

Chapter 5

Sludge treatment

5.1 Sludge definition:

Sludge is made of solid materials separated from the water line during wastewater treatment. In addition to solids, sludge contains a high percent of water.

5.2 Sludge sources:

In wastewater treatment sludge is classified into the following types:

A. Grit sludge:

It is all the solids collected in the grit removal chamber, because grit can be easily drained and is relatively stable in terms of biological activity, it dose not need treatment and is generally disposed directly to landfills.

B. Primary or raw sludge:

Primary sludge is the sludge taken from the bottom of the primary settling tanks. It contains from 3-8% solids ($1\% \cong 10,000 \frac{mg}{L}$). This sludge is composed of settleable raw solids. Almost 7% of the primary sludge is organic.

C. Secondary Sludge:

This sludge consists of microorganisms and inert materials that has been wasted from the secondary treatment processes. Thus 9% of this sludge is organic this sludge contains from 0.8 to 2% solids (*i.e.* $8,000 - 20,000 \frac{mg}{L}$).

5.3 Sludge quantities:

A. Primary sludge:

The quantity of primary sludge is calculated using the following equation:

$$M_p = E \bullet ss \bullet Q_{in} \dots\dots\dots (5.1)$$

Where,

$$M_p = \text{mass of primary sludge}, \frac{kg}{d}$$

$$ss = \text{suspended solids in the influent}, \frac{kg}{m^3}$$

E = efficiency of primary sedimentation tank → taken from (Figure (1))

$$Q_{in} = \text{influent flow to primary sedimentation tank}, \frac{m^3}{d}.$$

To convert the sludge quantity from $\frac{kg}{d}$ to $\frac{m^3}{d}$:

$$Q_p = \frac{M_p}{X_p} \dots\dots\dots (5.2)$$

Q_p = flow rate of primary sludge, $\frac{m^3}{d}$.

X_p = concentration of solids in primary sludge, $\frac{kg}{m^3}$.

$$X_p = \rho_{sludge} \bullet S \dots\dots\dots (5.3)$$

where,

ρ_{sludge} = sludge density, $\frac{kg}{m^3}$ (usually taken as $\rho_{water} = 1000 \frac{kg}{m^3}$ unless given

S = solids fraction in sludge expressed as decimal fraction (i.e. 0.05 = 5%).

Example 5.1:-

Determine the quantity of primary sludge both in $\frac{kg}{d}$ and m^3/d , given the

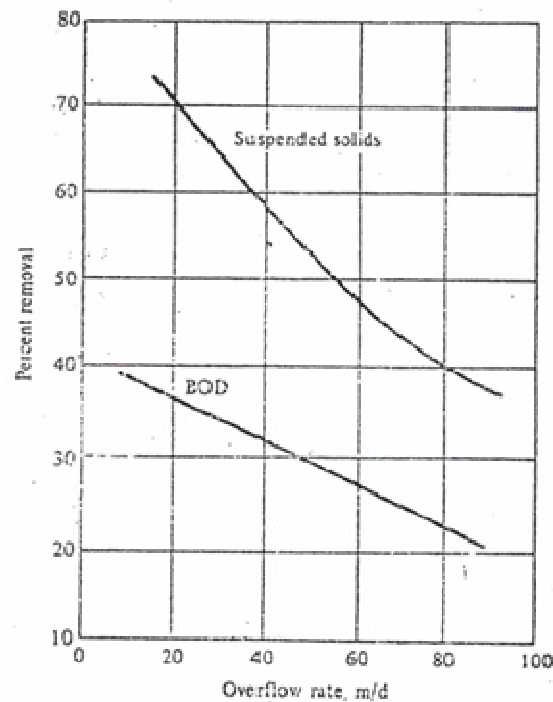
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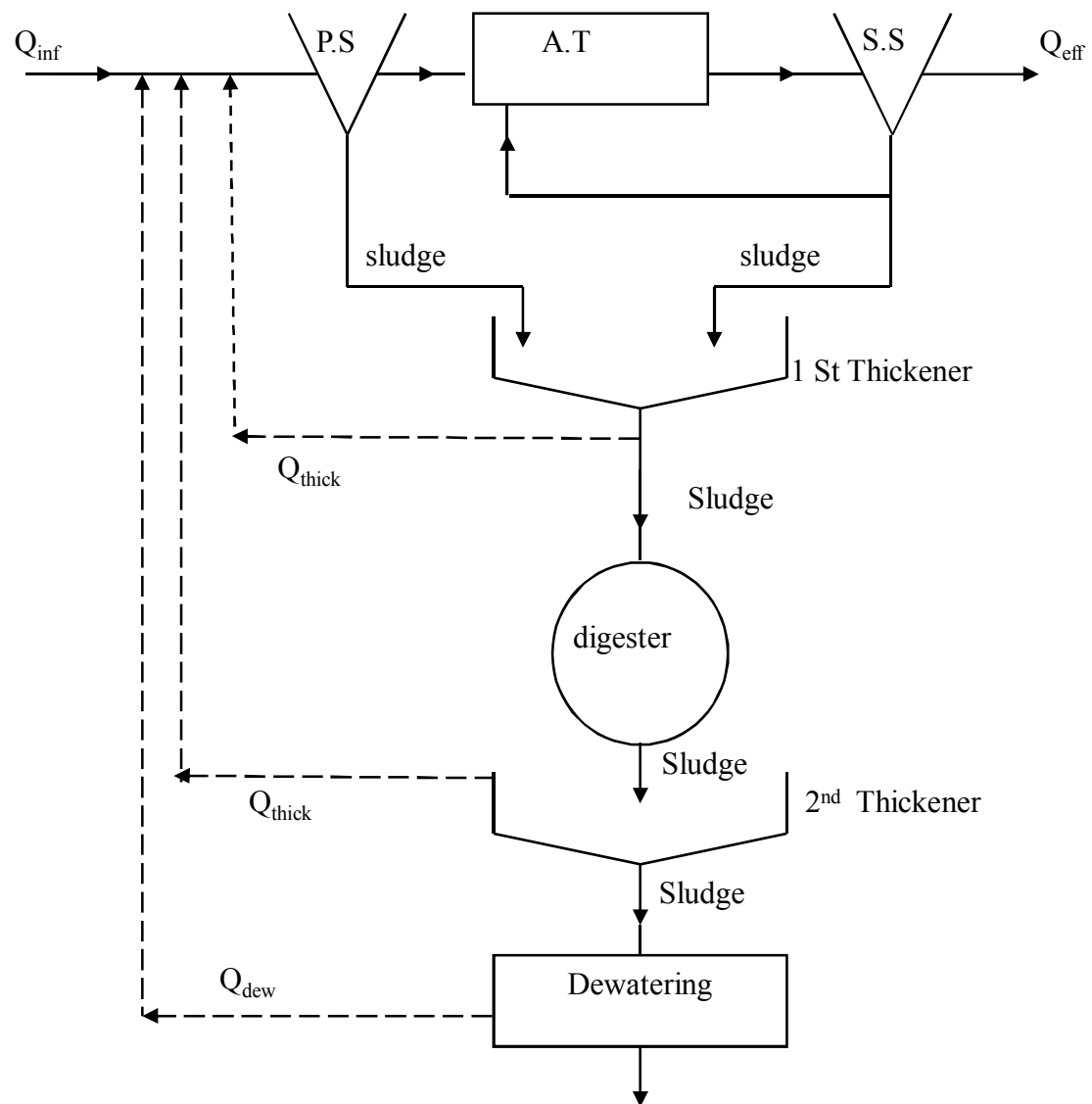
$$SS = 700 \text{ mg/l}$$

$$Q_{in} = 2000 \text{ m}^3/\text{hr}$$

$S = 5\%$ dry solids in the sludge.

$D = 36 \text{ m}$ (diameter of primary sedimentation tank)





Solution:-

a) find the overflow rate to the primary sedimentation tank:-

$$O/F = \frac{Q_{in}}{A}$$

$$A = \frac{\pi D^2}{4} = \frac{\pi * 36^2}{4} \cong 1018 m^2$$

$$O/F = 2000 \frac{m^3}{hr} \bullet \frac{1}{1018 m^2} \bullet \frac{24 hr}{d} = 47 \frac{m^3}{m^2 \bullet d} = 47 \frac{m}{d}$$

b) Find the sedimentation efficiency (E):-

from figure (1), E = 54%

c) Calculate sludge quantity:-

$$M_P = E * SS * Q_{in}$$

$$SS = 700 \frac{mg}{L} \bullet \frac{10^3 L}{m^3} \bullet \frac{kg}{10^6 mg} = 0.7 \frac{Kg}{m^3}$$

$$Q_{in} = 2000 \frac{m^3}{hr} \bullet \frac{24 hr}{d} = 48000 \frac{m^3}{d}$$

$$M_P = 0.54 \bullet 0.7 \frac{Kg}{m^3} \bullet 48000 \frac{m^3}{d} = 18144 \frac{Kg}{d}$$

$$Q_P = \frac{M_P}{X_P}$$

$$X_P = \rho_{SL} \bullet S = 1000 \frac{Kg}{m^3} \bullet 0.05 = 50 \frac{Kg}{m^3}$$

$$Q_P = \frac{18144 Kg}{d} \bullet \frac{m^3}{50 Kg} \cong 363 \frac{m^3}{d}$$

b) Secondary sludge quantities:-

Secondary sludge quantities were discussed previously in the suspended growth treatment:-

$$P_x = \text{sludge production} \frac{kg}{d} = \frac{XV}{\theta_c}$$

$$Q_w = \frac{P_x}{X_r}, \text{sludge production in } \frac{m^3}{d}$$

For more details on these quantities return to chapters 3 and 4.

5.4 sludge treatment:-

The main goal of sludge treatment is to convert it to an inert solid product that can be safely disposed in the environment or reused for useful purposes.

The main sludge treatment steps are-

- a. Sludge thickening.
- b. Sludge stabilization.
- c. Sludge dewatering.

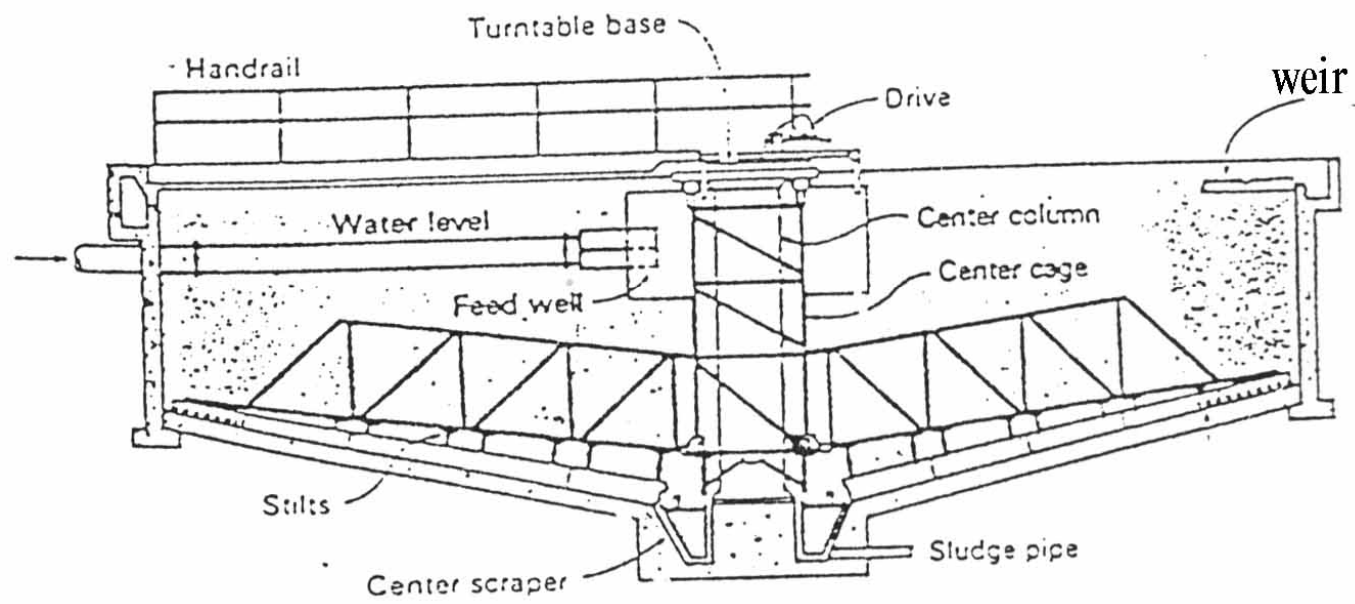
In the following section, a detailed discussion of these treatment steps is given.

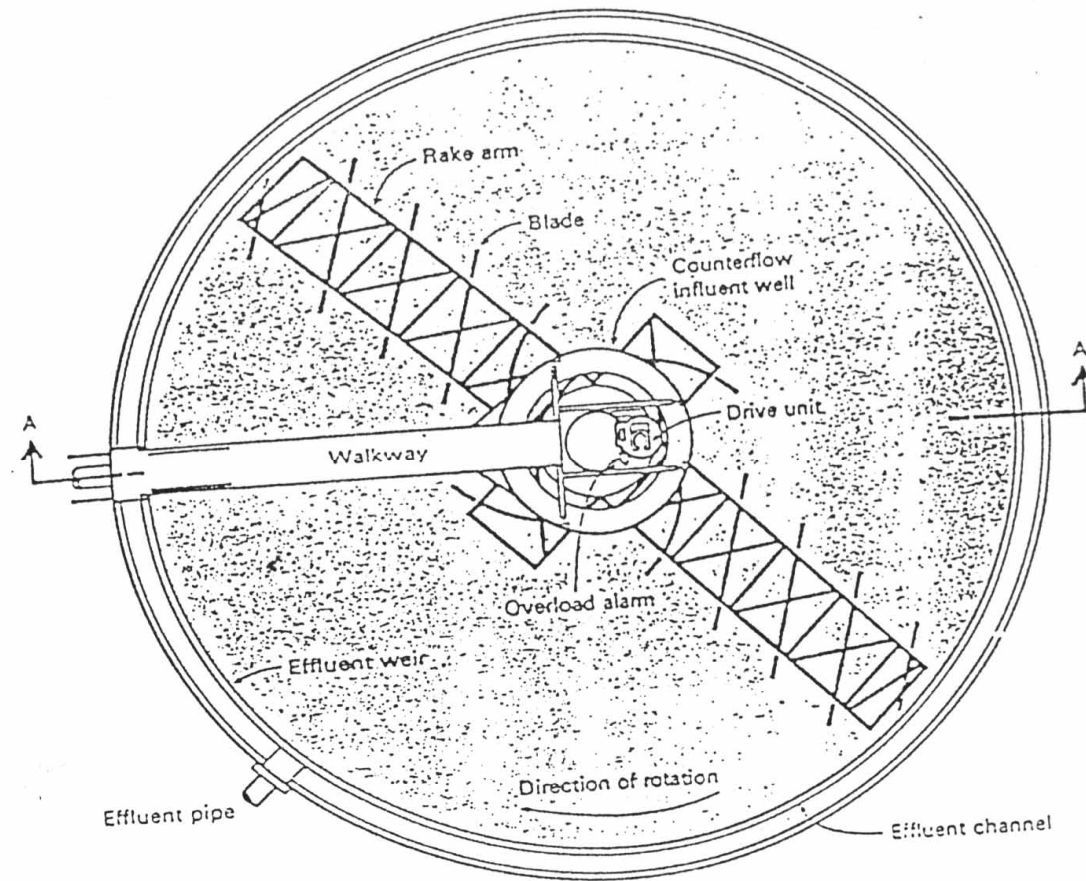
5.5 Sludge thickening:-

The main goal of sludge thickening is to reduce the sludge volume by removing as much as possible of the water content of sludge, leading to the increase of the solids content of sludge. Thickening is achieved by the following three methods:-

a) Gravity thickening:-

Gravity thickening is achieved in circular tanks similar to sedimentation tanks. Sludge is allowed to settle and compact. The thickened sludge is withdrawn from the bottom of the thickener. To improve thickening some chemicals are added, this process is called sludge conditioning. Sludge conditioning is discussed below.





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b) Flotation thickeners:-

For sludges with low weights, gravity thickeners are not efficient. In this case, the sludge floats on the surface and then removed by scum removal arms.

c) Mechanical thickening:-

Mechanical thickeners include centrifuges, rotary drums and filter belts. The centrifuges and rotary drums use the centrifugal force to separate solids from liquids. Filter belts are squeezing machines in which the sludge is inserted between two moving belts resulting in the separation of solids from liquids.

5.6 Sludge conditioning:-

Sludge conditioning is a pretreatment step to increase the efficiency of sludge thickening and dewatering of sludge. The two most common methods of sludge conditioning are:-

a) Chemical conditioning:-

- Addition of lime $\text{Ca}(\text{OH})_2$.
- Addition of ferric chloride FeCl_3
- Addition of alum $\text{Al}_2(\text{SO}_4)_3$.
- Addition of organic polymers.

These chemicals are coagulants as they neutralize and destabilize the electrically charged particles in the water and allow them to settle efficiently.

- Organic polymers replace FeCl_3 and $\text{Al}_2(\text{SO}_4)_3$ salts in order to overcome the major problems involved with these inorganic chemicals.

Advantages of organic polymers over inorganic chemicals are:-

- Dosage is around 10 times lower than that of inorganic chemicals (typical dosage is 5-10 kg/ ton_{sludge})
- Cost saving obtained in capital cost and running cost.
- Treated sludge does not contain inorganic chemical such as Fe^{3+} and Al^{3+} .
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b) Heat treatment:-

Heat treatment is a conditioning process that involves heating of sludge for short periods of time under pressure. By heat treatment, the structure of sludge flocks is altered to liberate more water from particles. The high capital cost of equipment limits the use of this method to small treatment plants only.

5.7 Design of gravity thickeners:-

Primary and secondary sludge are either treated in separate thickeners or in one common thickener. The following table gives the design criteria for gravity thickeners according to the sludge source:-

Sludge source	Influent S (%)	Expected under flow S (%)	Mass loading kg/d.m²
- Separate sludges	2-7	5-10	100-150
PS	1-4	3-6	40-50
TF	1-3.5	2-5	35-50
RBC	0.5-1.5	2-3	20-40
WAS.....			
- Combined Sludges	0.5-4	4-7	25-70
PS + WAS	2-6	5-9	60-100
PS + TF	2-6	5-8	50-90
PS + RBC			

Note: PS = primary sludge., TF = Trickling filter sludge, RBC = Rotating biological contactor sludge, WAS = Waste activated sludge.

- The area of the thickener is determined using the mass loading criteria according to the sludge source as shown in the above table.
- The depth of the thickener is determined as follows.
As shown in Figure (4), the thickener depth is divided to the following regions:-

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h_1 = free board depth above sludge surface, typically taken as 0.6m.

h_2 = clear liquid zone, typically taken as 1.0m.

h_3 = settling zone, typically taken as 1.5m.

h_4 = Thickening zone, it is a sludge storage region and have to be calculated as shown later.

So, the thickener side wall depth (H) is calculated as :-

$$H = h_1 + h_2 + h_3 + h_4$$

The depth at the center of the thickener is calculated by adding (H) to h_5 :-

$$h_5 = \frac{d}{16}, \quad d = \text{thickener diameter.}$$

To calculate (h_4), the thickening zone height, we assume that this zone has a volume enough to store one day thickened sludge. So the total solids entering the thickener will accumulate in this zone but the concentration of solids in the thickened zone will be much more than that in the sludge entering the thickener so, to calculate (h_4):-

$$V_{TZ} = A_T \cdot h_4$$

$$V_{TZ} = \text{Volume of sludge in the thickening zone, } m^3$$

$$A_T = \text{Surface area of the thickener, } m^2$$

$$V_{TZ} = \frac{(m_T)_{in}}{(X_T)_{out}} \dots\dots\dots 5.6$$

$$(m_T)_{in} = (M_T)_{in} \bullet t \dots\dots\dots 5.7$$

$$(X_T)_{out} = (\rho_{SL})_T \bullet (S_T)_{out} \dots\dots\dots 5.8$$

$(m_T)_{in}$ = mass of sludge dry solids accumulated in the thickening zone, (kg)

$(M_T)_{in}$ = mass of sludge dry solids entering the thickener per day, $\frac{Kg}{d}$

t = time, days.

$(X_T)_{out}$ = concentration of solids in sludge in the thickening zone and in the thickened sludge coming out of the thickener, (kg/m³)

$(\rho_{SL})_T$ = density of thickened sludge, (kg/m³)

$(S_T)_{out}$ = concentration of solids in the thickened sludge expressed as decimal fraction.

Combine equations (5.4) and (5.6) and solve for h_4 :

$$h_4 = \frac{(m_T)_{in}}{A_T (X_T)_{out}} \dots\dots\dots (5.9)$$

Example (5.2):-

Design a gravity thickener to treat a combined primary and activated sludge. The following data is given:-

Primary sludge:-

$$Q_P = 500 \text{ m}^3 / \text{d}, \rho_{SL} = 1100 \frac{\text{kg}}{\text{m}^3}, S = 5\%$$

Secondary sludge (activated sludge):-

$$Q_s = 150 \text{ m}^3 / \text{d}, \rho_{SL} = 1040 \frac{\text{kg}}{\text{m}^3}, S = 1\%$$

Thickener design criteria:-

- L_S = solids loading rate = $50 \text{ kg/m}^2 \cdot \text{d}$ (assumed)

- Thickened sludge concentration $(S_T)_{\text{out}} = 7\%$

$(\rho_{SL})_T$ = density of thickened sludge = 1120 kg/m^3

Solution:-

1) calculate $(M_T)_{in}$, $(m_T)_{in}$:-

$$(M_T)_{in} = M_P + M_S$$

$$M_P = Q_P \cdot X_P = Q_P \cdot \rho_{SL} \cdot S = 500 \frac{m^3}{d} \cdot 1100 \frac{kg}{m^3} \cdot 0.05 = 27500 \frac{kg}{d}$$

$$M_S \cdot Q_S \cdot X_s = Q_S \cdot \rho_{sl} \cdot S = 150 \frac{m^3}{d} \cdot 1040 \frac{kg}{m^3} \cdot 0.01 = 1560 \frac{kg}{d}$$

$$(M_T)_{in} = 27500 \frac{kg}{d} + 1560 \frac{kg}{d} = 29060 \frac{kg}{d}$$

$$(m_T)_{in} = (M_T)_{in} \cdot t = 29060 \frac{kg}{d} \cdot 1d = 29060 kg$$

(note: $-t=1d$ always for the design of thickeners)

2) calculate the area of the thickener " A_T ":-

$$A_T = \frac{(M_T)_{in}}{L_S} = \frac{29060 kg / d}{50 kg / m^2 \cdot d} = 581 m^2$$

- Find the diameter:-

$$d = \sqrt{\frac{4}{\pi} A_T} = \sqrt{\frac{4}{\pi} \bullet 581} = 272 \text{ m} > 20 \text{ m (not o.k)}$$

(note:- the maximum diameter for thickeners is 20m)

Use two thickeners:-

$$\text{Area of each thickener} = \frac{581}{2} = 291 \text{ m}^2$$

$$d = \sqrt{\frac{4}{\pi} \bullet 291} = 19 \text{ m} < 20 \text{ m} \quad \text{o.k}$$

3) calculate the depth of each thickener:-

$$h_4 = \frac{(m_t)_{in}}{A_T (X_T)_{out}}$$

$$(X_T)_{out} = (\rho_{sl})_T (S_T)_{out}$$

$$= 1120 \frac{kg}{m^3} \bullet 0.07 = 78.4 \frac{kg}{m^3}$$

$$(m_T)_{in} = \frac{29060}{2} = 14530 kg$$

$$h_4 = \frac{14530 kg}{291 m^2 \bullet 78.4} \bullet \frac{m^3}{kg} \cong 0.64 m, say \ 0.65 m$$

$$h_5 = \frac{d}{16} = \frac{19}{16} = 1.19 m, say 1.2 m$$

side wall depth:-

$$H = h_1 + h_2 + h_3 + h_4 = 0.6 + 1.0 + 1.5 + 0.65 = 3.75m$$

$$\text{Depth at the center} = 3.75 + 1.2 = 4.95m = H_C$$

4) Calculate the reduction of sludge volume:-

$$\text{Thickend discharge} \rightarrow Q_T = \frac{(M_T)_{out}}{(X_T)_{out}} = \frac{29060 / 2}{78.4} = 185 \text{ m}^3 / d$$

$$(Q_w)_{\text{Removed}} = \frac{Q_p + Q_s}{n} - Q_T = \left(\frac{500 + 150}{2} - 185 \right) \text{ m}^3 / d = 140 \text{ m}^3 / d$$

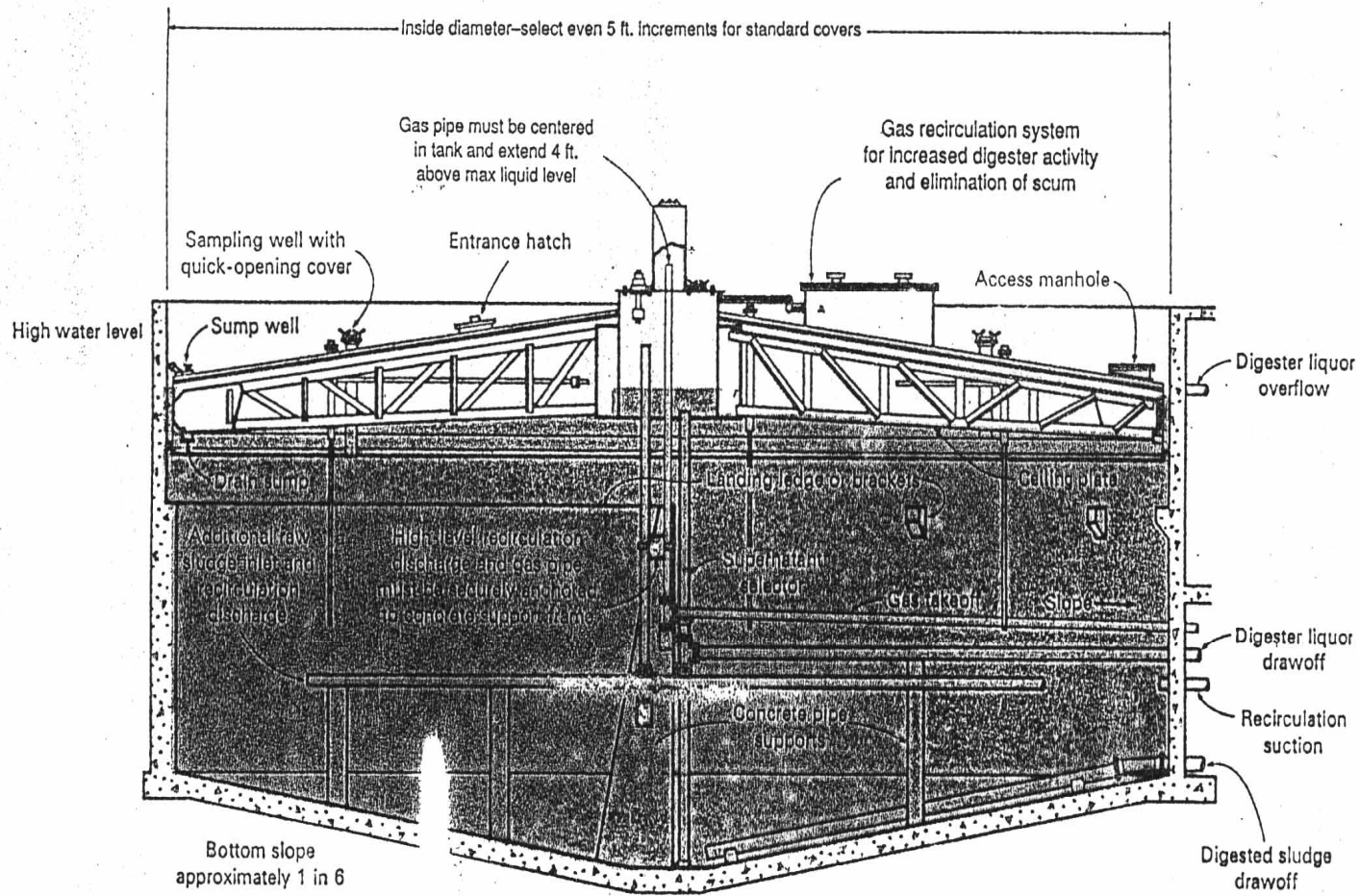
$$\% \text{ reduction} = \frac{(Q_w)_{\text{Removed}}}{\left(\frac{Q_p + Q_s}{n} \right)} \bullet 100 = \frac{140}{\left(\frac{500 + 150}{2} \right)} \bullet 100 = 43\%$$

5.8 sludge stabilization:-

Sludge stabilization is the process in which the biodegradable organic matter is converted to non-biodegradable (or inert) matter. The main purpose of this process is to produce a sludge that will not undergo any further decomposition when disposed to the environment (i.e stable sludge). If sludge is disposed without stabilization it will create bad odor and health hazards.

The most common method used for sludge stabilization is the anaerobic digestion. This process is achieved in a closed anaerobic tank called digester. Figure (2) shows a typical digester cross section. The digester shown is a cylindrical tank with a conical shaped bottom. It is an anaerobic completely mixed reactor.

The cover of the digester is a floating cover to give flexibility for gas accumulation and to prevent explosion. The sludge in the digester is heated to 35°C to give the best digestion efficiency. The digested organic matter is converted into gases such as methane (CH_4), carbondioxide (CO_2) and (H_2O). The produced methane is collected and used for energy production



Cross section through a typical standard rate digester

5.9 Solids reduction in digesters:-

The solids in the sludge entering to the digester is classified as follows:-

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From this classification, we understand that the solids reduction will be performed only on the biodegradable portion of the organic matter, while the inorganic and the non-biodegradable portions will leave the digester without reduction.

5.10 Anaerobic digester design:-

The volume of the digester is determined based on the sludge detention time

(θ_c) using the following relation:-

$$V = Q_{in} \theta_c \dots\dots\dots (5.10)$$

and (θ_c) is selected in the range of 15-20 days based on the percent of organic matter destruction. The following equation is used to calculate the percent reduction as a function of (θ_c):-

$$R_s = 13.7 \ln ((\theta_c)) + 18.9 \dots\dots\dots (5.11)$$

Where:-

R_s = percent Reduction of organic matter, %

θ_c = sludge detention time, days.

The diameter of the digester is typically in the range 5-20m. The sidewall depth should not be less than 8m because of mixing difficulties in shallow tank, and maximum sidewall depth is 15m. The floor of the digester is usually conical with a bottom slope of 1:6.

The rate of gas production in digesters is typically taken as 0.5 m^3 gas for each "kg" organic matter destroyed. The percent of methane is approximately 65% of the total gas production. The produced gas is collected from the top of the digester and passed through a water tank in which CO_2 and H_2S and other gases are dissolved while CH_4 (methane) is collected a gas and stored in a cylindrical tank called gas holder. Then, methane is used for power generation that can be used in the wastewater treatment to operate the electrical equipments. Methane is 60-70% of the total gas produced

Example (5.3):-

Anaerobic digester is to be designed to treat a thickened sludge having the following data:-

$$Q_T = 370 \text{ m}^3/\text{d}, S = 7\%, M_T = 29060 \text{ kg/d}, S.G = 1.12$$

$\theta_c = 20$ days, 70% of M_T is organic, S.G = 1.05 after digestion.

1) Calculate the required digester volume:-

$$* V = Q_T \cdot \theta_c = (370 \text{ m}^3/\text{d}) * 20 \text{ day} = 7400 \text{ m}^3$$

This volume dose not include the volume of the conical volume at the bottom.

Assume the sidewall height

H = 8m , So the surface area $A_s = \frac{V}{H}$

$$A_s = \frac{7400}{8} = 925 m^2$$

$$d = \sqrt{\frac{925 * 4}{\pi}} = 34 m > 20 m \text{ not.ok}$$

So we can either increase the depth "H" to a value in the range of 8-15m, or we can use two digesters. Let us first try to increase H to 15m:-

$$So \Rightarrow A_s = \frac{7400}{15} = 493 m^2$$

$$d = \sqrt{\frac{493 * 4}{\pi}} = 25 m > 20 m \text{ not.ok,}$$

so let us use 2 digesters.

$$H = 8\text{m} , \text{ So the surface area } A_s = \frac{V}{H}$$

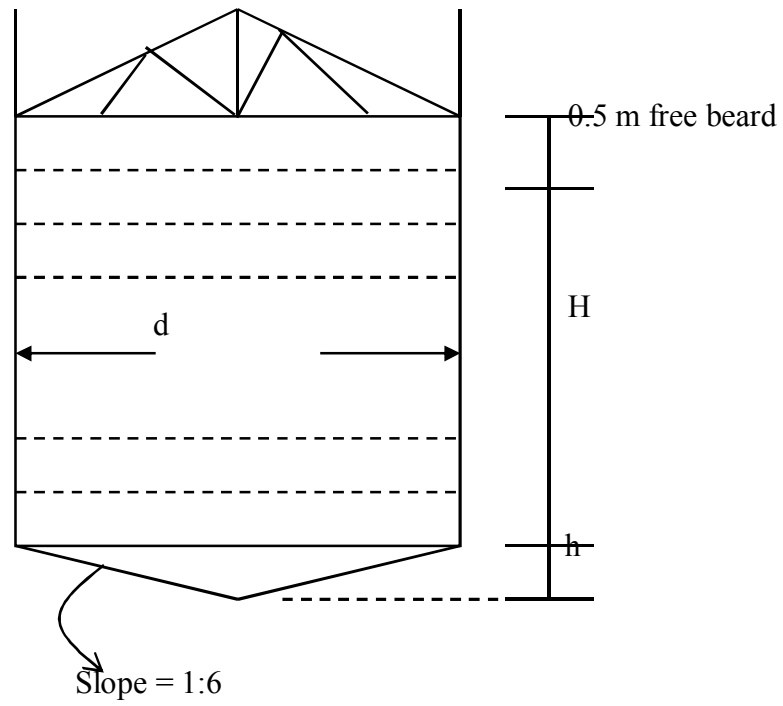
$$\text{So} \Rightarrow Q_T = \frac{370}{2} = 185 \text{ m}^3 / d \text{ (for each digester)}$$

$$V = Q_T \cdot \theta_c = (185 \text{ m}^3 / d) * 20 = 3700 \text{ m}^3$$

$$\text{assum } H = 15\text{m}$$

$$A_s = \frac{3700}{15} \cong 247 \text{ m}^2$$

$$d = \sqrt{\frac{247 * 4}{T}} = 17.7\text{m}, \text{ say } 18\text{m}$$



if the digester is needed to be lower than 15m we can use 3 or 4 digesters to get smaller digesters.

Correct "H" for $d = 18\text{m}$:-

$$A_s = \frac{Td^2}{4} = 254.47 \text{ m}^2$$

$$H = \frac{V}{A} = \frac{3700}{254.47} \cong 14.5 \text{ m}$$

add a (0.5m) as freeboard between the maximum sludge level and the floating cover

- Calculate the conical part depth:-

$$h = \frac{d}{12} = \frac{18}{12} = 1.5 \text{ m}$$

2. Calculate the efficiency of solids reduction:-

$$R_s = 13.7 \ln \theta_c + 18.9$$
$$= 13.7 \ln 20 + 18.9 \cong 60\%$$

3. Calculate the organic matter weight:-

$$M_T = \frac{29060}{2} = 14530 \text{ kg / d (for each digester)}$$

$$M_o = \text{organic matter} = 70\% \times 14530 = 10171 \text{ kg / d}$$

$$(M_{\text{iaert}})_{\text{Raw}} = \text{inert matter} = 30\% \times 14530 = 4359 \text{ kg / d}$$

4. Calculate the weight of the destroyed organic matters.

$$M_{\text{dest}} = 60\% * \text{organic matter}$$
$$= 0.60 * 10171 \text{ kg/d (for one digester)}$$
$$= 6103 \text{ kg/d}$$

$$(M_{\text{inert}})_d = 10171 - 6103 = 4068 \text{ kg/d (inert matter)}$$

• Calculate the total inert materials leaving the digester(Md):-

$$M_d = (M_{\text{inert}})_{\text{Raw}} + (M_{\text{inert}})_d = 4359 + 4068$$
$$= 8427 \frac{\text{kg}}{\text{d}}$$

5. Calculate the gas production:-

$$\text{Gas} = 0.5 \text{ m}^3/\text{kg} \times M_{\text{dest}}$$

$$= 0.5 \frac{\text{m}^3}{\text{kg}} \bullet 6103 \frac{\text{kg}}{\text{d}} \cong 3052 \frac{\text{m}^3}{\text{d}}$$

$$\text{Methane} = 60\% \bullet 3052 \frac{\text{m}^3}{\text{d}} \cong 1831 \frac{\text{m}^3}{\text{d}} \text{ from each digester}$$

Note: this volume is at standard conditions i.e. $T = 20^\circ\text{C}$, $P = 1$ atmospheric. It is usually stored in gas holders (or gas storage tanks) at a pressure larger than the atmospheric pressure to reduce the volume of gas holders for example, if the gas is stored at $P = 2 \text{ atm}$ the volume

$$V_2 = \frac{V_1 P_1}{P_2} = \frac{1831 \cdot 1}{2} \cong 916 \text{ m}^3 \text{ so we can size the gas holder.}$$

6. Calculate the percent reduction of total solids by the digester:-

$$\%R = \frac{M_{dest} \bullet 100}{M_T} = \frac{6103}{14530} \bullet 100 \cong 42\%$$

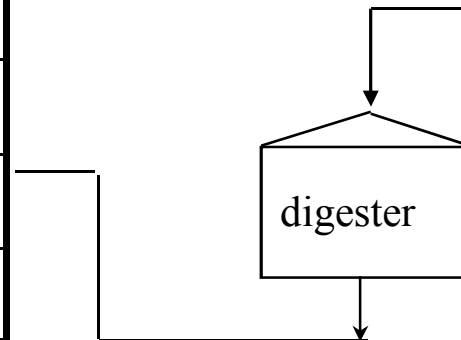
7. Calculate the concentrations of solids after digestion:-

$$X_d = \frac{M_d}{Q_d} = \frac{8427 \text{ kg} / d}{185 \text{ m}^3 / d} = 45.6 \frac{\text{kg}}{\text{m}^3}$$

$$S_d = \frac{X_d}{\rho_{se}} = 45.6 \frac{\text{kg}}{\text{m}^3} \cdot \frac{1}{1000 \frac{\text{kg}}{\text{m}^3} \bullet 1.05} \cong 0.043 = 4.3\%$$

8. Mass and flow balance for the digester:-

M_d	8427 kg/d
Q_d	185 m ³ /d
X_d	45.6 kg/m ³
S_d	4.3%
ρ_{se}	1050 kg/m ³



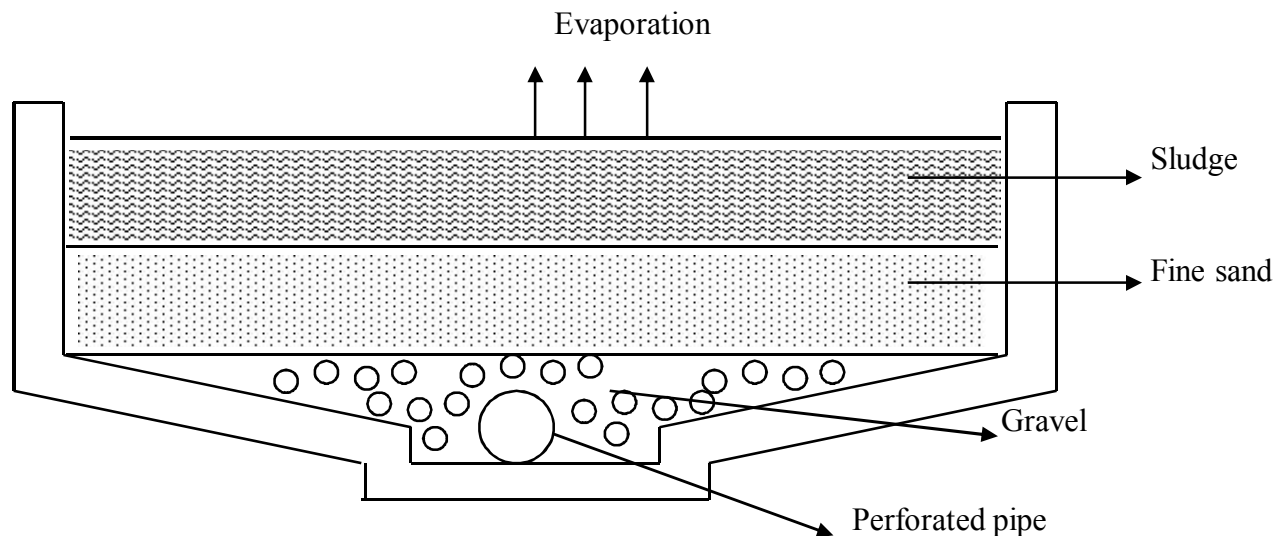
M_T	14530 kg/d
Q_T	185 m ³ /d
X_T	78 kg/m ³
S_T	7%
ρ_{se}	1120 kg/m ³

5.10 Sludge de watering:-

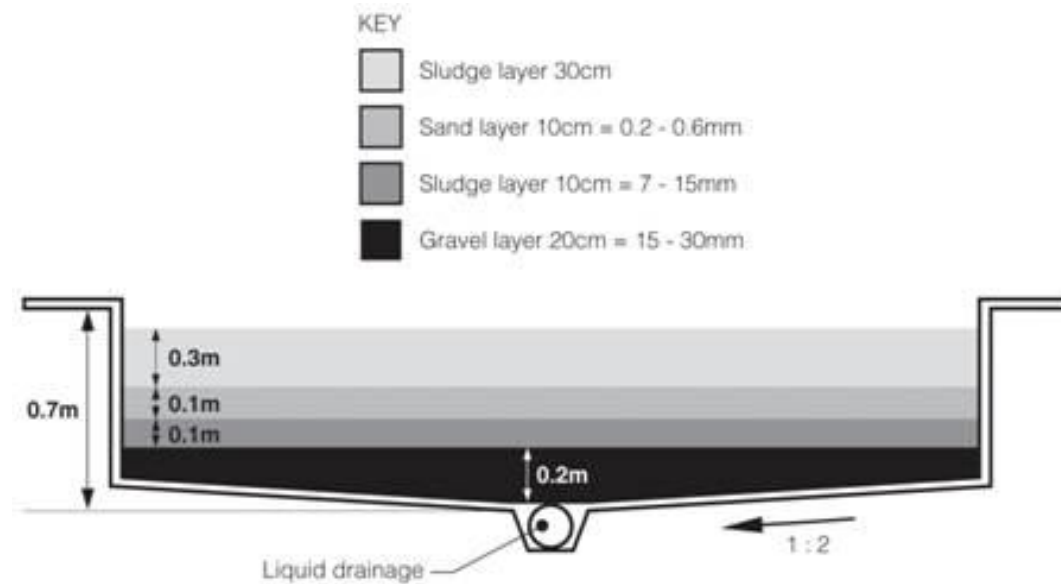
Dewatering is a physical process used to reduce to water content of sludge after stabilization. Several methods are used for dewatering as follows:-

A) Natural dewatering:-

Natural dewatering depends on evaporation and percolation. Sludge drying beds are the most common example of natural dewatering.



Sludge drying beds



B) Mechanical dewatering:-

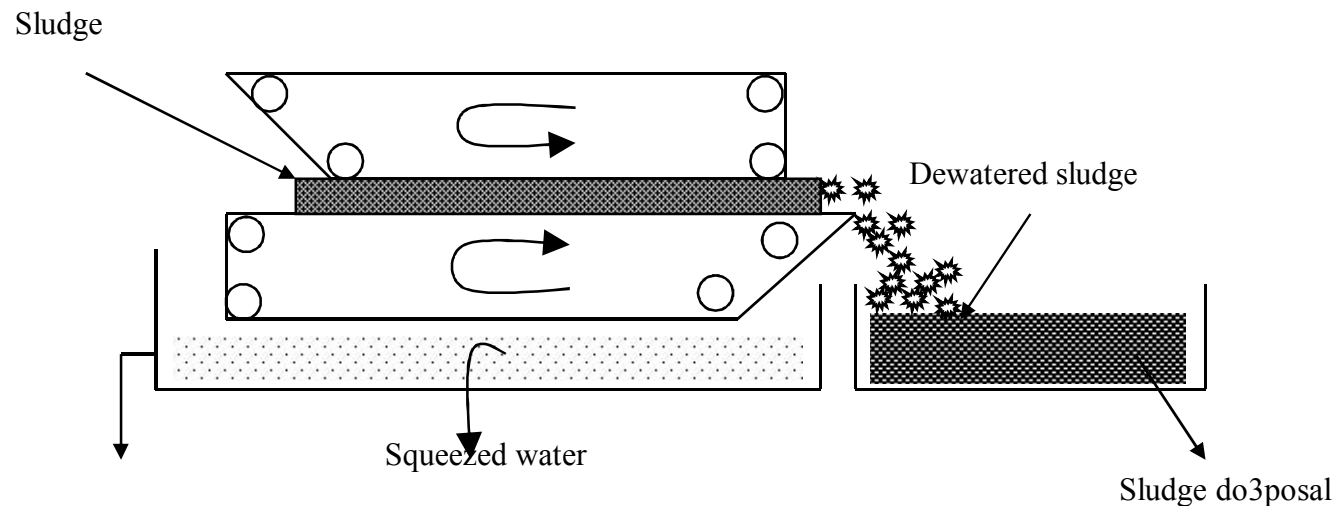
Mechanical dewatering methods are divided to three main categories:-

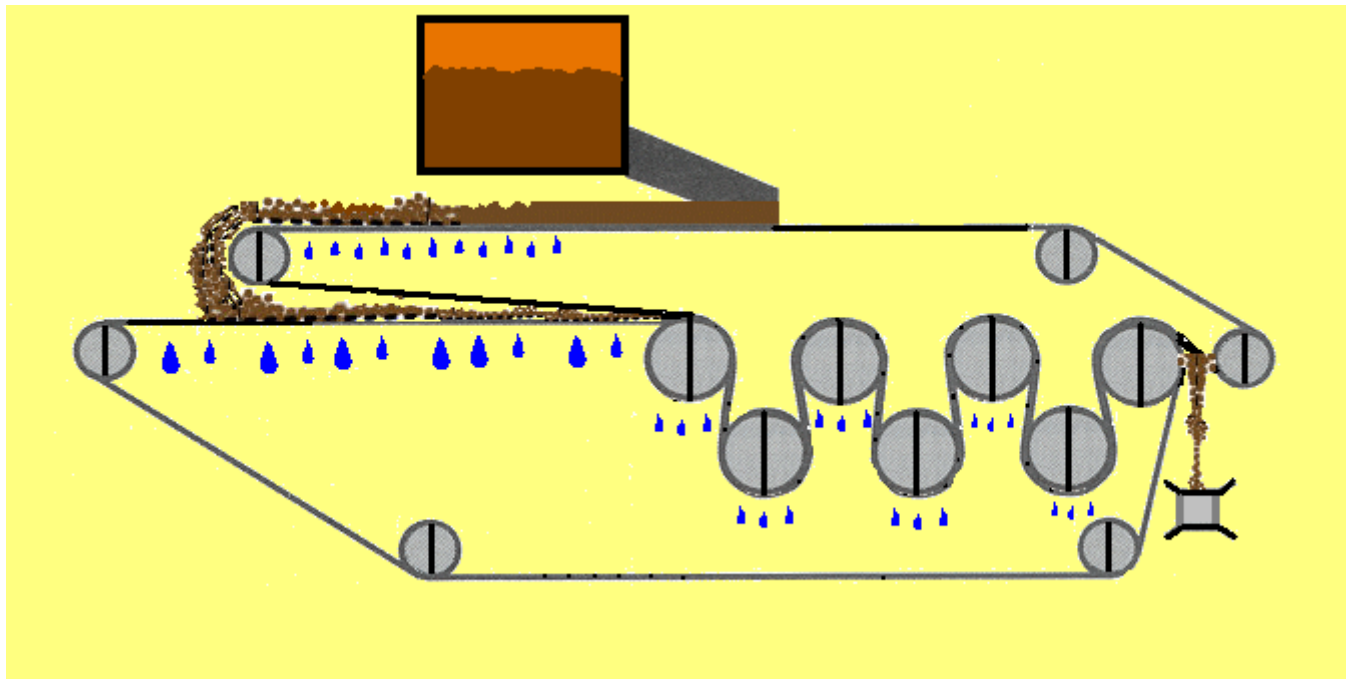
a) Vacuum filtration:-

Water is removed under applied vacuum through a porous media that retains solids and allow water to pass.

b) Pressure filtration:-

Water is removed by applying pressure (squeezing). Belt filter process is the most common example on this method.

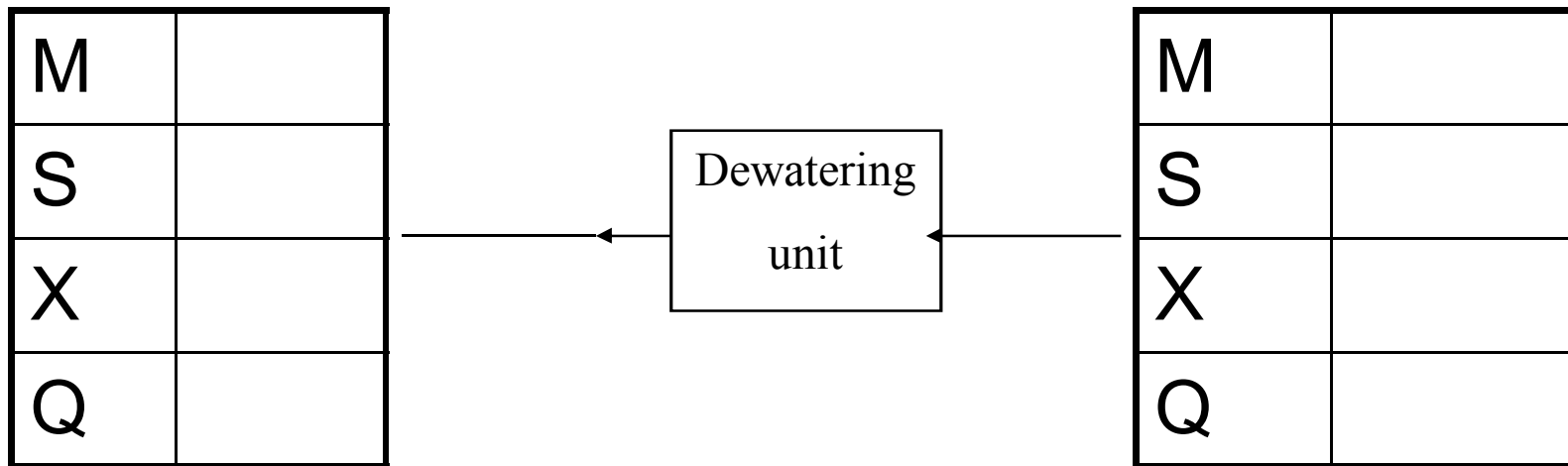




3) Centrifugation:-

Solids are separated from liquid by centritugal forces. Solid bowl centrifuge is an example on this method.

Mass and flow balance is performed on dewatering units as follows:-



Note:- "S" after dewatering in the range of 25 – 50%.



