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UP-RATING UNDERGROUND SEDIMENTATION TANKS SUBJECT TO HYDRAULIC OVERLOADING

Sven-Helmut Barthelma

A project report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 1987

DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

S Barthelmo

(Signature of candidate)

5 day of March 1987

ABSTRACT

The research in this project report is aimed at improving effluent qualities of existing sedimentation tanks which are overloaded either because the incoming flow rate is higher than the design flow or because the incoming suspended solids concentration is higher than that which was predicted in the design stages of the clarifier.

Conventional methods of up-rating tanks, usually in the form of rectangular tube modules, were discarded since they do not lend themselves to general design when the intention is to up-rate circular clarifiers. Instead a unique type of conical lamella settler was designed which comprises of one cone stacked on top of the other. The cones can be installed within an existing settler, and in so doing up-rate it.

A conventional upward flow tank and the up-rated version in the form of the conical lamella settler were tested in the laboratory. It was found that the conical lamella settler produces considerably better effluent qualities in comparison with the conventional clarifier, especially at high overflow rates. In addition, the conical lamella settler is comparatively insensitive to changes in hydraulic loading and influent suspended solids concentrations making it ideal in absorbing shock loads.

A conical lamella settler is modelled mathematically and it is shown that theoretically conical plates are a much more efficient form of settling than conventional rectangular lamella plates.

The conical lamella settler can result in substantial savings in cost and space and therefore more research is needed to perfect it and to make it as generally applicable as possible.

ACKNOWLEDGEMENTS

The assistance of the following persons and orga s is gratefully acknowledged:

Professor D. Stephenson	-	for supervision
C.S.I.R.	-	for financial assistance
Chamber of Mines	-	for financial assistance

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LIST OF SYMBOLS

A - area of plate projected onto the horizontal (m^2)

α - angle of inclination of inclined settling surface

b,b' - plate entrance width (m)

Co - initial SS concentration (mg/l)

d - plate spacing (m)

d_e - effective hydraulic radius (m)

H - outer cone radius corresponding to R (m)

h - inner cone radius corresponding to r (m)

h_0 - arbitrary cone radius corresponding to r_0 (m)

h' - vertical settling depth between plate spacings (m)

k - constant, arbitrary height of suspension between cones (m)

k_0 - initial height of suspension between cones (m)

L' - relative transition length

l' - actual transition length (m)

L - relative length of fully developed laminar flow

l - actual length of fully developed laminar flow (m)

L_d - relative design length of plates

l_d - actual design length of plates (m)

n - number of plate spacings

Q - total flow rate through the lamella unit (m^3/s)

Q' - flow rate between two plates only (m^3/s)

R - outer horizontal truncation radius of cone (m)

r - inner horizontal truncation radius of cone (m)

r_0 - arbitrary radius where $r \leq r_0 \leq R$ (m)

Re - Reynolds number

S - S-factor (constant from integration)

T - temperature ($^\circ C$)

t - time (s)

U - operating overflow rate of lamella settlers (m/h)

u - local velocity in the x-direction (m/s)

ν - kinematic viscosity (m^2/s)

V - volume occupied by liquid between inclined plates (m^3)

v - batch settling overflow rate in a vertical cylinder (m/s)

v_0 - average velocity between two parallel plates (m/s)

v_s - design overflow rate between inclined plates (m/s)

1.0 INTRODUCTION

Mining operations and fissure seepage produce considerable quantities of water which runs from the stopes via the drains into underground clarifiers. En route the water picks up a great deal of suspended matter which can result in extremely turbid waters. Pumping the water directly to the surface with high-lift centrifugal pumps without first treating it, will result in considerable wear and tear to the pumps, necessitating frequent maintenance and replacement. One solution is to treat this water in the underground clarifiers to acceptable levels of clarity before pumping it.

The primary process in the clarification procedure is the sedimentation of suspended solids (SS). The majority of underground settlers are of the upward flow tank ty[illegible]e shapes vary from square, rectangular to circular cross-sectio[illegible]ular cross section is the most advantageous from a rock mech[illegible] point of view. This is because vertical cross-sections with circular profiles have a more uniform stress distribution round their edges and are therefore structurally stronger. Conical settlers have a shape approximating a vertical cylinder and smooth-wall blasting techniques can be more effectively applied to this type of excavation than a square or rectangular cross section.

An expansion in mining activities means that more water needs to be treated if flooding of the mine is to be prevented. Excavating underground is expensive and since space is of a premium, methods of up-rating existing installations as opposed to building new ones can result in considerable cost and time savings.

It is recognised that surface areas of settling basins are calculated from permissible overflow rate conditions only and that it is advantageous to make the basin as shallow as possible. There have been many attempts at applying shallow depth sedimentation principles. The first attempts met only with limited success and consisted of introducing shallow trays

into basins of conventional designs. The shallow trays suffered from limited space for mechanical equipment for de-sludging. It is for this reason that continuously de-sludging systems have been designed and are in use today.

The continuous de-sludging systems, mostly in the form of inclined tube modules, have met with considerable success in up-rating existing installations. The modules are however rectangular in form and do not lend themselves to general design of up-rating or mass production of a standard size module. Problems are experienced in introducing rectangular modules into circular sedimentation tanks and often a new effluent launder system is also required if the full potential of the tube modules is to be realised. The problem is further aggravated in that the diameters of clarifiers vary widely in practice.

The aim of this study is to devise a shallow depth sedimentation mechanism which is reproducible for all sizes of clarifiers for a specified up-rating quantity. The principles of settling under inclined plates are investigated and laboratory sedimentation tank models of a conventional design and the up-rated version are tested to see whether any improvement in effluent qualities is obtained through up-rating the conventional clarifier. The results are modelled mathematically in order to generalise them for any possible future design.

1.0 LITERATURE REVIEW

1.1 THEORIES FOR BATCH SETTLING OF PARTICLES UNDER INCLINED SURFACES

The first person to observe that solid suspensions settled faster under inclined surfaces was Boycott(1920). He observed that the settling velocity of blood corpuscles in test tubes increased as the inclination of the tube to the horizontal was decreased. It was also noticed that sedimentation was quicker in test tubes with a smaller bore and in test tubes in which the initial vertical height of the suspension was greater. Boycott attributed these phenomena to Brownian motion effects.

Nakamura and Kuroda(1937) presented the first theoretical model to describe this phenomena. They assumed that only the downward facing surface accelerated settling and that particles remain at constant distances during sedimentation (ie. unhindered settling according to Stoke's Law) until they alight upon a solid surface or other particles. The model describes settling in a tilted square section tube set on it's edge (see figure 1).

Assuming also uniform suspension concentration the following theory was advanced. At an intermediate stage in settling, the suspension will have fallen from its original level to plane AB. During the time interval dt, it is assumed that all particles settle a distance vdt vertically to the position indicated, neglecting the volumes represented by the two small triangles. The clear liquid on the inclined face AC is less dense than the suspension, and it moves to the upper surface A'B' due to the action of gravity so that the level of the suspension falls by a total amount -dk. A material balance shows that the ratio of the initial velocity of settling in a tilted tube (dk/dt) to the sedimentation velocity in a vertical tube (v given according to Stoke's Law) is:

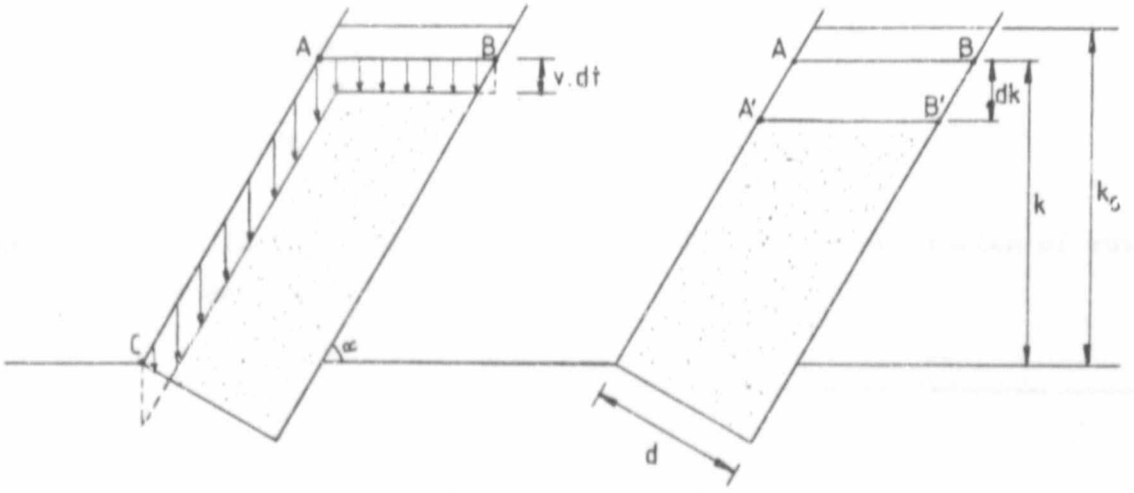


Figure 1. Nakamura and Kuroda theory.

$$-\sqrt{v}(dk/dt) = (1+k_0.\cos\alpha/d) \quad ---(1)$$

where k_0 is the initial height of the suspension and b the width of the tube or plate. Similar derivations for a tilted tube of circular cross section is:

$$-\sqrt{v}(dk/dt) = (1+1,27k_0.\cos\alpha/d) \quad ---(2)$$

and for a square tube resting on one corner:

$$-\sqrt{v}(dk/dt) = (1+1.414k_0.\cos\alpha/d) \quad ---(3)$$

Clearly the tube configuration plays an important role in the settling rates which are obtained in lamella settlers. This model however, takes into account only the geometry of the vessel and neglects effects of solids concentration changes and actual rising liquid velocities (convection) under the inclined plane.

Graham and Lama(1963) found that experimental results did not correlate well with the Nakamura model. They found that equation (1) only represents an upper limit to the rate of sedimentation. They proposed the

introduction of an empirical constant F to correct for the inadequacies of equation (1). Equation (1) then becomes:

$$-dk/dt = Fv(1+k_g.\cos\alpha/d) \qquad ---(4)$$

The correction factor F was found to vary with the concentration of suspended solids and angle of inclination α.

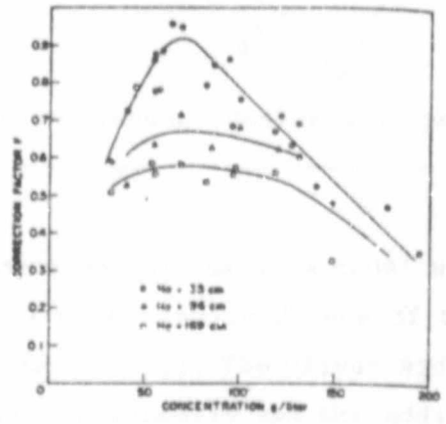


Figure 2. Correction factor F.: F as a function of $CaCo_3$ concentration in rectangular settlers with $\alpha = 50°$.

They concluded that the equations suggested by Nakamura cannot be used to calculate inclined settling rates from vertical settling data and serve only at best as an upper limit to the rate of sedimentation. Also if inclined batch settling tests are to be used to correlate continuous settling, one should perform the batch tests in a vessel having similar dimensions and angle of inclination as the continuous unit.

Oliver and Jenson(1964) observed that the clear liquid on the inclined face AC (figure 1) became almost triangular viewed from the side and of roughly constant maximum width y (see figure 3).

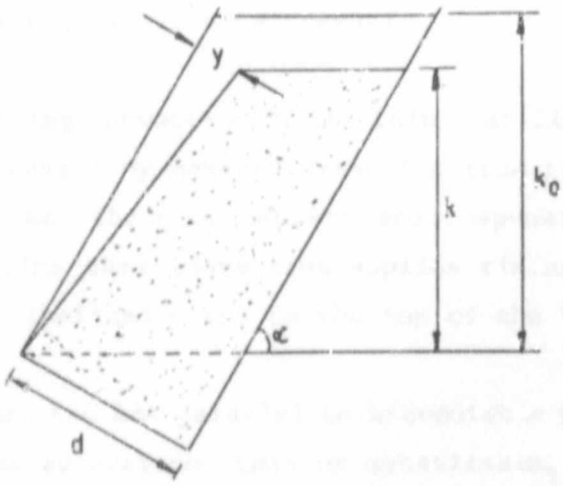


Figure 3. Oliver and Jenson idealised shape of settling suspension.

This is an improvement on the Nakamura model which assumes that the clear liquid formed on the upper inclined face of the tube is instantaneously transferred to the upper layer. The Oliver and Jenson model was developed from the implied dynamic geometry and the addition of a simple convection term containing an empirical function of concentration and angle of inclination. The solution, giving the two parameters (ie. concentration and angle of inclination) as a function of time, was obtained on an analog computer. Agreement between model and experimental data was only fair.

Zahavi and Rubin(1975) observed settling under inclined plates by injecting dye near the plates. They found that the increase in settling rate in the presence of inclined planes originates from the formation of a thin clear liquid layer under the planes which rises relatively quickly to join the clear liquid region above the suspension caused by ordinary settling. The clear liquid layer is constantly supplied from liquid in the suspension. Their experiments also showed that the sedimentation rate decreases with tube spacing d, increases with initial height of suspension k_0, and increases with decreasing angle of elevation to the horizontal α as is borne out in equation (1). For the clay suspensions studied (Sg = 2,71g/cm^3), they found that particles will slip down the inclined surfaces on which they settle for angles of $\alpha > 43^\circ$. Within the constraints of

their experimental apparatus it was found that initial batch settling rates in the presence of inclined planes can be higher by a factor of up to 3 compared to settling in a regular vertical vessel.

Hill(1977) showed that the settling convection of the thin clarified layer under the inclined surface is caused by momentum transfer from particles to fluid. He also postulated that three mechanisms are responsible for causing settling convection. (The term convection applies rising of the thin clarified layer under the inclined plane to the top of the tube.)

- Suspension density gradients are not parallel to hydrostatic pressure gradients. Convection tries to overcome this by establishing a downward gradient of density.

- Return flow of liquid displaced by settling particles channels through regions of lower particle density.

- Particles collect near and flow down along upward facing inclined surfaces thus displacing liquid to the top.

The more elaborate kinematic models of Graham and Lama(1963), Oliver and Jenson(1964) and Zahavi and Rubin(1975) are all an extension of the simple Nakamura model. However since all these models contain expressions with adjustable parameters which in general are complicated functions of concentration and the geometry of the vessel and must be evaluated by the best fit to inclined settling data or extensive computer programs, their usefulness and significance to the practical design of continuous settlers is rather limited.

Acrivos and Herbholzheimer(1979) showed that the simple Nakamura theory should be adequate for the design of both continuous and batch settling tanks for clarifying suspensions. They also showed that the main deviations from the Nakamura theory arise from instability between the feed or the suspension and the thin, particle free, clarified liquid layer which forms on the upper inclined surface of a tube. Such instability would cause entrainment of particles into the rapidly rising clarified

layer and hence the fluid above the suspension would become contaminated. It would therefore be advantageous in continuous settlers if there is a large reservoir above the plates which could allow such particles to settle out.

2.2 CONTINUOUS SETTLING UNDER INCLINED PLATES IN LAMELLA SETTLERS.

2.2.1 TYPES OF LAMELLA SYSTEMS.

The flow in lamella settlers takes advantage of two elementary sedimentation concepts. Firstly the dynamic operation of a sedimentation unit creates some turbulence because of the flow through the unit. Lamella settlers divide the settling zone into a myriad of miniature sedimentation tanks wherein turbulence and velocity are minimised. Secondly the settling distance of individual particles is minimised. Instead of the usual 3 to 5 metres of settling depth in a standard sedimentation unit, the depth is minimised to a few millimetres to separate solids from the feed liquid. Space utilisation is also maximised. The area required for clarification is the same as with conventional units. However, in the lamella settlers this area is compressed by inclining each plate or lamella so that the apparent settling area (surface area of the tank) appears much smaller than a conventional unit. To build a conventional sedimentation system with the same efficiency, the theoretical settling surfaces would have to be spread out side by side (see figure 4). The result would be a settling tank whose total length could be up to 10 times the length of an equivalent lamella system.

Currently four different types of lamella settlers are in use. The four types are classified according to the flow regimes of the influent or feed and the sludge layer. The four types are:

- Cocurrent flow
- Countercurrent flow
- Diagonal current flow

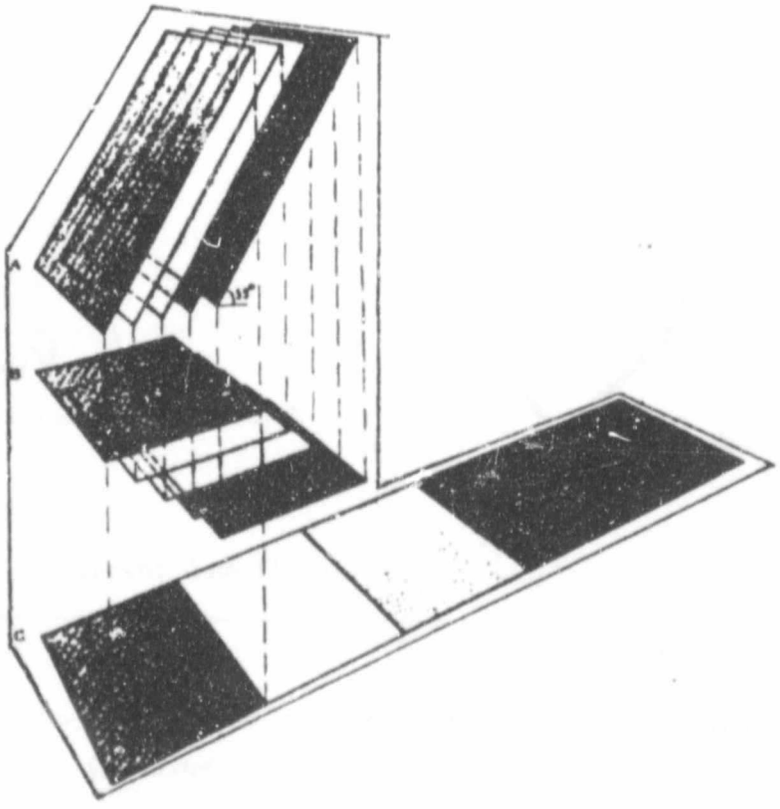


Figure 4. Lamella plates showing large horizontal projection.

o Crossflow

With the cocurrent flow settler, suspensions are introduced into the top and the clear liquid layer and sludge flow simultaneously downwards (see figure 5).

One advantage of this system is that the sludge removal is aided by the downward flow of the feed. Disadvantages are turbulence created at the drawoff of effluent because of the proximity of the sludge and the clear water. Also there exists the danger of blocking the exit at inclination angles of less than 55°. This can be a serious problem in cocurrent units that are designed using the theoretical optimum plate angle of 35° to the horizontal.

In the countercurrent method the influent is fed in at the bottom and the sludge layer and clear water move relative to each other with clear water

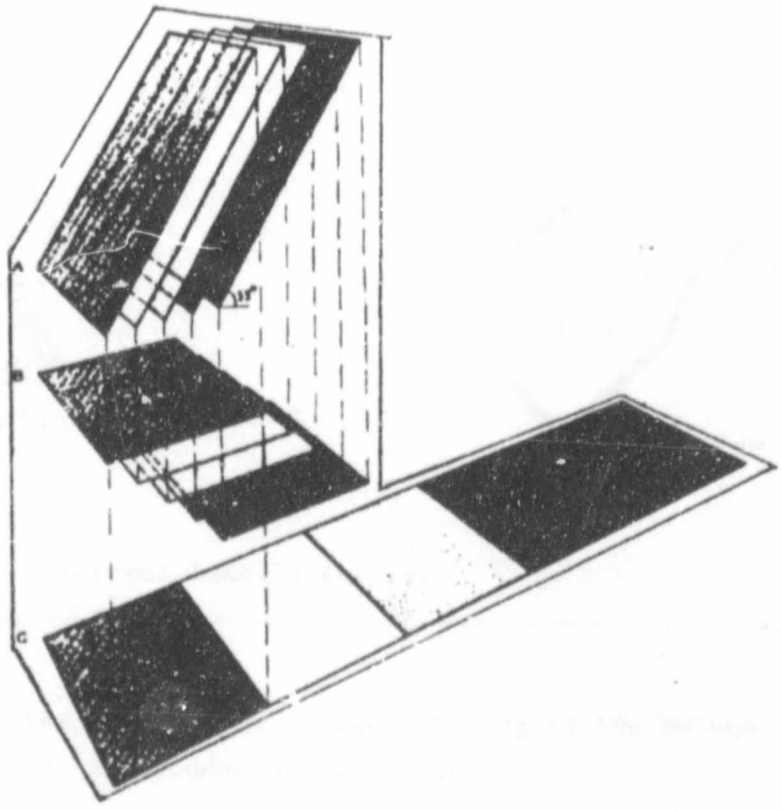


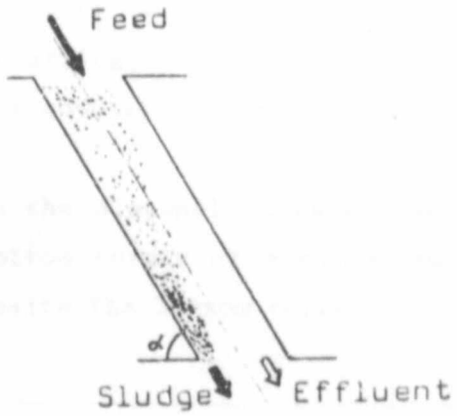
Figure 4. Lamella plates showing large horizontal projection.

- Crossflow

With the cocurrent flow settler, suspensions are introduced into the top and the clear liquid layer and sludge flow simultaneously downwards (see figure 5).

One advantage of this system is that the sludge removal is aided by the downward flow of the feed. Disadvantages are turbulence created at the drawoff of effluent because of the proximity of the sludge and the clear water. Also there exists the danger of blocking the exit at inclination angles of less than 55°. This can be a serious problem in cocurrent units that are designed using the theoretical optimum plate angle of 35° to the horizontal.

In the countercurrent method the influent is fed in at the bottom and the sludge layer and clear water move relative to each other with clear water



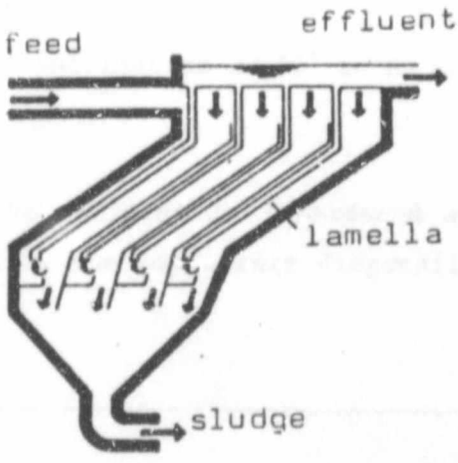
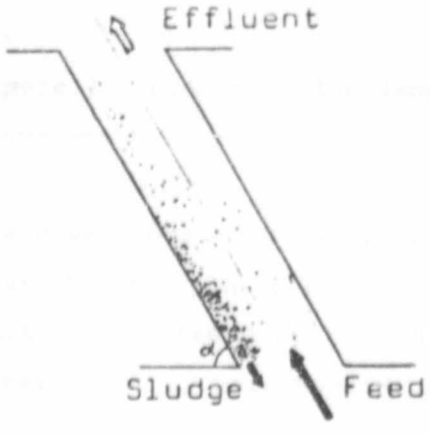


Figure 5. Cocurrent lamella settler.

drawn off at the top and the sludge settling to the bottom. This effectively separates the sludge and effluent.



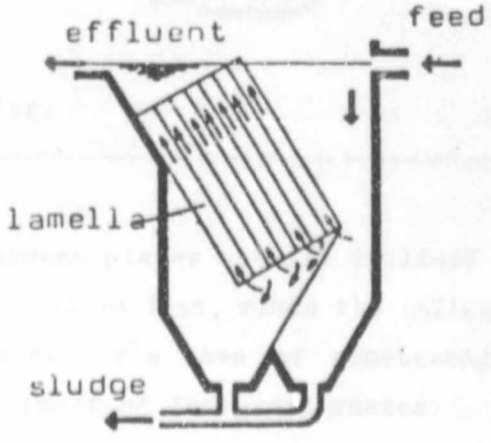


Figure 6. Countercurrent lamella settler.

Higher angles of plate inclination are required compared to a cocurrent flow system since the downward movement of the sludge is retarded by the shear between the feed layer and the sludge. Plates can be closer together since sludge and effluent are drawn off at different points. Also higher

influent concentrations can be fed into the system without any blocking occurring. It has been found that a plate inclination of 55° is an optimum for countercurrent systems.

In the diagonal current flow settler the influent is introduced at the bottom corner of a plate and drawn off at the top corner diagonally opposite the bottom corner.

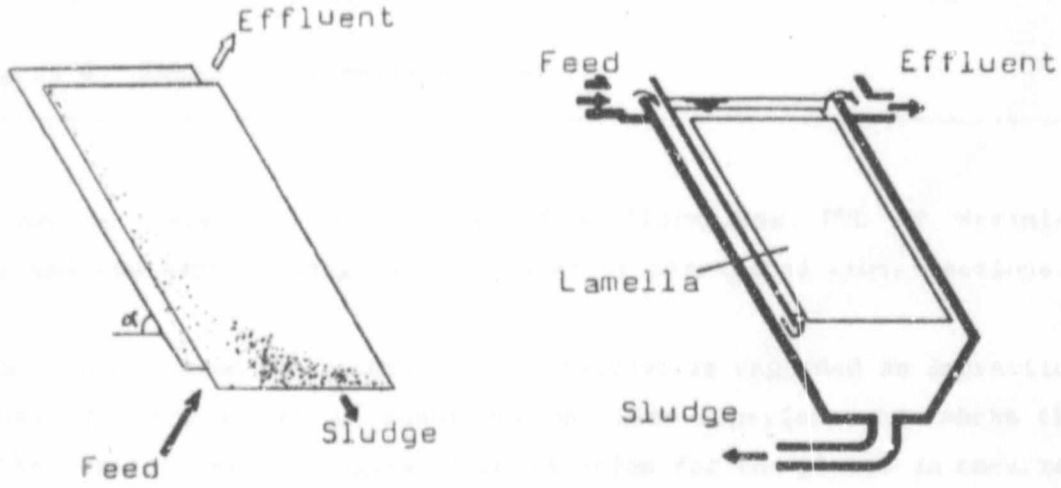


Figure 7. Diagonal flow lamella settler.

The sludge flows vertically downwards between plates usually inclined at between 50°-60°. The efficiency of such a unit is less, since the influent is not evenly fed over the inclined plates. It's ease of construction however makes it very popular in the treatment of inorganic wastes.

In the crossflow settler influent flows horizontally from one end to the other while the sludge settles vertically (see figure 8).

It is important in this system to provide an even distribution of influent over the entire plates. The lamella are usually corrugated. These type of settlers have been found to be most effective in separating two liquids of different densities eg. oil and water suspensions.

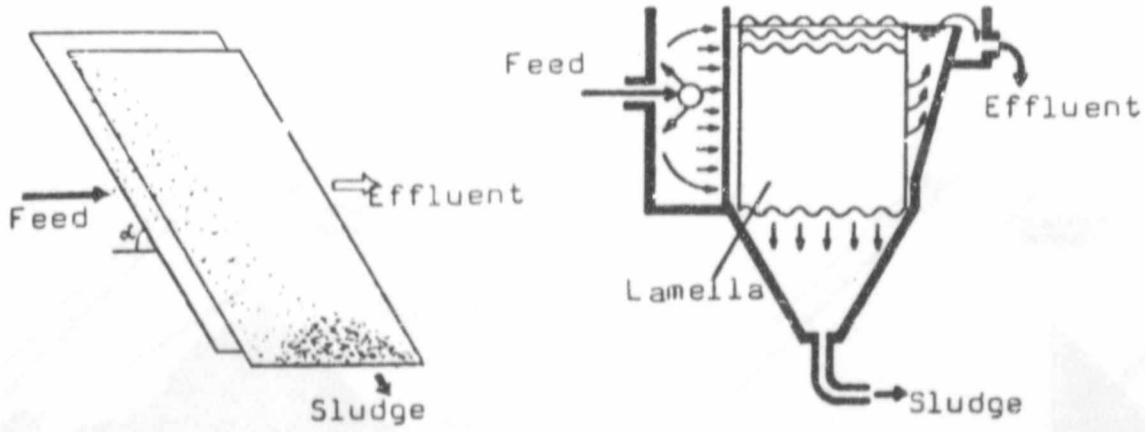


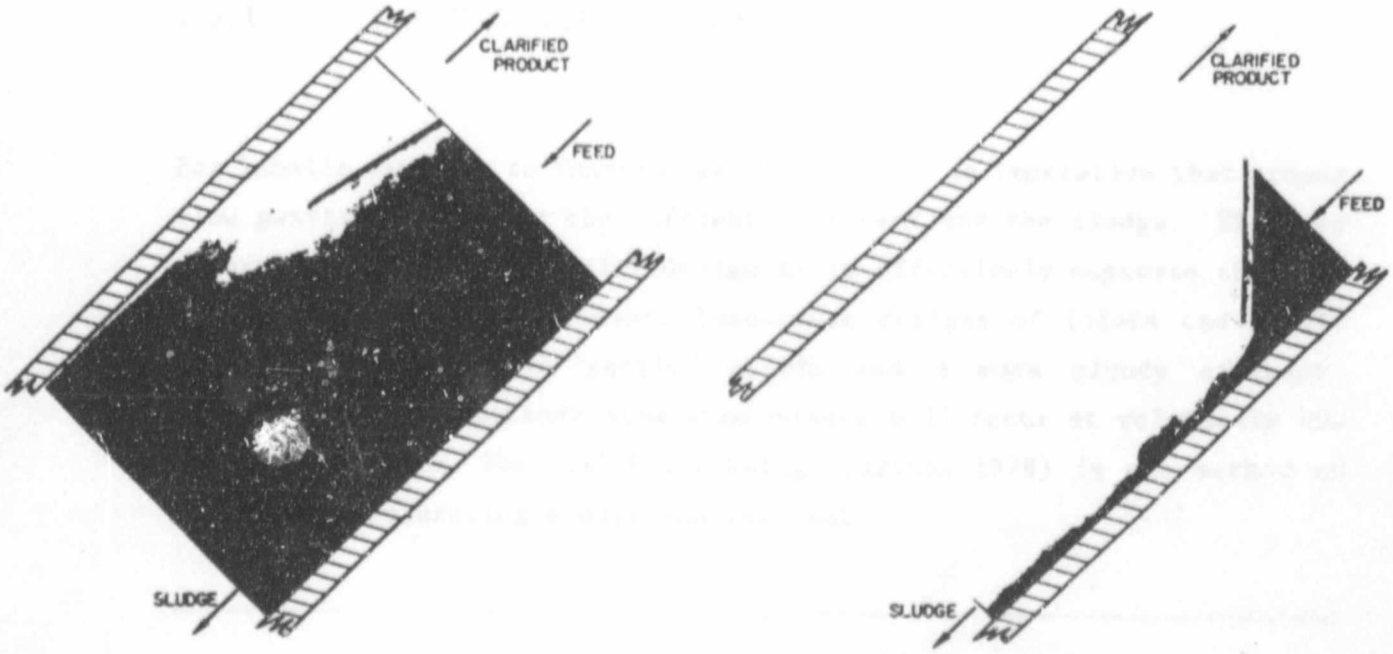
Figure 8. Crossflow lamella settler.

The lamella plates are usually made from fibreglass, PVC or Stainless Steel and can have rectangular, circular or corrugated cross-sections.

Of the above systems the cocurrent flow settler is regarded as impractical because of difficulties in construction. Also experience has shown that the theoretical smaller angles of inclination for the plates in cocurrent systems (35°-45°) have to be increased to 55° to prevent blocking of the outlet. This is the same angle used in countercurrent systems. Plate spacings had to be increased to accommodate the sludge layer and effluent. For these reasons only countercurrent, diagonal and crossflow lamella settlers are in use today.

Leung and Probstein(1983) however, showed that if the feed layer which enters a cocurrent settler from the top, is less than half the width of the plate spacing, then a supercritical mode of flow occurs between the plates. In this supercritical mode the feed or influent layer contracts in it's direction of flow. This results in an increased efficiency of ur to ≈ 90% over the subcritical mode in which the feed layer is greater than half the width of the plate spacing and which is the mode of flow in all present lamella settlers. The supercritical mode of operation results in a cocurrent lamella settler in which the feed is fed in from the top but the effluent is also drawn from the top as apposed to the more conven-

tional cocurrent system where the clarified liquid is drawn off at the bottom.



Photographs of a lamella settler with a water-alumina feed slurry (250 ml/min) of 5 percent volume concentration of alumina; (a) subcritical mode, (b) supercritical mode.

Figure 9. Super and subcritical modes of flow in cocurrent lamella systems.

2.3 PRACTICAL DESIGN CONSIDERATIONS IN LAMELLA SETTLERS.

2.3.1 INLET AND OUTLET DESIGN.

For lamella settlers to function as theorised it is imperative that proper flow patterns exist for the influent, effluent and the sludge. The most important aspect of the inlet design is to effectively separate the settling sludge and the influent. Inadequate designs of inlets can result in the resuspension of settled solids and a more cloudy effluent. Re-entrainment of already separated sludge will occur at relatively low upflow velocities. The Dual Entry Design (Grimes 1978) is one method of effectively separating sludge and influent.

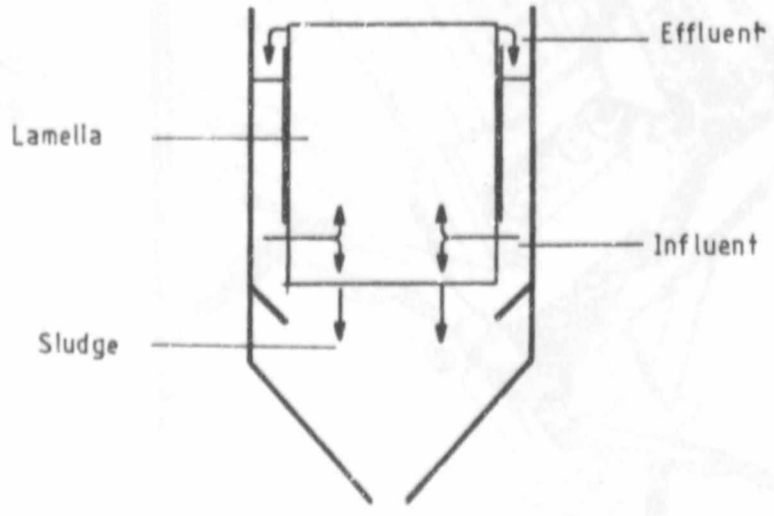


Figure 10. Dual Entry system lamella flow pattern.

The feed enters the side of the plate near the bottom. This allows for countercurrent operation and the separation of sludge and feed at the same time. For economic reasons the plate width should be as wide as possible. However, the wider the plate becomes the more difficult it is to distribute the influent evenly across the entire width. The Dual Entrance

Design overcomes this by allowing the feed to enter from both sides of the plate. The effective distance that the influent has to traverse is hereby halved.

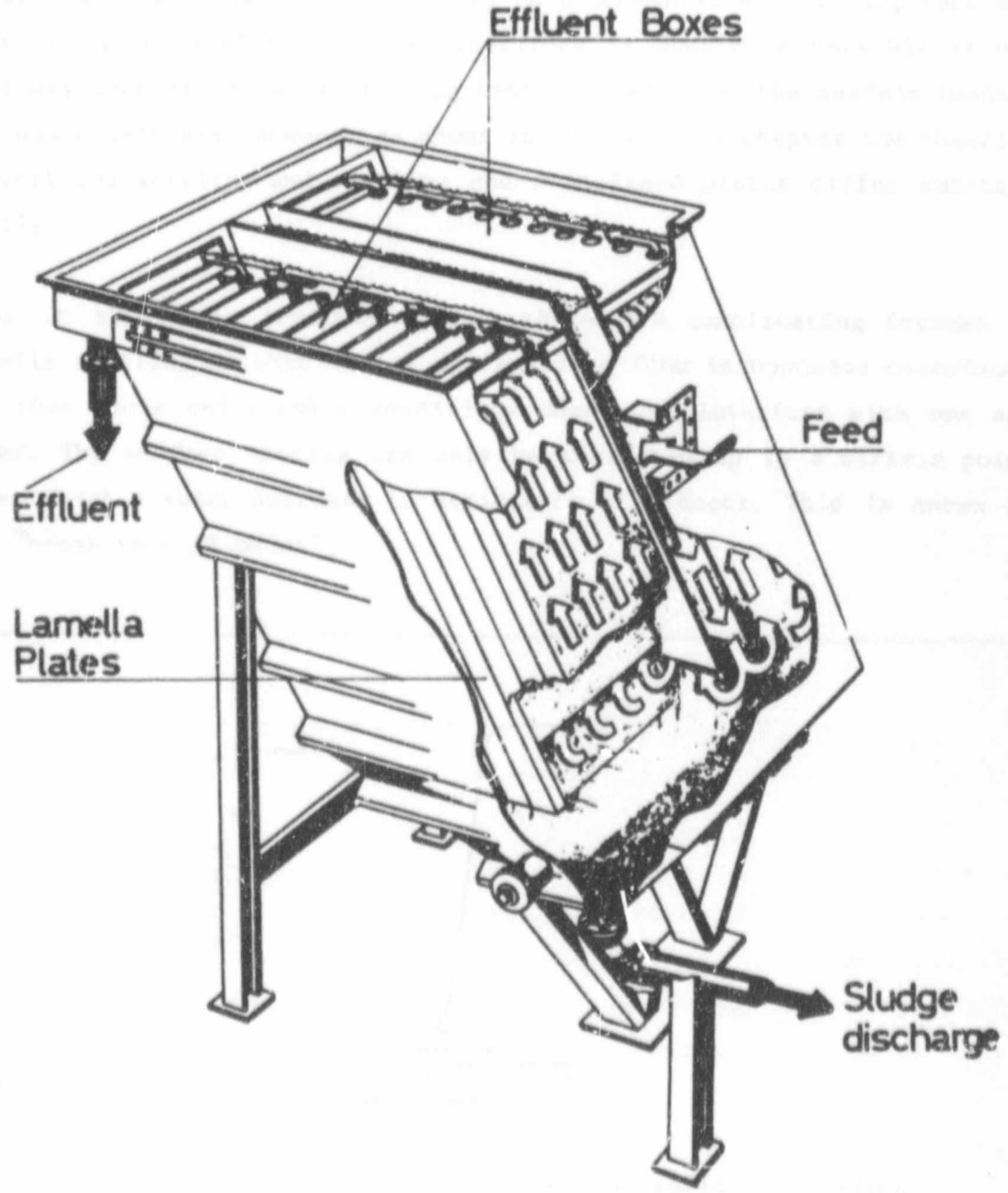


Figure 11. Typical layout of a lamella settler.

2.3.2 SURFACE LOAD.

Theoretically there should be no difference between the surface load (overflow rate or settling velocity) in a conventional settling tank and that found in lamella settlers. Therefore it should be possible to use ordinary laboratory batch settling tests to establish the surface loading for plate settlers. However as shown in the previous chapter the theories of vertical settling and settling under inclined plates differ substantially.

Also it should be remembered that there are complicating factors in lamella settling in that the sludge and feed flow in opposite directions and that under unfavorable conditions these can interfere with one another. The surface loading can only be increased up to a certain point after which a sharp decrease in efficiency will occur. This is known as the "break through point".

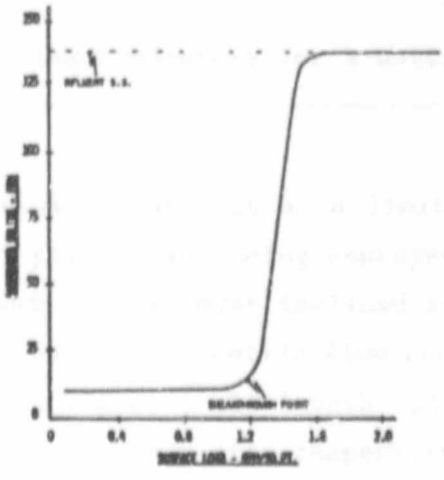


Figure 12. Breakthrough curve for suspended solids vs loading.

At this "break through point" velocities in the lamella settler are high enough for turbulent conditions. It is therefore necessary to establish this point so that the unit is never operated beyond it. This point can

only be determined by tests in a pilot plant as it varies from unit to unit.

If the dimensions of the lamella settler are fixed then an approximation of the surface load can be calculated as follows:

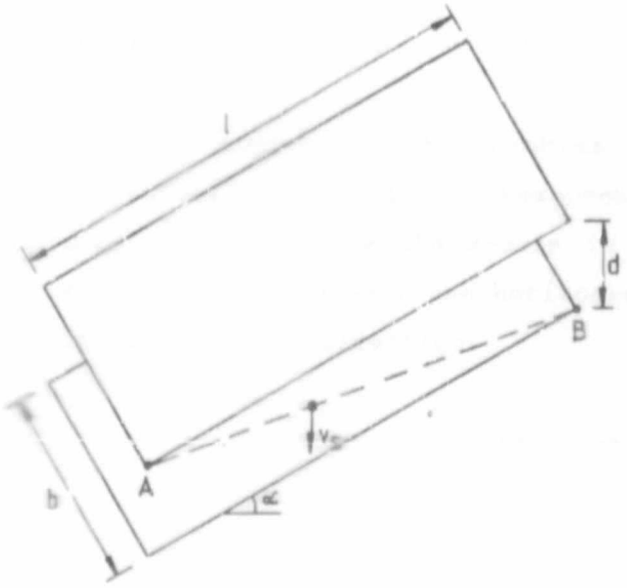


Figure 13. Limiting trajectory for a settling particle.

The figure above shows a particle on a limiting trajectory entering the separating zone at point A and being captured at point B in a plane vertically above A and on the lower inclined surface. Plug flow conditions are assumed. Let Q be the volumetric flow rate through the settler, n the number of separating zones, l the length and b and d the width and separation distance between the plates respectively.

The residence time of a particle is given as:

$$t = bdln/Q \quad ---(4)$$

Let v_s be the settling rate or surface load. The distance fallen by the particle is $d/\cos\alpha$ so the time t taken to settle is:

$$t = d/(\cos\alpha . v_s) \quad ---(5)$$

and therefore

$$bln = Q/(\cos\alpha . v_s) \quad ---(6)$$

If equation (1) is substituted for v_s with $k_\theta = l\sin\alpha$ then (6) becomes:

$$bln = Q/[v(1+l\sin 2\alpha/2d)\cos\alpha] \quad ---(7)$$

This is an oversimplified approach to the problem. A model which takes into account the trajectory of the particle has been given by Yao(1970). Consider the coordinate system where the x-axis is parallel to the direction of flow. α is the angle between the horizontal and the x-axis and u is the local velocity in the x-direction.

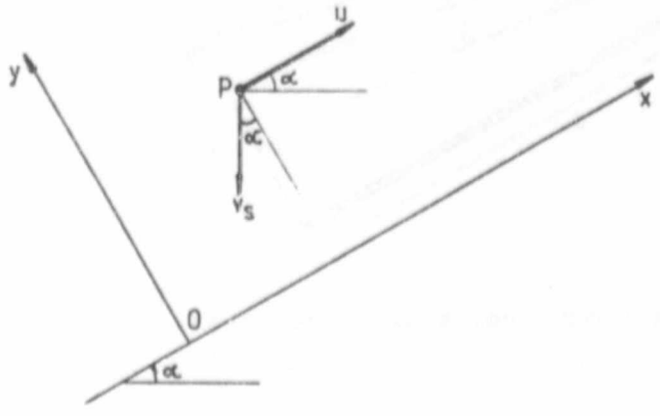


Figure 14. Coordinate system.

Particle velocities in the x and y directions respectively can be written as follows:

$$v_{px} = u - v_s \sin\alpha \quad ---(8)$$
$$v_{py} = v_s \cos\alpha \quad ---(9)$$

By definition $v_{px} = dx/dt$ ---(10)

$v_{py} = dy/dt$ ---(11)

Combining the above equations gives:

$$dy/dx = -v_s \cos\alpha/(u-v_s \sin\alpha) \quad ---(12)$$

Equation (11) is the differential equation of the particle trajectory resulting from the combined effects fluid drag and gravitational settling

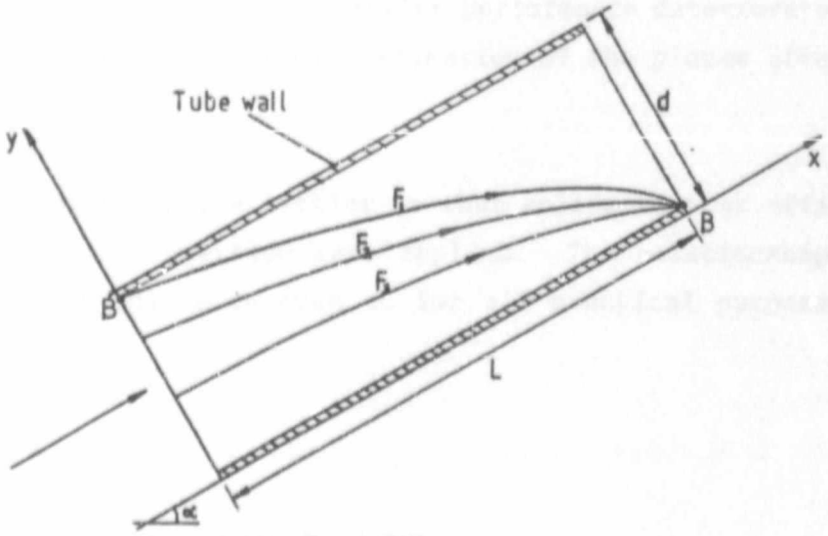


Figure 15. Particle trajectories in a continuous settler.

Equation (12) can be integrated and divided by v_0 the average flow velocity through the settler and d the depth of flow measured normal tc the direction of flow to render the equation dimensionless. Using the boundary conditions of the limiting trajectory F_1 which starts at B' and represents the uppermost trajectory in the family, gives:

$$v_s = Sv_0/(\sin\alpha+L\cos\alpha) \quad ---(13)$$

where L = 1/d

and v_s defines the critical particle fall velocity or critical surface loading in inclined tubes.

The **S** value varies with the shape of the plate. Critical **S** values are given below:

SETTLER TYPE	S VALUE
Circular	4/3
Shallow open tray	1
Parallel plates	1
Square conduits	11/8

Yao(1970) also showed that theoretically settler performance deteriorates rapidly with an increase in the angle of inclination of the plates after the angle reaches 40°.

A particular advantage of the plate settler is that solids removal efficiency is proportional to the overflow rate applied. The relationship, overflow rate to percent solids removed is for all practical purposes linear.

2.3.3 CONSIDERATIONS FOR LAMINAR FLOW.

Flow stability and laminar flow are assured in lamella sedimentation units since the settling area is divided into many small settling tanks. For laminar flow to occur between parallel plates the Reynolds number must be less than or equal to 500. Reynolds numbers of Rc = 100 have been measured in some existing installations. There is therefore no reason to adjust sedimentation efficiency because of turbulence as is done in conventional settlers (usually laboratory figures are derated by 25% - 75%), except at the inlet zone.

Provision has to be made for this inlet turbulence. At the entrance there exists a transition region in which turbulent flow is gradually changed to laminar flow due to the restrictions of the plates. The relative length of this transition can be estimated from:

$$L' = 0.058 v_0 d/\nu \qquad ---(14)$$

where ν is the kinematic viscosity of the fluid.

This value must be added to L in equation (13). Yao(1970) recommends that in cases where L is greater than L' a total relative length of 2L be used instead of the sum of L' and L.

2.3.4 PLATE SPACING D.

Theoretically it would be best to make the plate spacing as small as possible to increase the performance of a continuous plate settler. However, the floc and sludge volumes constrict the inlet and can bring about the critical velocity at the "breakthrough point". This must be avoided. Also the lamella distance must be large enough such that feed flow upward and sludge flow downward on the lamella plates do not interfere with each other. The two loads must run independently.

Other factors influencing the critical spacing is the ability of the sludge to roll or slide off the lamella. This influences the tendency of the sludge layer to build up on the lamella. It is therefore not possible to calculate the spacing mathematically. Pilot plants are usually necessary for accurate design. Typical plate spacings range from 40 to 80mm in countercurrent settlers and up to 120mm for diagonal flow settlers.

2.3.5 SLUDGE AND SLUDGE REMOVAL.

The retention time in lamella settlers ranges from about 10-15 minutes. This is considerably less than the 4 to 6 hours in a conventional settling tank. Sludge concentration, besides being dependant on the surface loading is also a function of retention time and sludge bed thickness. Since the retention time is so short in lamella settlers, sludge concentration is usually less than that obtained in conventional systems. The sludge concentration obtained in lamella systems is dependant on the design of the unit. Various techniques can be employed to overcome low sludge concentrations. It has been demonstrated that low amplitude vibrations considerably increase sludge densities of finely dispersed mineral sludges by enhancing the packing of the sludge particles.

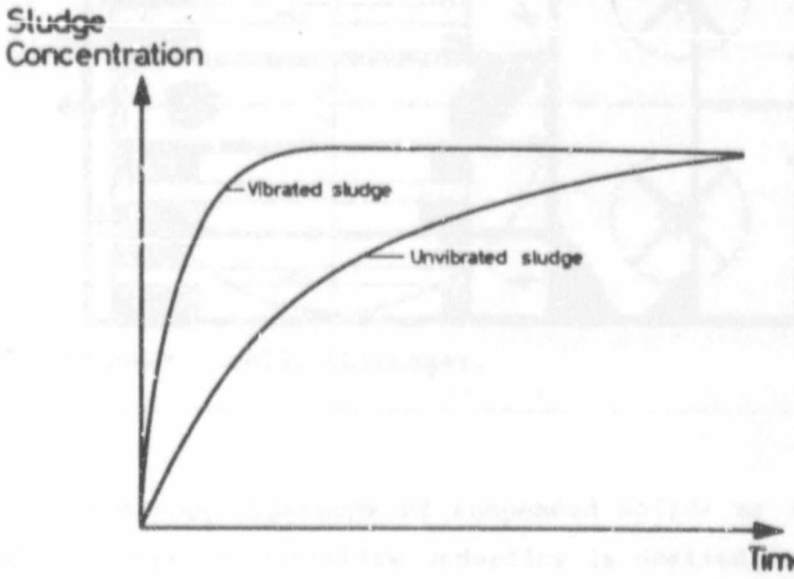


Figure 16. Effect of low amplitude vibrations on compression of sludge.

For sludges forming networks it has been found that low amplitude vibrations have less effect on the compression process. It has been found that gentle agitation of the sludge by mechanical stirrers produces good results.

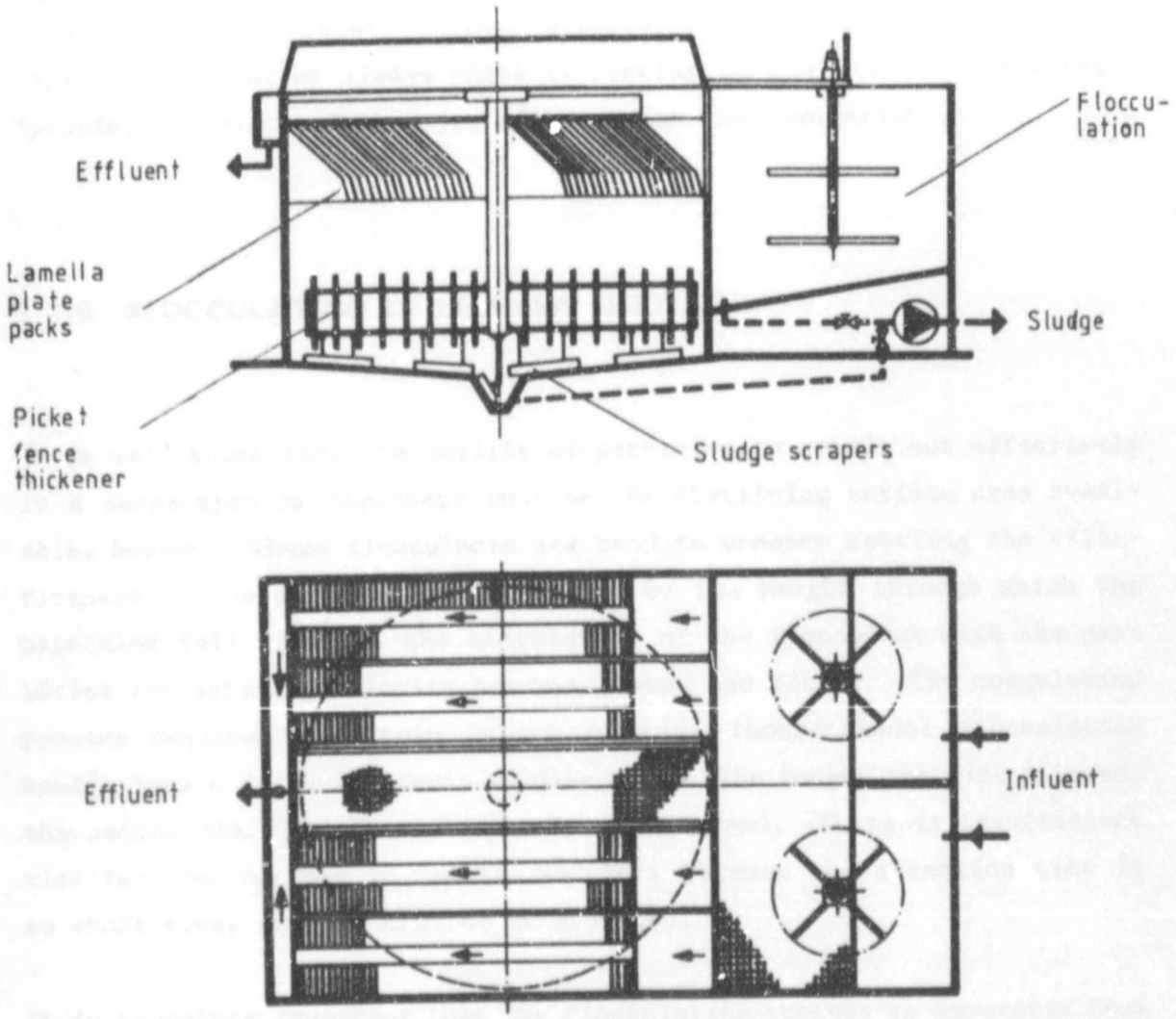


Figure 17. Compact lamella thickener.

For extremely high concentrations of suspended solids or in situations where a higher sludge concentration underflow is desired, a conventional thickener can be placed below the lamella unit. The conventional thickener has the same design as used for the underflow from a standard clarifier except that solid transport in this case is just a straight fall from the lamella plates.

Plate attachment is another important variable in sludge handling. It should be kept in mind that for some reason or another, sludge could block the lamella plates. In this event they will require some type of cleaning.

Author Barthelme Sven-Helmut
Name of thesis Up-rating Underground Sedimentation Tanks Subject To Hydraulic Overloading. 1987

PUBLISHER:

University of the Witwatersrand, Johannesburg
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