrifugation or filtration). Because of the high volumetric flow rates associated with water and wastewater treatment systems, gravity sedimentation is the only practical, economical method to remove these solids. i.e., processes such as centrifugation are not economical, in most cases.

Gravity separation can obviously be applied only to those particles which have density greater than water. But this density must be significantly greater than that of water due to particle surface effects and turbulence in the sedimentation tanks.

Goals of gravity sedimentation:

1) Produce a clarified (free of suspended solids) effluent.

2) Produce a highly concentrated solid sludge stream.

Review of Type I and II sedimentation

Type I (Discrete sedimentation):

•Occurs in dilute suspensions, particles which have very little interaction with each other as they settle.

•Particles settle according to Stokes law

•Design parameter is surface overflow rate (Q/A_s)

Type II (flocculent sedimentation)

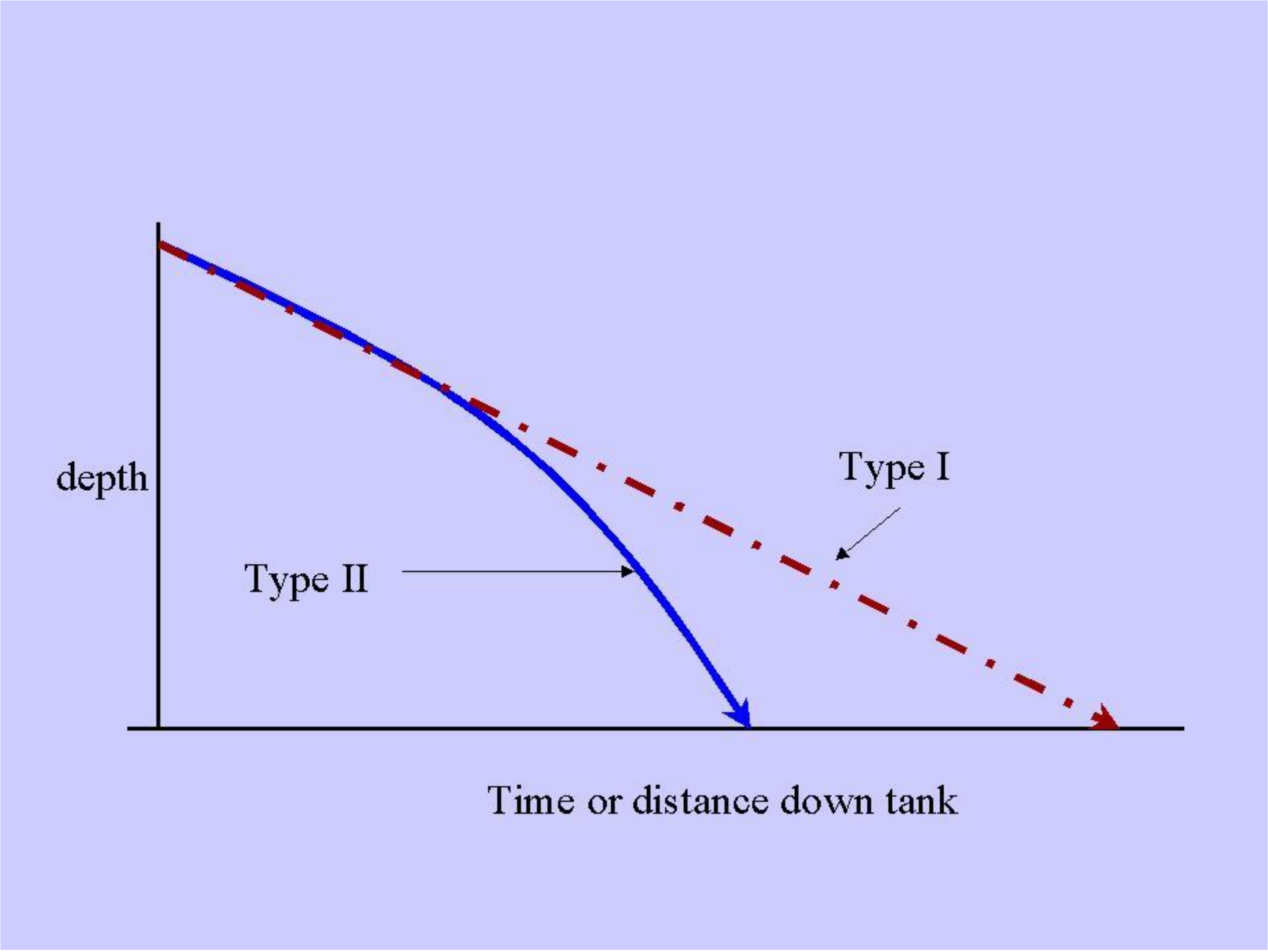
- Particles flocculate as they settle
- Floc particle velocity increase with time
- Design parameters:

1. Surface overflow rate
2. Depth of tank

or,

3. Hydraulic retention time

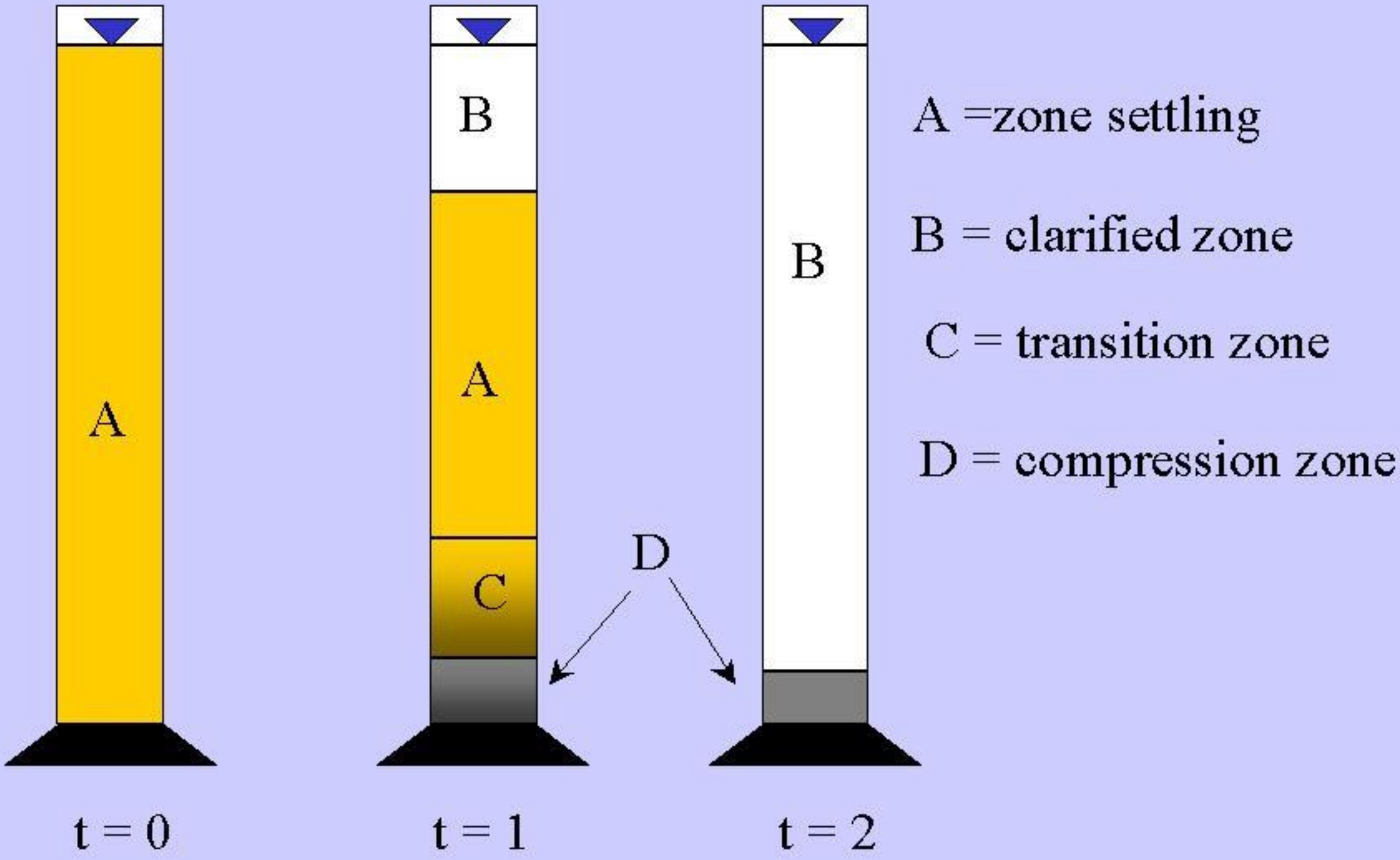
Comparison of Type I and II sedimentation

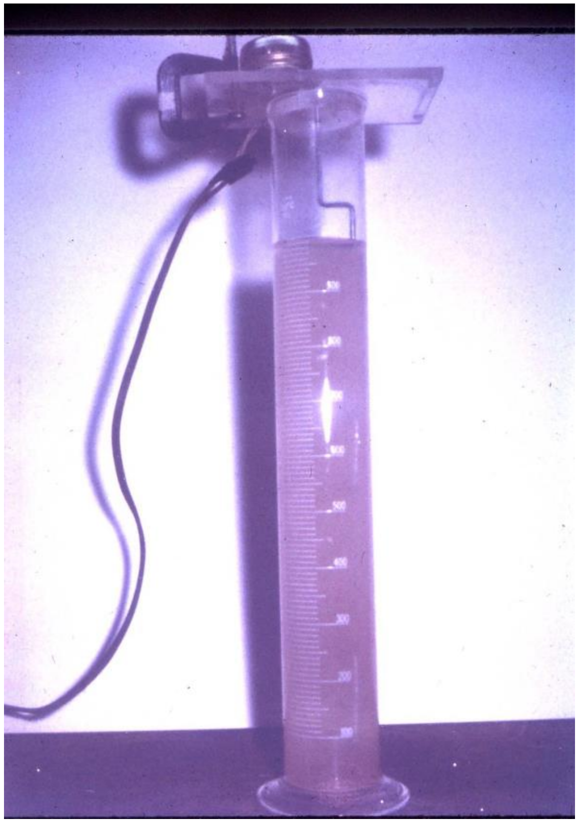


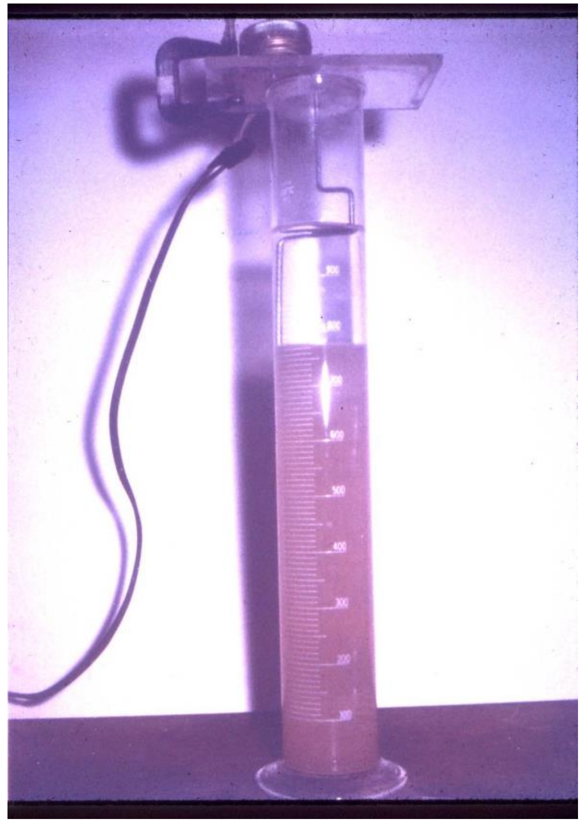
Zone Settling &Compression (Type III and IV)

Zone settling occurs when a flocculent suspensions with high initial concentration (on the order of 500 mg/L) settles by gravity. Flocculant forces between particles causes settling as a matrix (particles remain in a fixed position relative to each other as they settle). When matrix sedimentation is constrained from the bottom the matrix begins to compress. Such a situation occurs when the matrix encounters the bottom of tank in which it is settling. This is called compression (Type IV) settling.

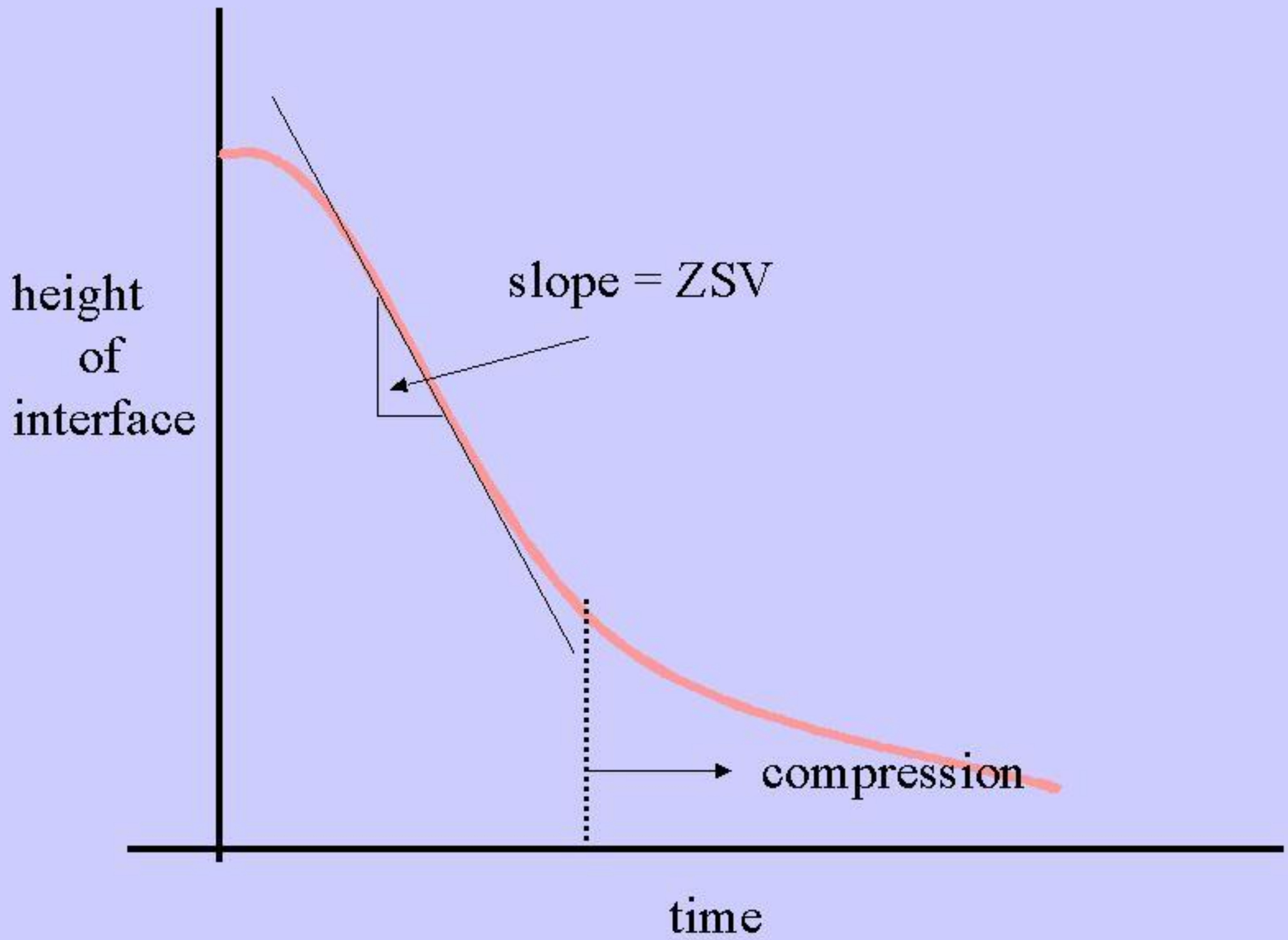
These settling types are demonstrated in a batch settling test as illustrated below:


B
A
A
C
D
B
t = 0
t = 1
t = 2
A =zone settling
B = clarified zone
C = transition zone
D = compression zone



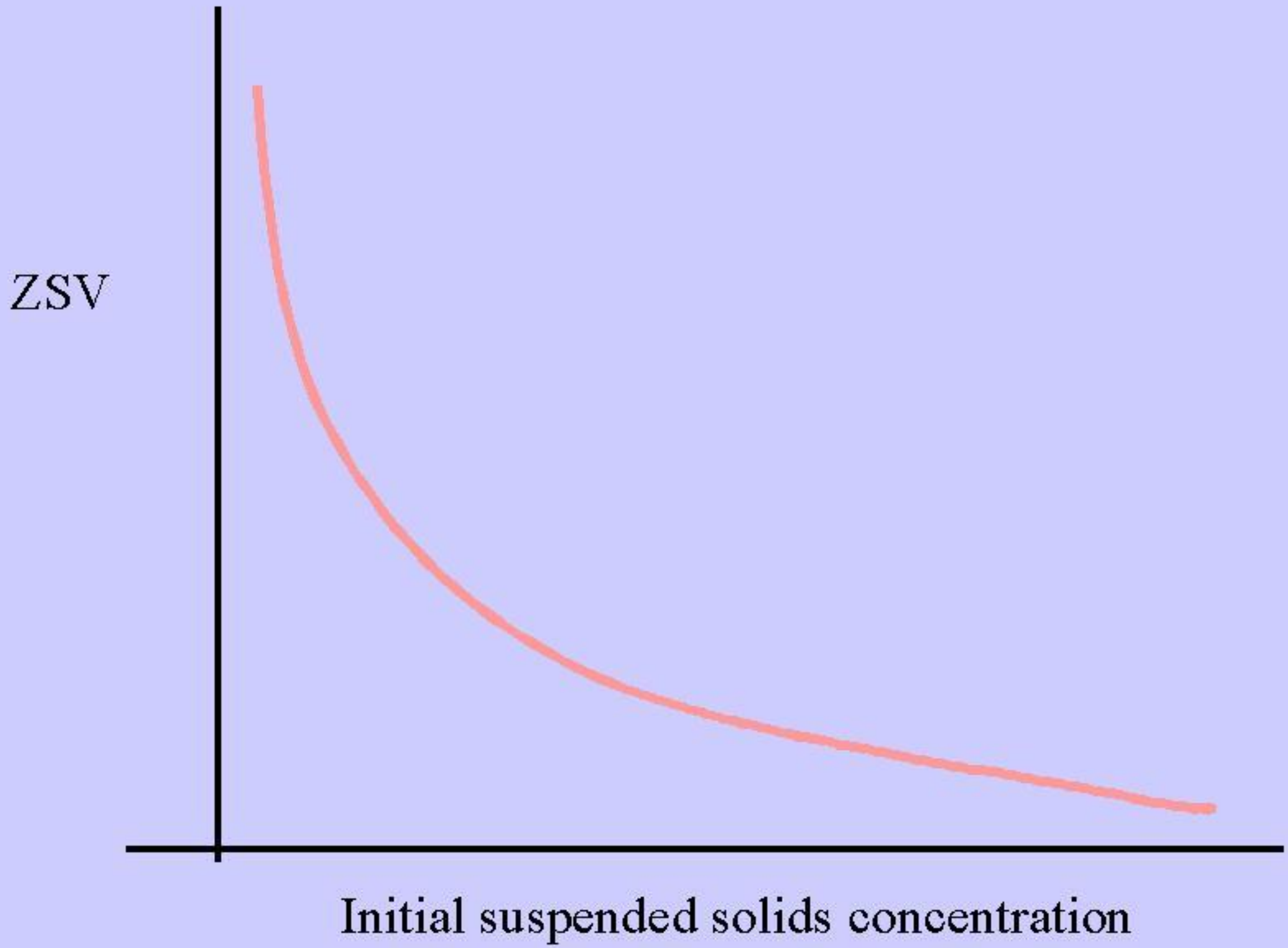


The height of the interface (between the clarified zone and the zone settling zone) versus time is plotted in the figure below to determine the "zone settling velocity" (ZSV). Velocity of this interface is steady after some induction period but changes with time as compression begins. The slope of the steady interface subsidence rate represents zone settling velocity.



height
of
interface
slope = ZSV
compression
time

Initial suspended solids concentration has a significant effect on the ZSV because the higher the suspended solids concentration the more difficult it is to pass water through the pore spaces in the settling matrix. (The only way a matrix can settle is if the water below it is allowed to pass upward through the matrix).   A typical relationship between initial suspended solids and ZSV is shown here.


ZSV
Initial suspended solids concentration

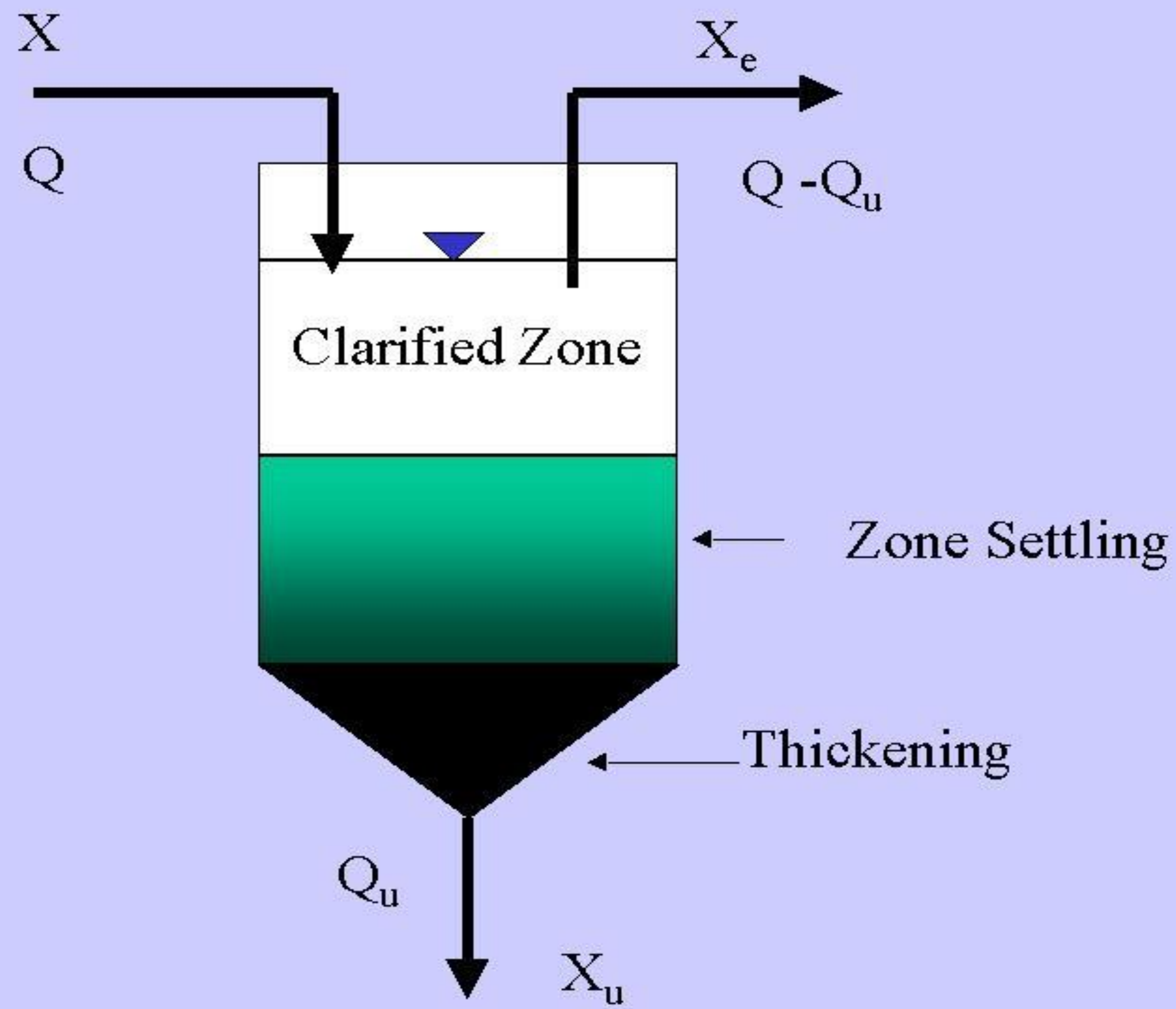
Factors affecting zone settling velocity:

1. Suspended solids concentration
2. Depth of settling column (or tank)
3. Stirring (0.5 – 2 rpm to prevent “arching”)
4. Temperature
5. Polymer addition (affects matrix structure)

Design of Zone Settling Tanks

Two important functions of these sedimentation tanks are : clarification and thickening.

For a continuous flow clarifier, operated at steady-state, mass flow of suspended solids can schematically represented as follows:



X
Q
Xe
Q -Qu
Clarified Zone
Zone Settling
Thickening
Qu
Xu

X = influent suspended solids concentration

X_e = effluent suspended solids concentration (often close to zero)

X_u = underflow (thickened) suspended solids concentration.

Q = influent volumetric flow rate

Q_u = underflow volumetric flow rate

Batch Flux Method

The batch flux method is one way to analyze and select design parameters for the clarifiers/thickeners. Start by considering the mass flux of solids through the clarifier/thickener. There are two components of this flux:

1. Subsidence (sedimentation)
2. Bulk transport (due to sludge withdrawal from bottom of tank)

Total flux of solids through the clarifier is given by:

$$G = v_i X_i + u X_i$$

Where:

G = mass flux (mass of SS transported/area-time)

V_i = zone settling velocity (ZSV) at X_i

u = bulk transport velocity due to sludge withdrawal from bottom of the tank.

$u = Q_u/A_s$

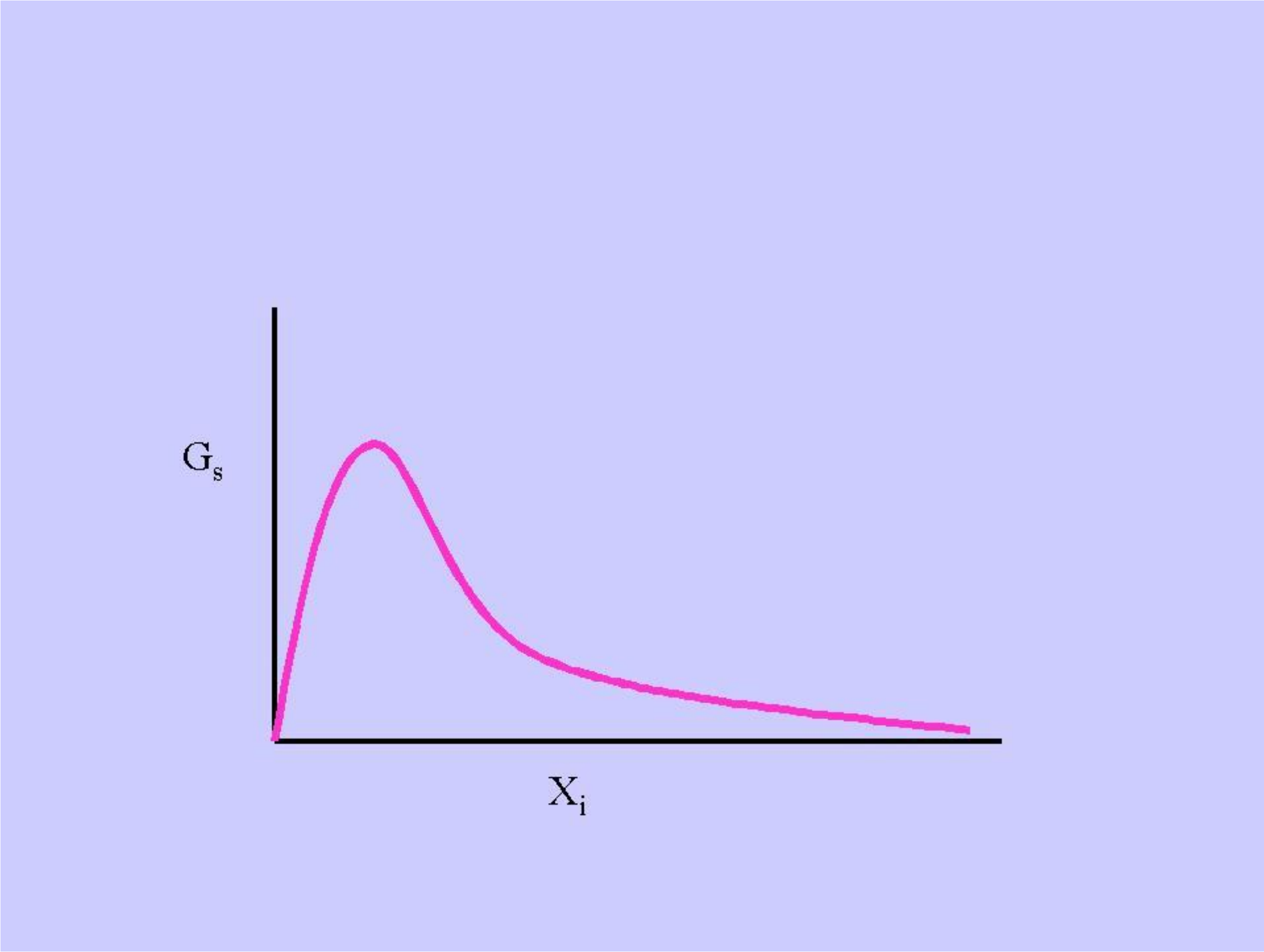
Q_u = underflow rate (withdrawal rate)

A_s = cross-sectional area of clarifier

Zone settling velocity is highly dependent on X_i, so to calculate the flux due to subsidence we need to assume a typical relationship (as shown above) between zone settling velocity and X_i to get:

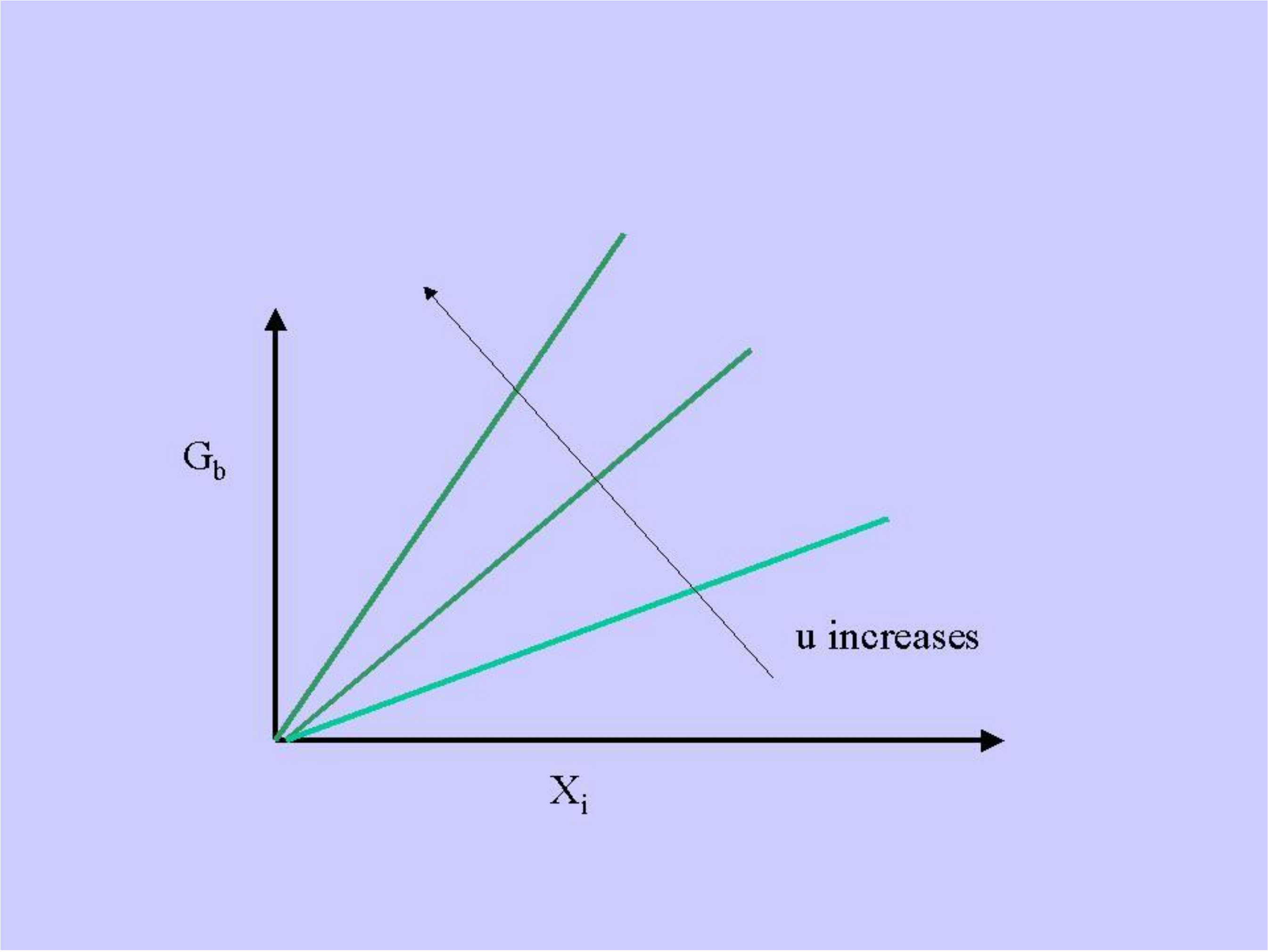
Solid flux due to subsidence (settling) is calculated by:

$$G_s = (v_i)(x_i) \quad \text{(mass/time-area)}$$

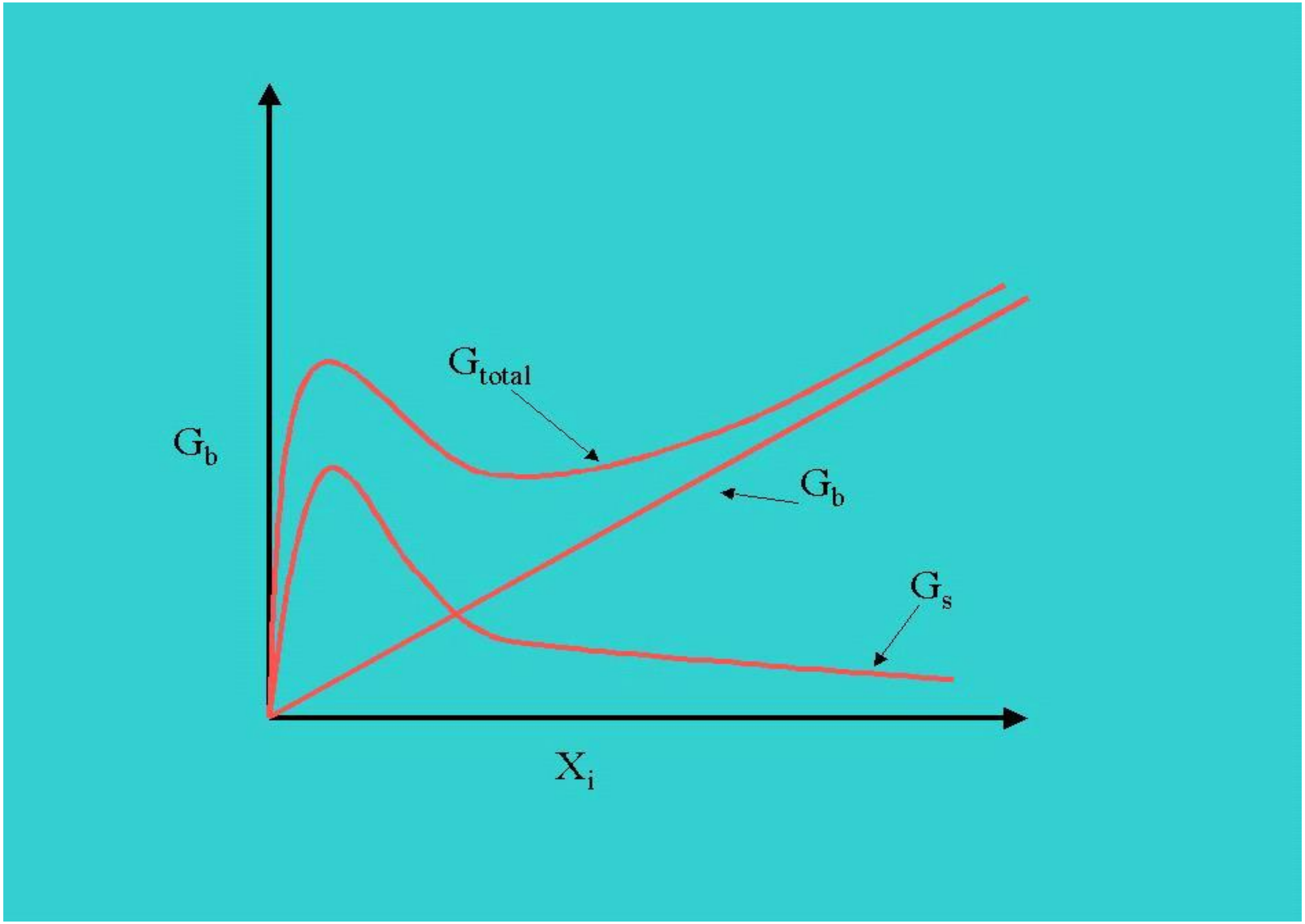


Flux due to bulk transport is given by:

$G_b = (u)(X_i)$



For a particular **u** the combined flux looks like:

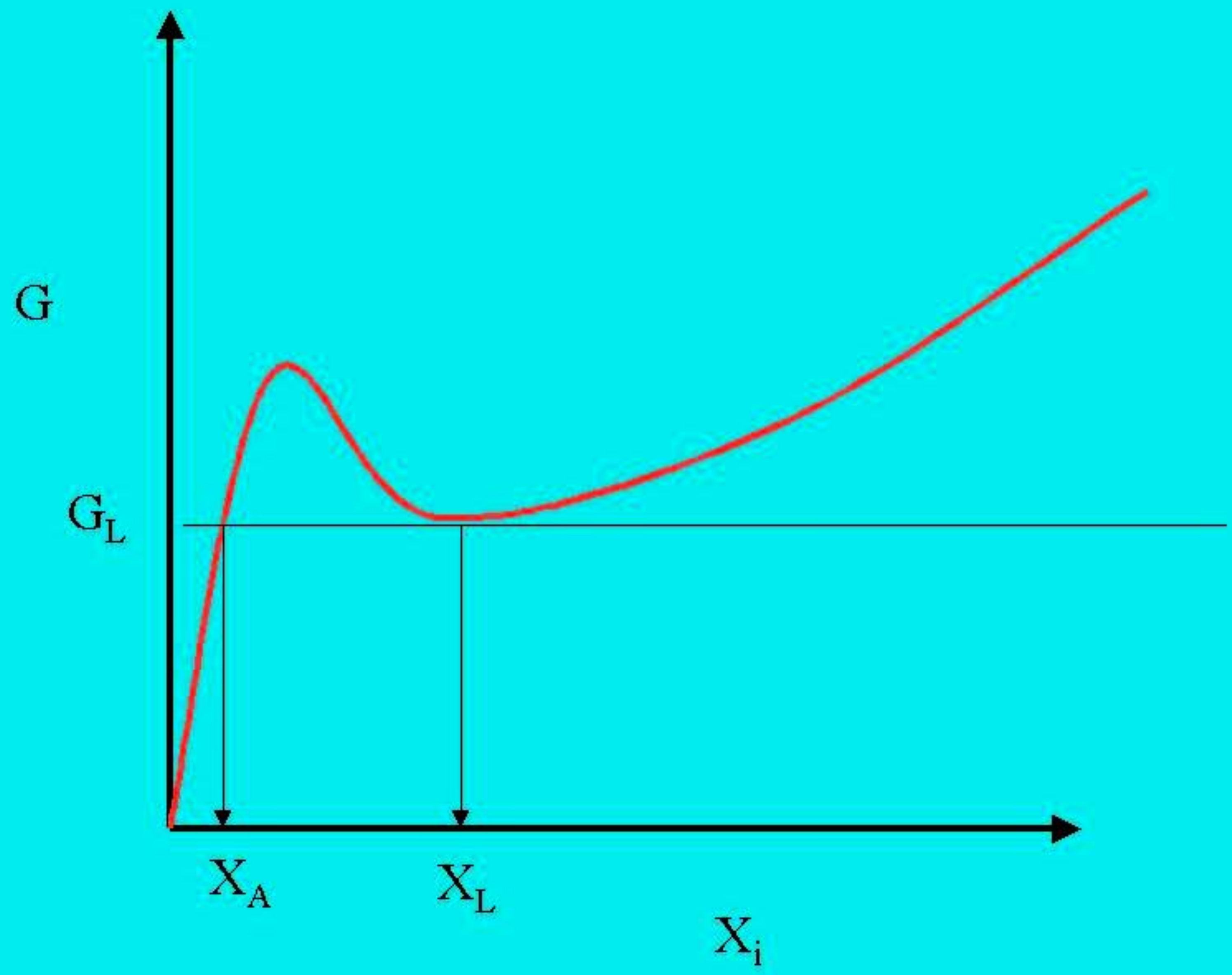


- For a particular underflow rate u there is a minimum in the flux capacity of the clarifier. This minimum occurs at $X_i = X_L$. (Note there is also a minimum G at the origin, but this has no relevance since even after the influent X is diluted X_i never gets this low). Therefore for a given underflow rate there is a "limiting flux" which can be transmitted through the clarifier. As X_i passes from X_f (suspended solids concentration in the influent) to X_u it must pass through this bottleneck $X_i = X_L$. This controls the solids loading rate to the clarifier.

•Essentially for a critically loaded clarifier there exists only two suspended solid concentrations, X_L and X_A if the compression zone is ignored. An explanation of "two concentration" critically loaded clarifier follows. Suspended solids enter the clarifier at some initial concentration X_f. These solids are diluted by clarified effluent. As the solids settle they concentrate and ultimately reach X_L.

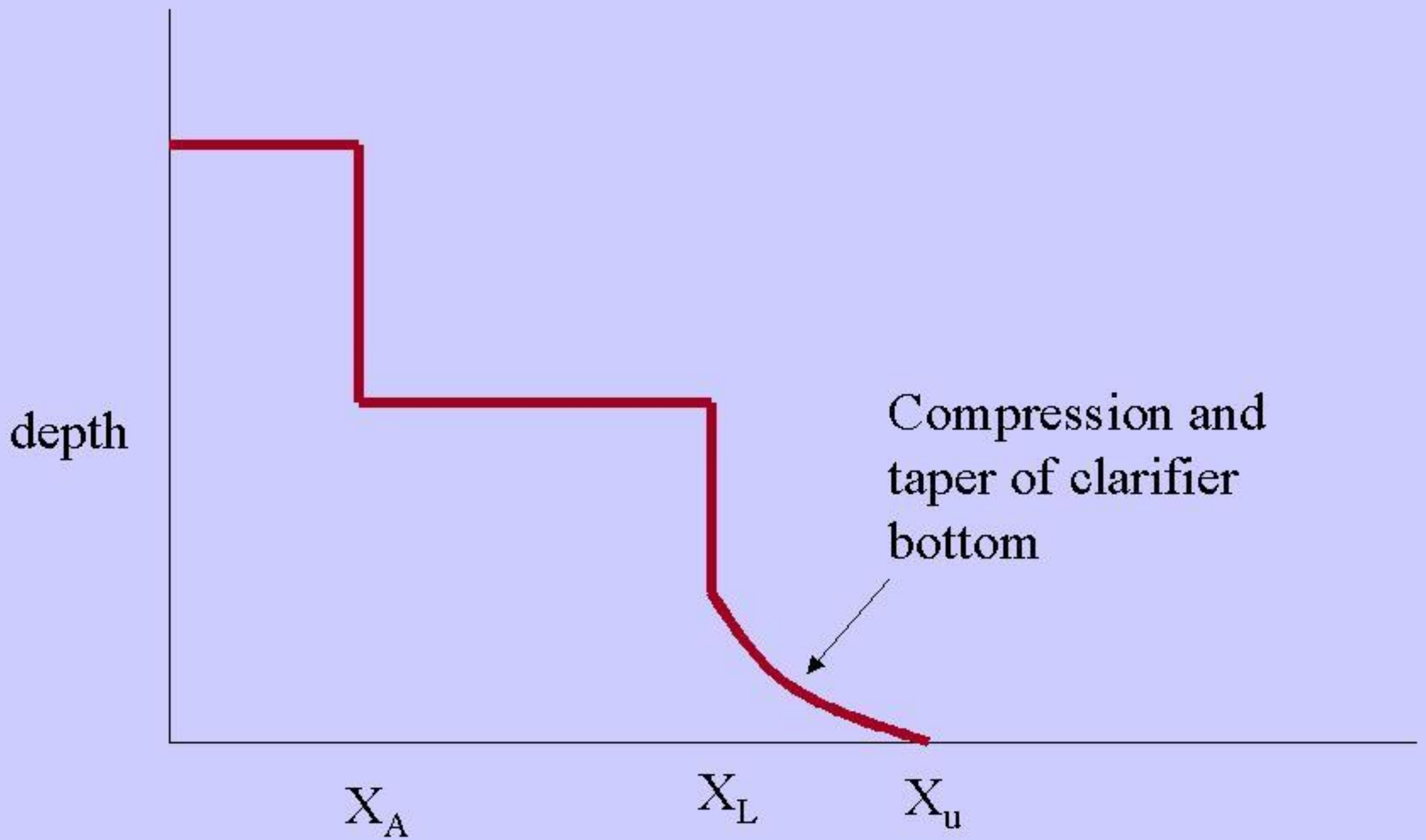
- Suspended solids cannot be transmitted as fast through this layer as in the layers above (because the influent has lower suspended solids concentration and therefore higher zone settling velocity) so there is a build up of suspended solids at X_L.

- At steady state the influent suspended solids have to be diluted to X_A to balance fluxes through the clarifier(at steady-state all the solids fluxes must be equal at all depths). Any other concentrations will cause the layers to disappear, either by washing out over the effluent or by being drawn through the bottom of the clarifier



G
G_L
X_A
X_L
X_i

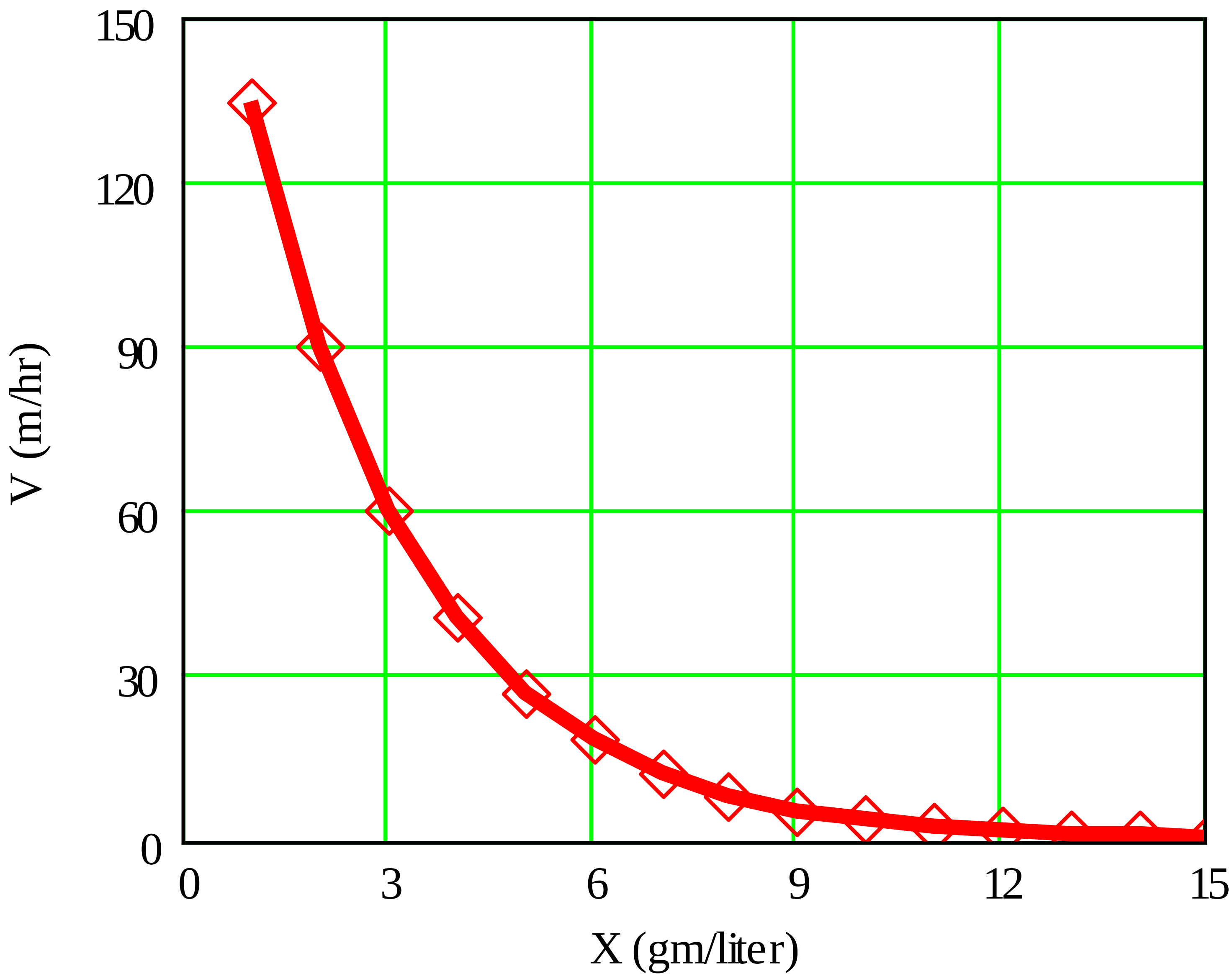
When the clarifier is critically loaded. i.e., when the loading rate equals the flux capacity of the clarifier, the resultant concentration profile in the clarifier is given by :


depth
Compression and taper of clarifier bottom
X_A
X_L
X_u

The batch settling data can be represented by an exponential function.For example the following equation is an exponential curve fit to the settling data shown in the following graph.

$$V = 200\frac{m}{hr}\cdot e^{-0.4\frac{liter}{gm}\cdot X}$$

$$X = gm/liter$$

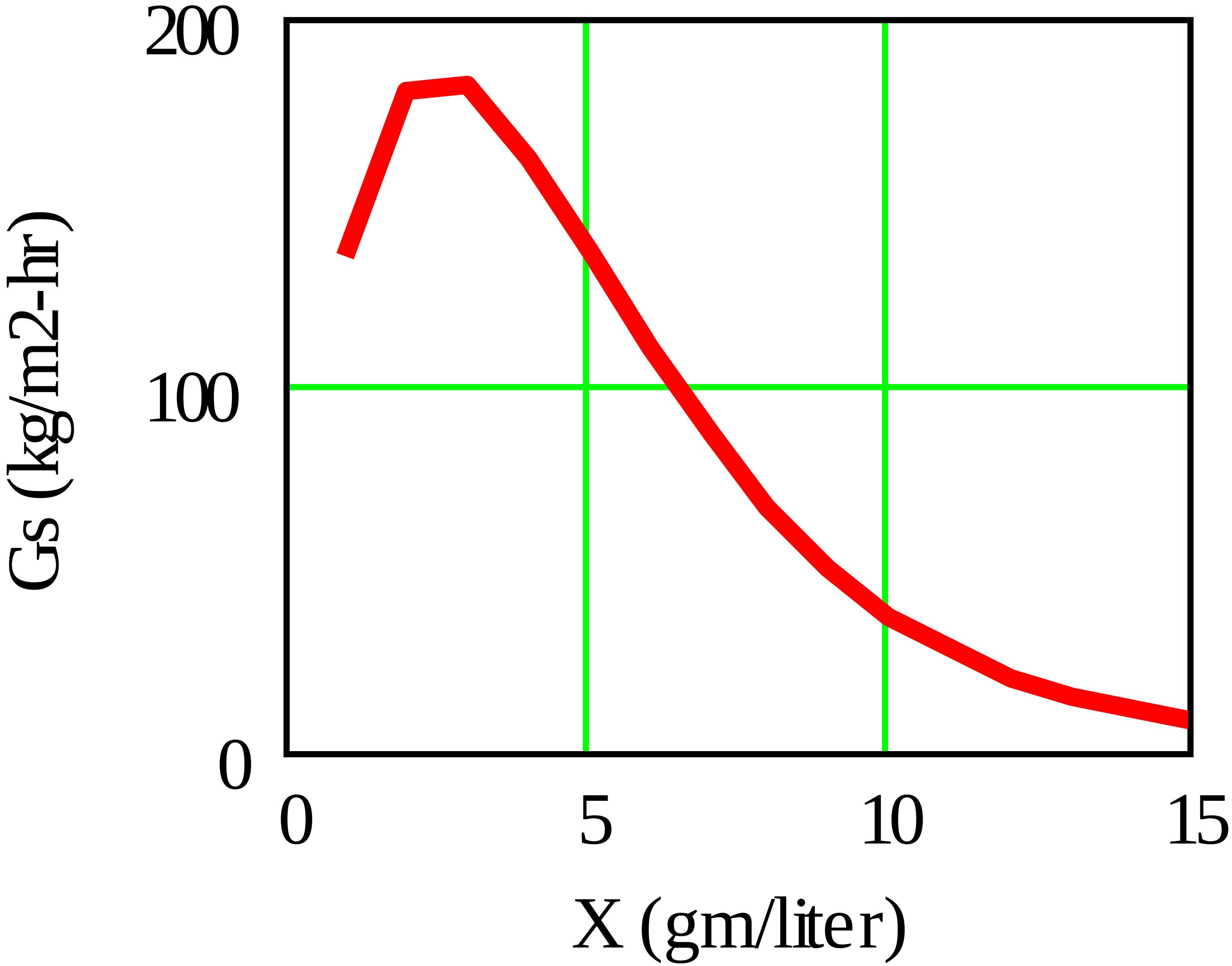

150
120
90
60
30
0
0
3
6
9
12
15
V (m/hr)
X (gm/liter)

Flux due to subsidence can then be calculated:

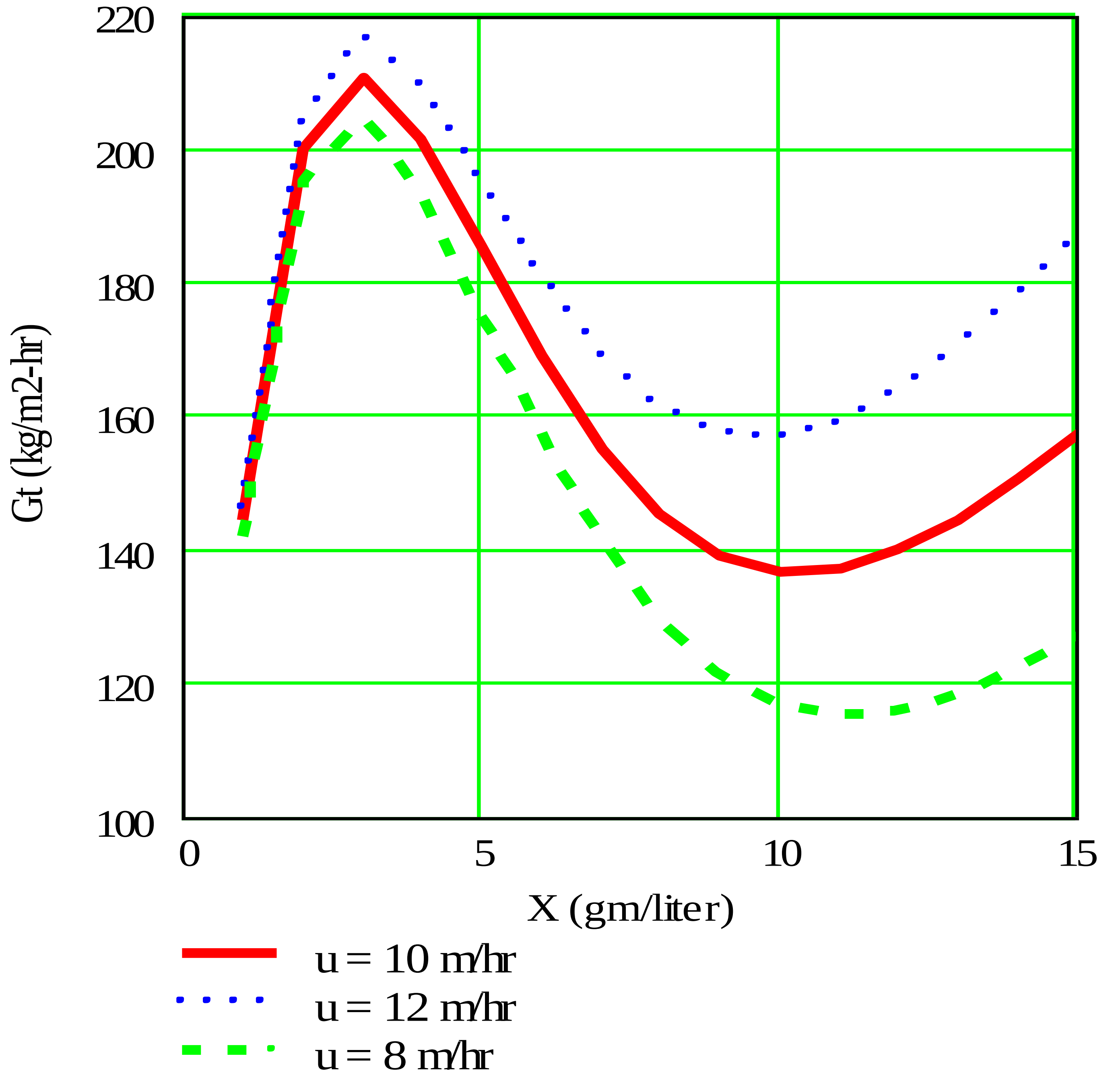
$$G_s = X \cdot 200\frac{m}{hr} \cdot e^{-0.4\frac{liter}{gm} \cdot X}$$

Be sure to make units consistent.

Typical units = kg/m^2-hr


200
100
0
0
5
10
15
Gs (kg/m2-hr)
X (gm/liter)

$$G_{total} = X \cdot 200\frac{m}{hr} \cdot e^{-0.4\frac{liter}{gm}\square X} + u \cdot X$$



220
200
180
160
140
120
100
0
5
10
15
Gt (kg/m2-hr)
X (gm/liter)
u = 10 m/hr
u = 12 m/hr
u = 8 m/hr

The limiting flux in for each underflow rate, u, is found by locating the minimum in the total flux curve. Note that minimum of interest occurs to the right of the curve peak for reasons discussed earlier. This minimum can be found graphically or by differentiating the flux curve with respect to X and setting the resulting equation equal to zero and then solve for X_{L}.

$$\frac{\partial G_{total}}{\partial X} = 200 \cdot e^{-0.4 \cdot X} - 200 \cdot X \cdot 0.4 \cdot e^{-0.4 \cdot X} + u$$

When $\frac{\partial G_{total}}{\partial X} = 0, \quad X = X_L$

For this particular problem:

u (m/hr)	X_L (mg/liter)
8	11,020
10	10,338
12	9,655

This means that if we choose to operate a clarifier with an underflow rate of 8 m/hr (Q_u/A_s) then the flux limiting concentration will be at 11,020 mg/L. In other words the subsidence flux will be:

$$G_s = (11.02\frac{gm}{L}) \cdot 200\frac{m}{hr} \cdot e^{-0.4\frac{liter}{gm} \square (11.02\frac{gm}{L})}$$

$$= 7.5 \cdot 10^{-3} \frac{kg}{m^2 \cdot sec}$$

And the bulk transport flux will be:

$$G_b = u \cdot X_L = 8 \frac{m}{hr} \cdot 11,020 \frac{mg}{L}$$

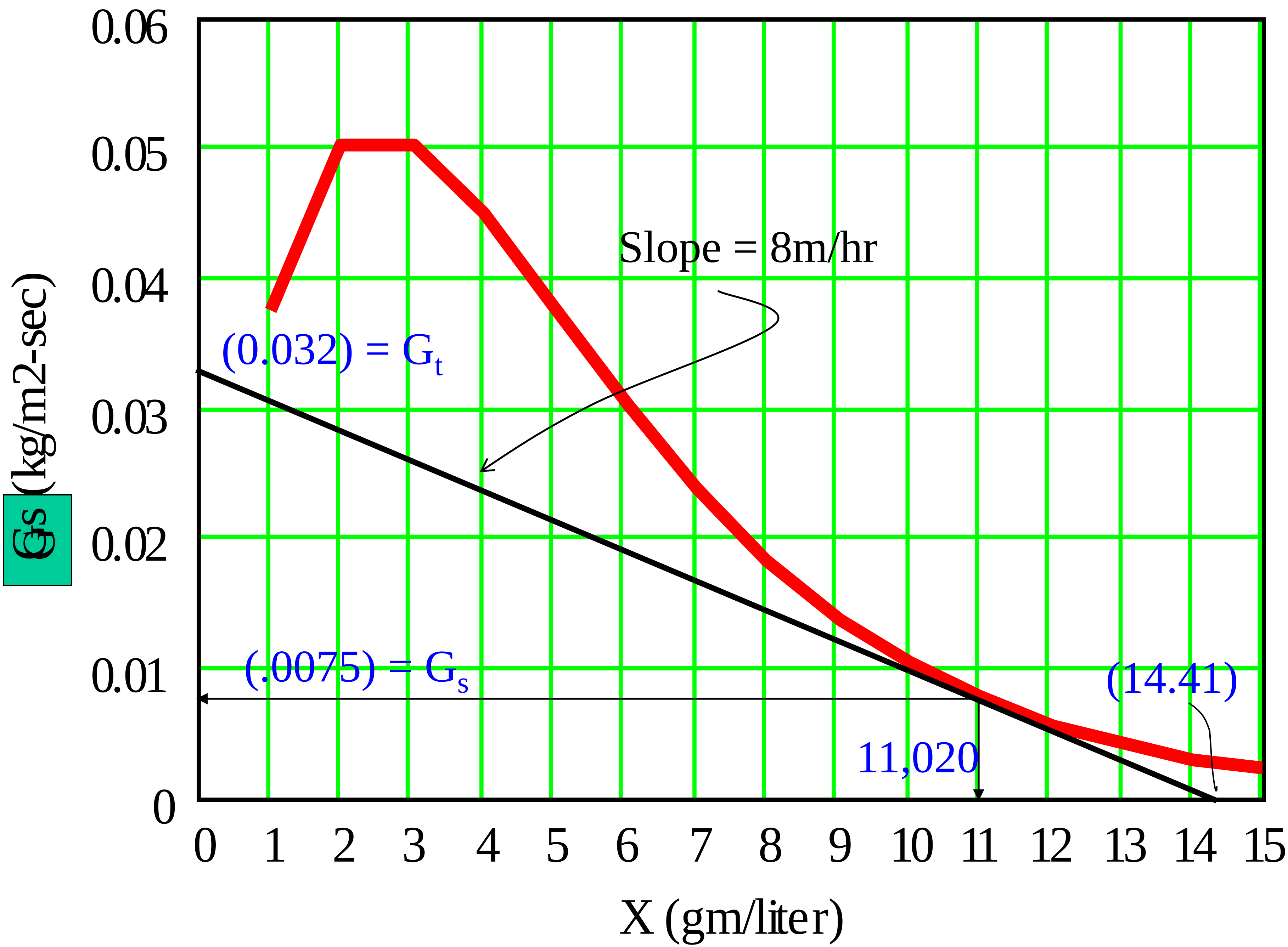
$$= 0.024 \frac{kg}{m^2 \cdot sec}$$

The total capacity of the clarifier to transmit solids under these conditions is:

$$G_t = G_s + G_b$$

$$= 0.0075 + 0.024 = 0.032 \frac{\text{kg}}{\text{m}^2 \cdot \text{sec}}$$

This same information can be obtained graphically. In fact once the subsidence flux curve is drawn a straight line at slope u drawn tangent to the subsidence curve will give all the required information. One important point is that the tangent line must remain below the subsidence curve otherwise the flux limiting capacity will be exceeded and the clarifier will fail.

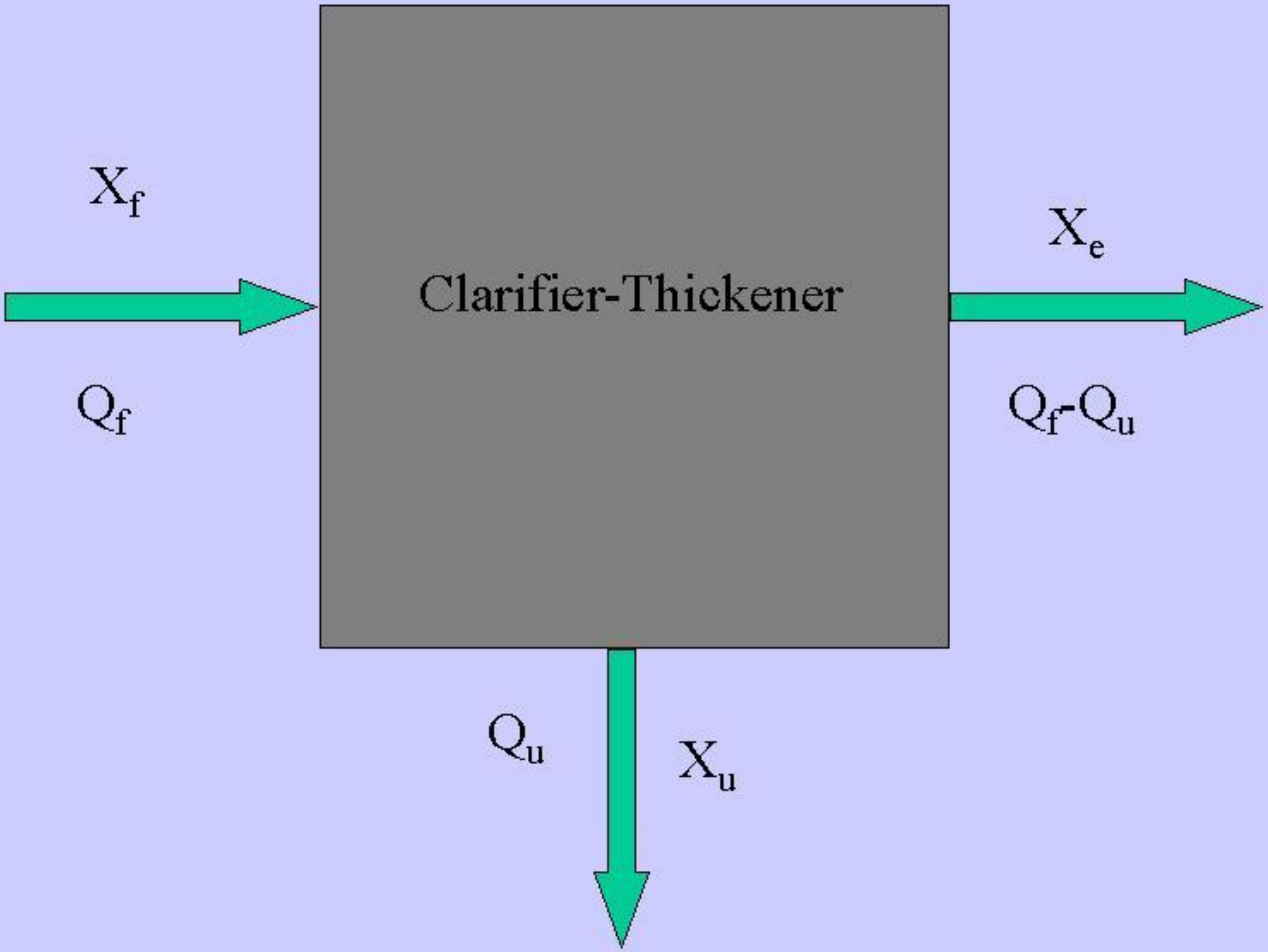


Gs (kg/m2-sec)
0.06
0.05
0.04
0.03
0.02
0.01
0
Slope = 8m/hr
(0.032) = G_t
(.0075) = G_s
(14.41)
11,020
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
X (gm/liter)

How is this information used to design a clarifier?

The major design parameters for a clarifier-thickener are the cross-sectional area, A_s, and the volumetric underflow rate Q_u. These parameters must be selected so that the solids loading capacity of the clarifier-thickener is not exceeded and the solids concentration of the underflow is adequate. These parameters can be selected by the following procedure.

Consider mass flow through a clarifier:



Perform a solids mass balance around the clarifier:

$$Q_u \cdot X_u = Q_f \cdot X_f - X_e (Q_f - Q_u)$$

Typically X_e is approximately zero so the last term can be ignored.

The clarifier cross-sectional area and underflow rate must be selected to satisfy mass balances and flux capacity limitations.

Start with:

$$X_f \cdot Q_f = L_f = X_u \cdot Q_u$$

$$Q_u = u \cdot A_s$$

$$L_f = X_u \cdot A_s \cdot u$$

$$G_{total} \cdot A_s = X_u \cdot A_s \cdot u$$

Consider the previous case.

Assume: $Q_f = 10^3 \ m^3/day$ and $X_f = 6500 \ mg/L$

We selected an underflow rate = 8 m/hr. This yielded an $X_u = 14,410 \ mg/L$.

Then $Q_u = L_f/X_u = 18.8 \ m^3/hr$. This determines

$A_s = Q_u/u = 2.355 \ m^2$

The way in which the problem was set up the clarifier is critically loaded. However, clarifiers do not need to be loaded critically to function.

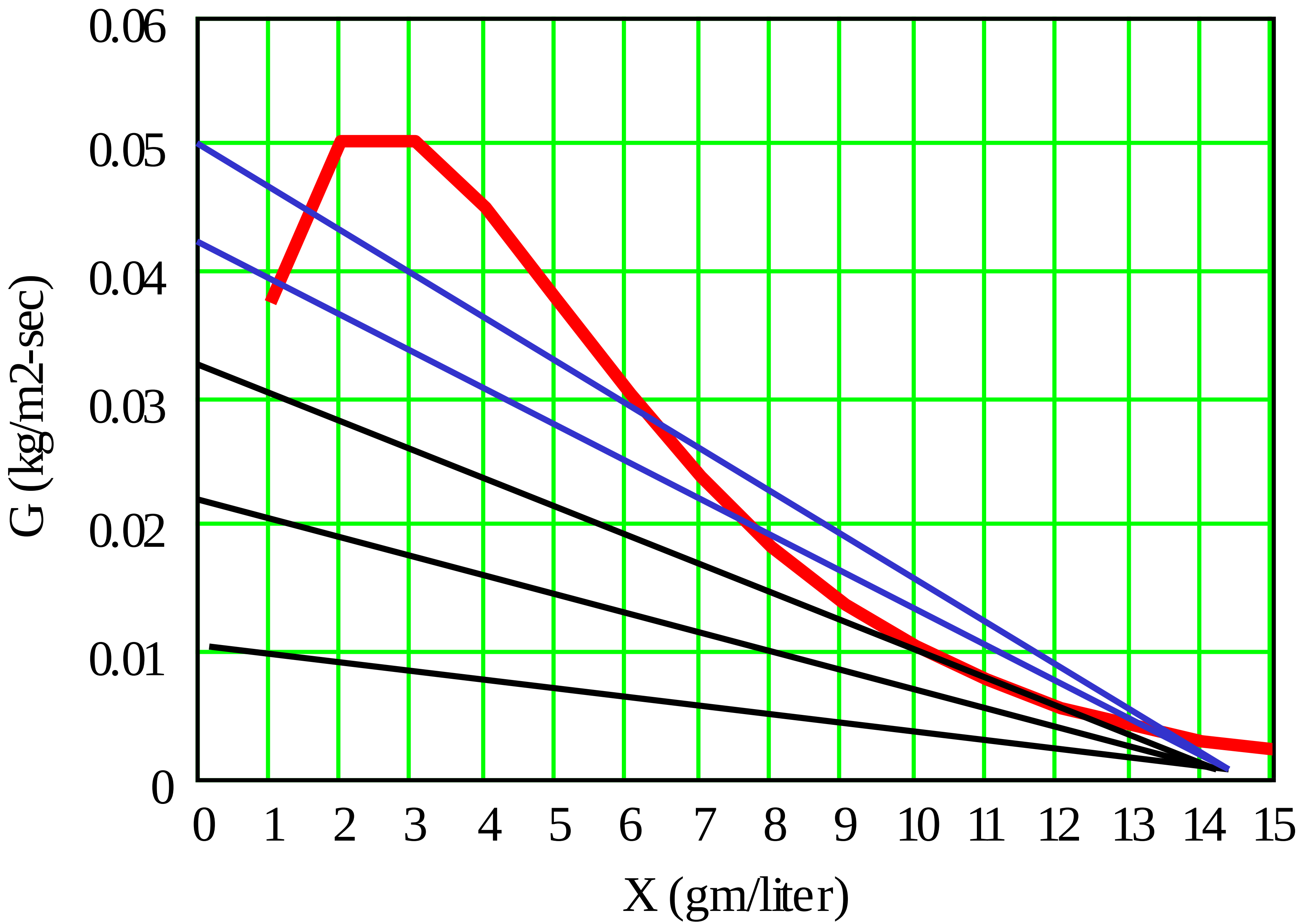
For example, the cross sectional area can be doubled to yield an underflow velocity of 4 m/hr. A mass balance dictates:

$$G_{total} \cdot \cancel{A}_s = X_u \cdot \cancel{A}_s \cdot u$$

If X_u is held constant u will be half of the previous value so G_{total} will be halved.

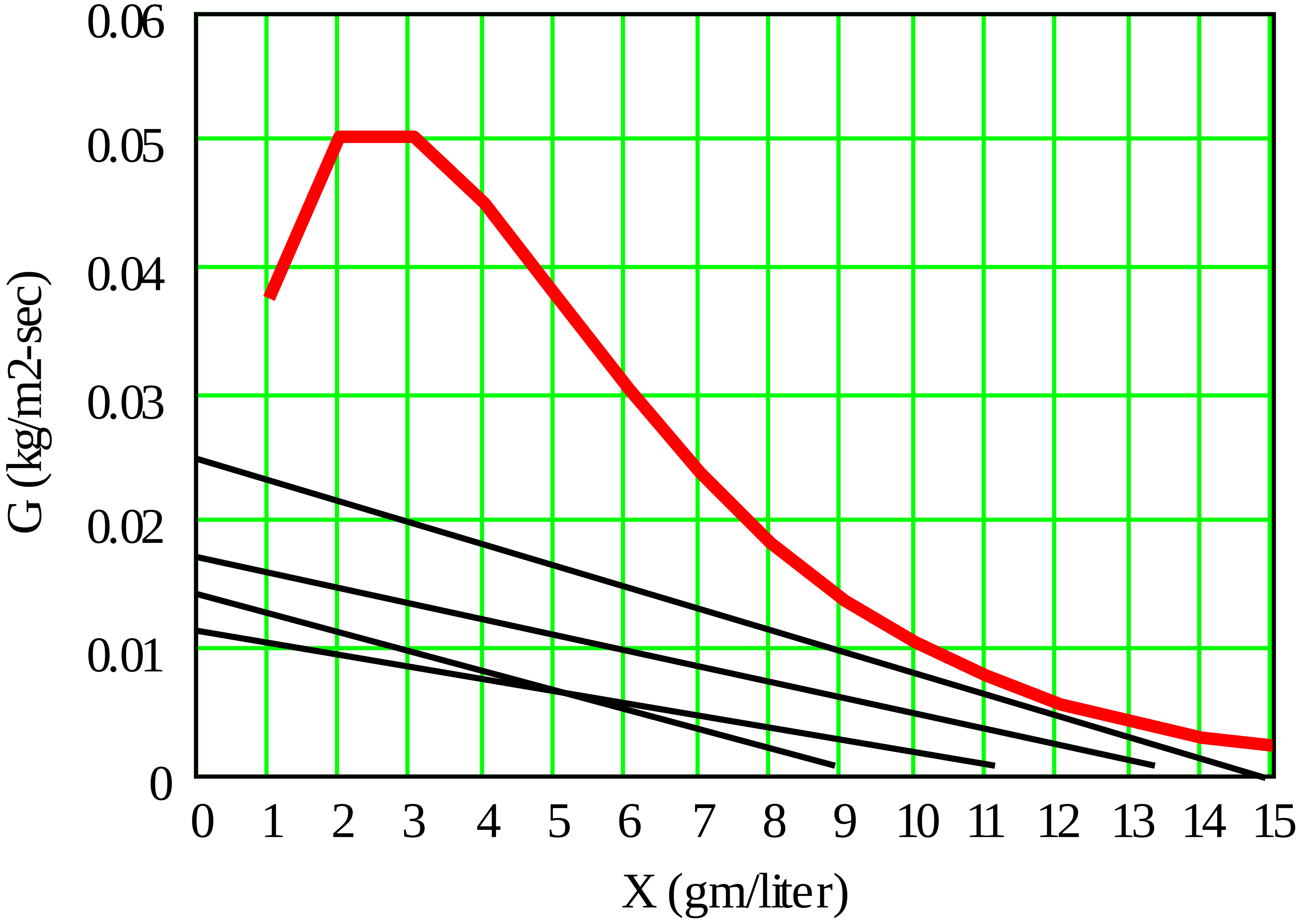
Assuming L_f ($Q_f * X_f$) is constant then lowering G_{total} by ½ is exactly compensated by doubling A_s. This analysis can be extended to any combination of changes in X_u, u, Q_u, etc. as long as the mass balance is met and as long as the line connecting G_{total} and X_u remains below the subsidence flux curve.

In the following graph black lines are acceptable operating conditions whereas blue lines are unacceptable conditions.



0.06
0.05
0.04
0.03
0.02
0.01
0
G (kg/m2-sec)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
X (gm/liter)

There are an infinite number of “non-critically loaded” conditions a few of which are shown in the following graph. All variations in X_u or u or G_{total} are allowed as long as mass balances are satisfied.



0.06
0.05
0.04
0.03
0.02
0.01
0
G (kg/m2-sec)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
X (gm/liter)

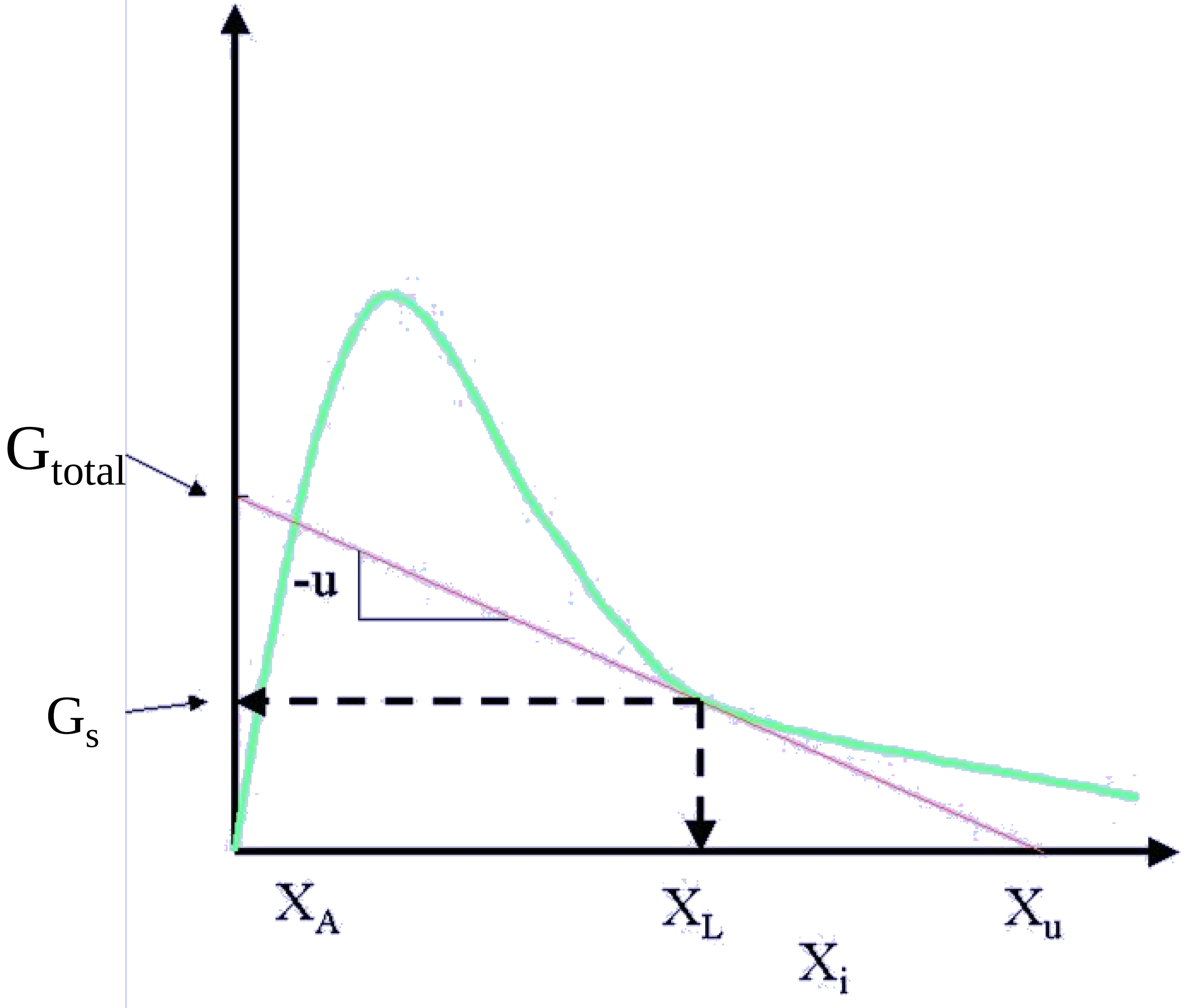
Critically loaded design can be accomplished graphically using the “Batch Flux: technique.

- Construct a batch flux curve for subsidence alone.

$(G_S = v_i X_i)$.

- Select an X_u . Draw a line tangent to the subsidence batch curve which originates at $G = 0$, $X = X_u$. Extend this line to the ordinate. The ordinate intercept is G_{total}. The G value at the point of tangency is G_s.

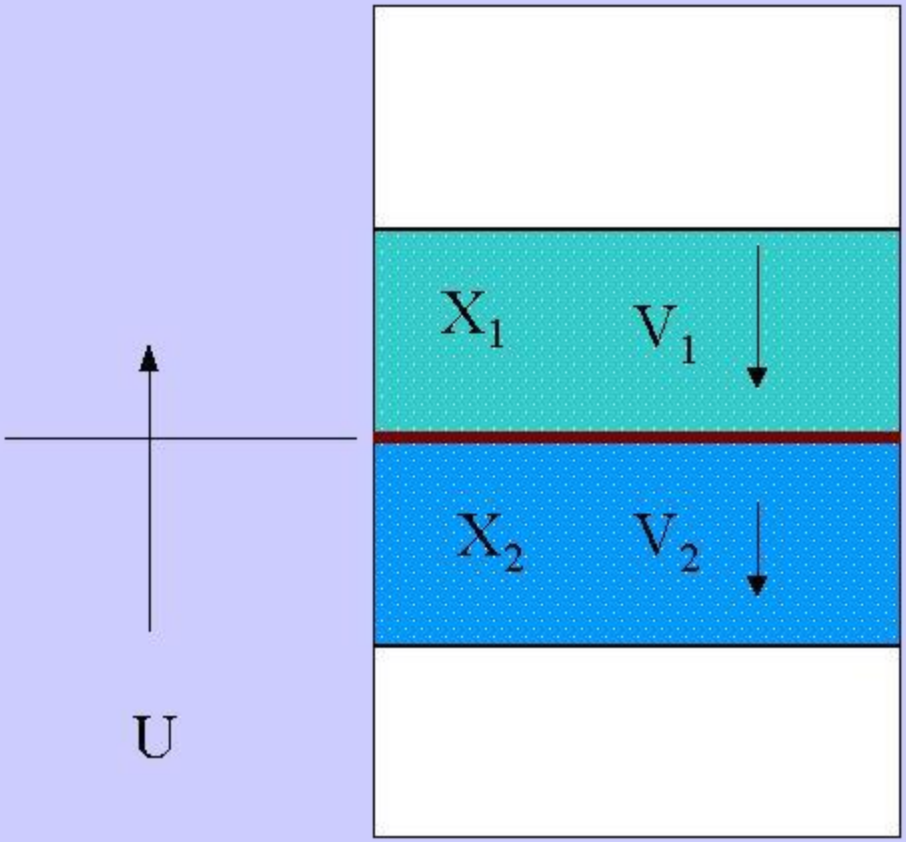
- The slope of the tangent line is the negative of the underflow rate u.



G_total
-u
G_s
X_A
X_L
X_u
X_i

Justification for this procedure can be shown from geometry or the Kynch analysis.

First use the Kynch analysis. Consider two layers (at different concentrations and, therefore, different settling rates) of zone settling solids. These layers are shown schematically here.



X1
V1
X2
V2
U

$X_1 < X_2$ and, therefore, $V_1 > V_2$

The interface between the layers will move upward with a velocity of U. A mass balance about the interface gives:

$X_1V_1 + X_1U = X_2V_2 + X_2U$ (assuming no accumulation in the interface, *i.e.*, *in* = *out*).

Let $G_1 = V_1X_1$ and $G_2 = V_2X_2$

Then:

$$G_1 + V_1X_1 = G_2 + V_2X_2$$

$$G_2 - G_1 = \Delta G = -U(X_2 - X_1) = -U(\Delta X)$$

or

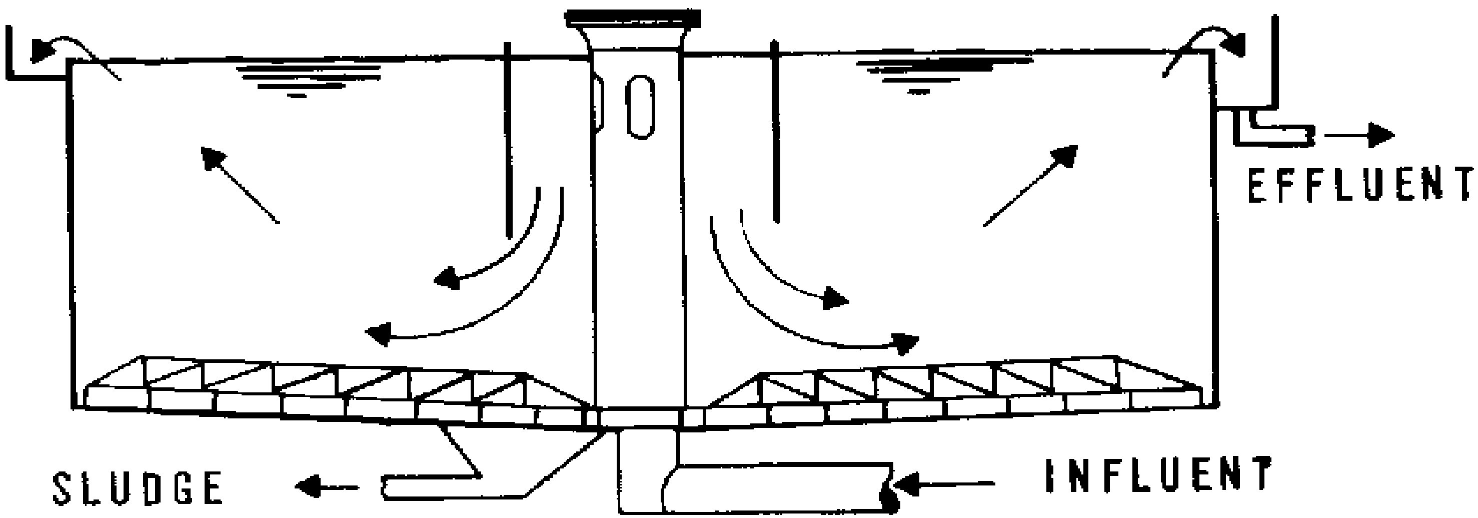
$$-U = \frac{\Delta G}{\Delta X} = \frac{\partial G}{\partial X} \quad \text{(for a thin layer)}$$

If the system is critically loaded (the downward bulk transport is equal to the upward U (propagation of solids upward) so that the solids flux is maintained at steady-state in a downward mode (u = U). Or viewed another way the slope of the subsidence curve at any point gives the underflow rate (u) necessary to maintain a critically loaded system at a selected X_u .

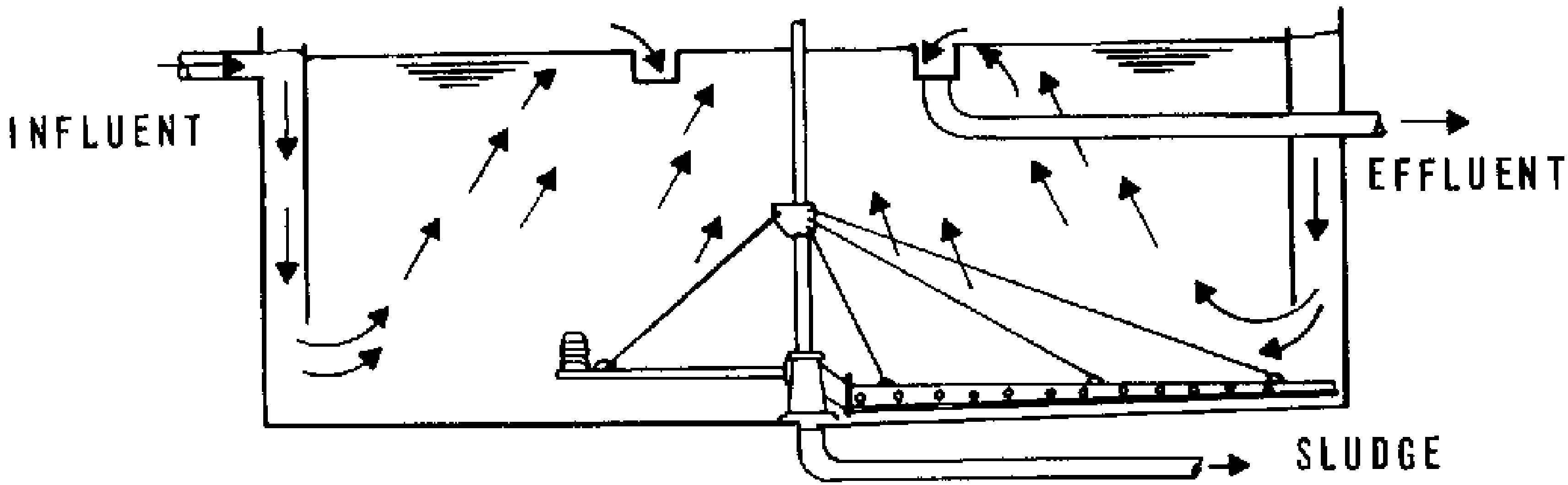
Recall that G_L ($G_t = G_L$) = the limit of solids loading which can be transmitted per unit area at a given underflow rate and sludge settleability.

Then:

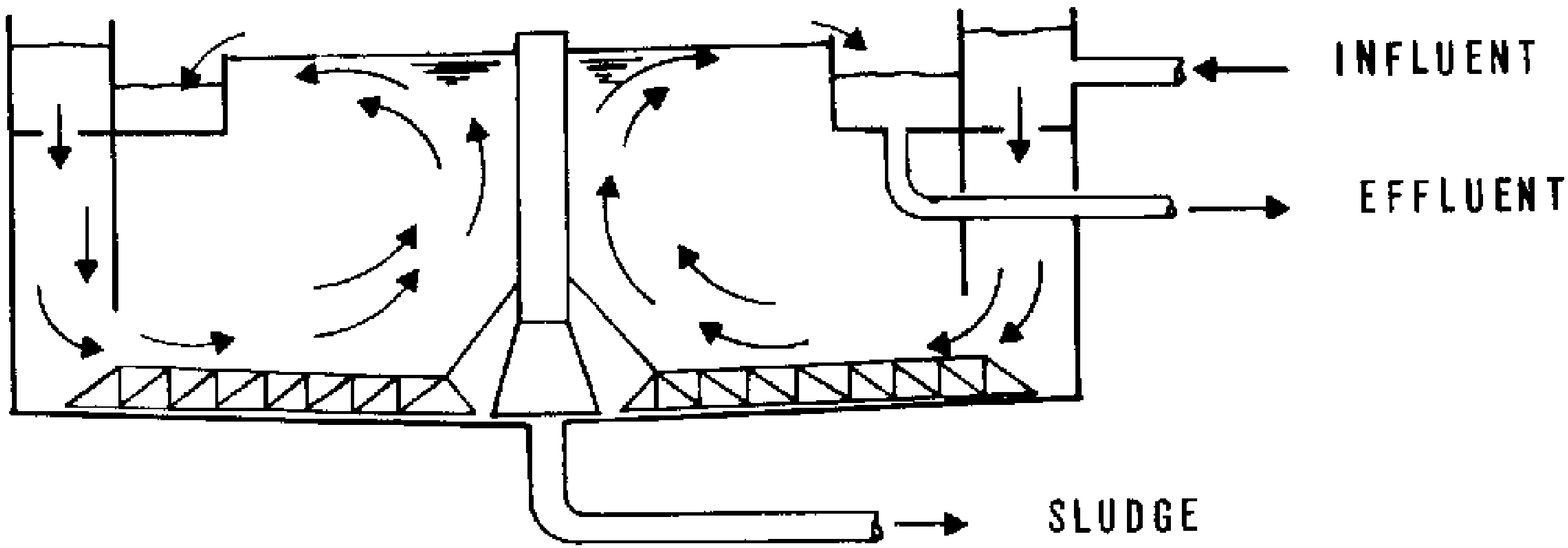
$$G_{total} = \frac{Q_u \cdot X_u}{A_s} = \frac{Q_f \cdot X_f - X_e(Q_f - Q_u)}{A_s}$$



(a) CIRCULAR CENTER-FEED CLARIFIER WITH A SCRAPER SLUDGE REMOVAL SYSTEM



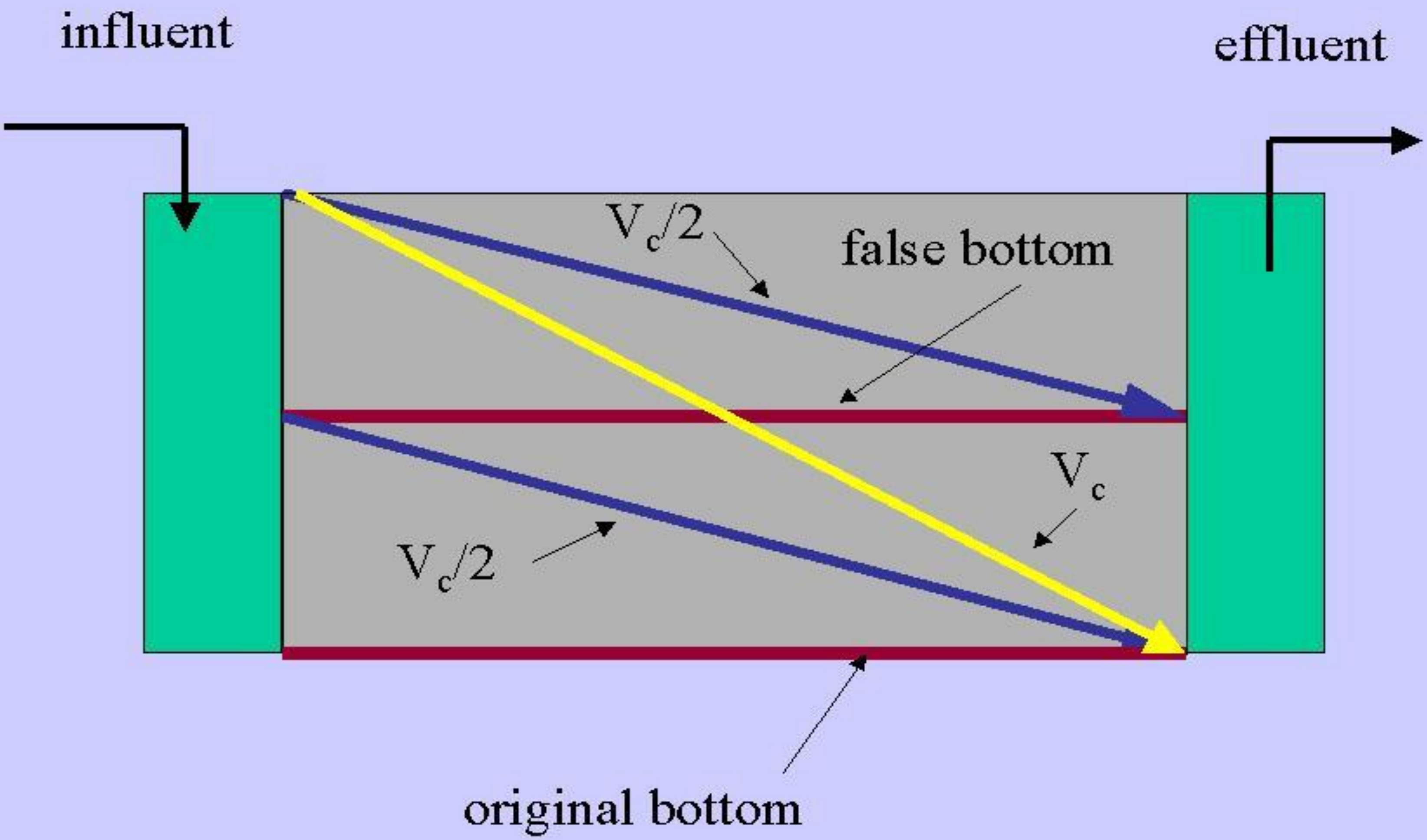
(b) CIRCULAR RIM-FEED, CENTER TAKE-OFF CLARIFIER WITH A HYDRAULIC SUCTION SLUDGE REMOVAL SYSTEM



(c) CIRCULAR RIM-FEED, RIM TAKE-OFF CLARIFIER

Tube Settlers:

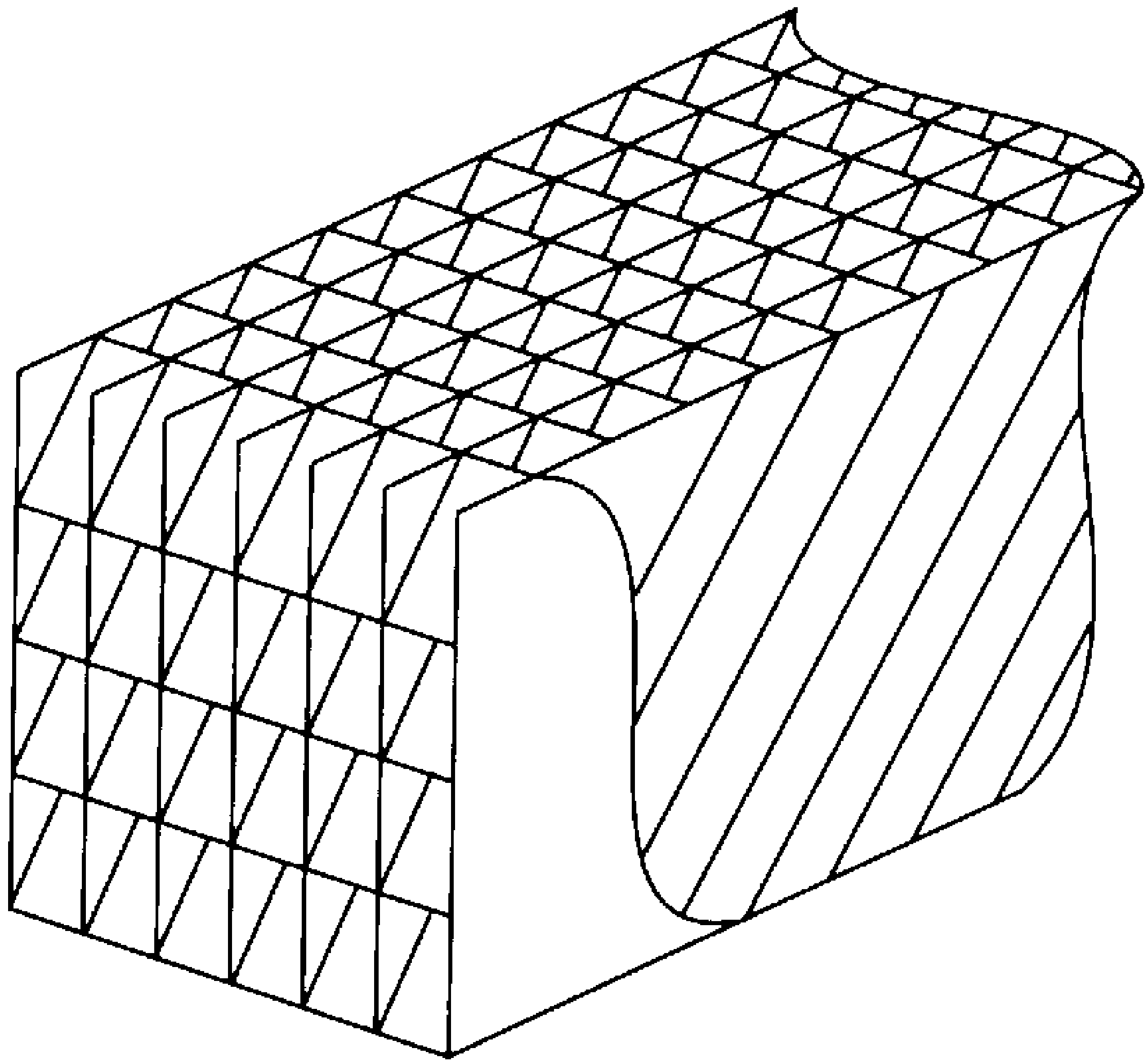
One method to increase the efficiency or increase the capacity of clarifiers is to install "false bottoms" in the clarifiers. For example in a rectangular clarifier such a "false bottom" would look like:

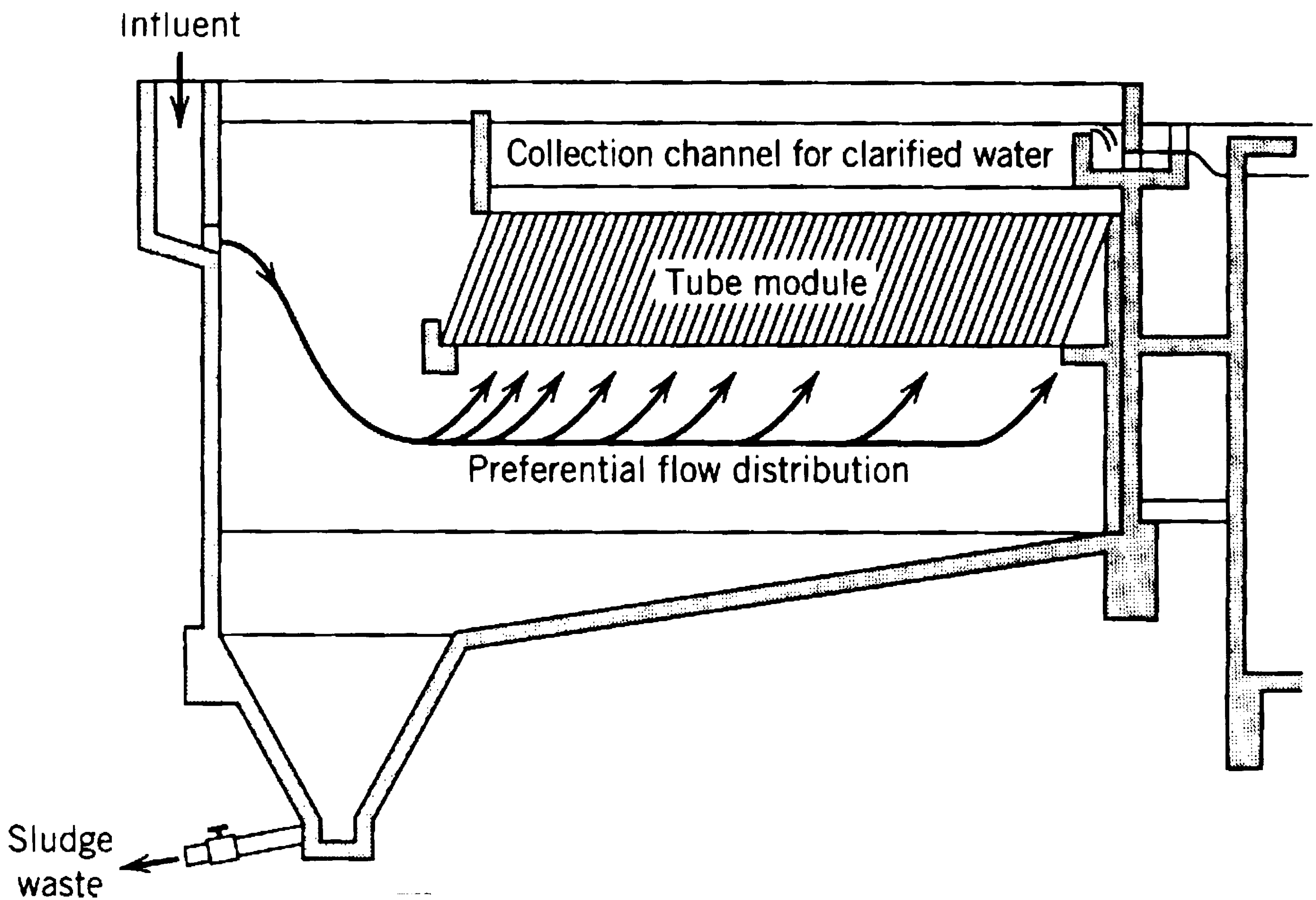

influent
effluent
V_c/2
false bottom
V_c
V_c/2
original bottom

Using Type I settling analysis, the effect of providing a single false bottom (of equal area of the original bottom) is to effectively reduce the critical velocity, V_c, by half if the false bottom is located at mid-depth.

It will be assumed that particle settling velocity is vertical (in direction perpendicular to the original bottom of the clarifier) therefore the distance a particle need to fall to be removed is increased by $1/\cos\theta$. Where θ is angle of incline.

If the false bottoms are replaced by a series of inclined tubes turbulence is minimized (particularly lateral turbulence) and the physical integrity of the false bottoms is increased compared to long flat sheets. Hence the term "tube settlers". Tube settlers are often used in retrofit situations.




Influent
Collection channel for clarified water
Tube module
Preferential flow distribution
Sludge waste