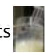
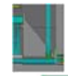
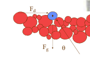

## Topics

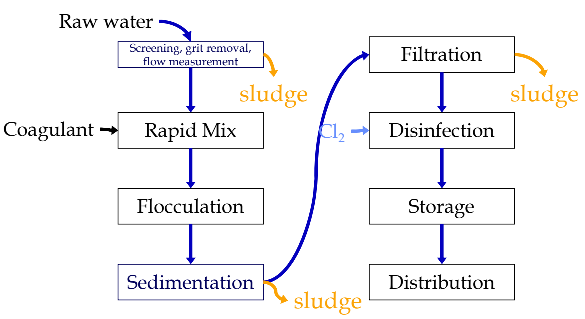
- Introduction 
- Capture velocity 
- Plate settlers 
- Floc rollup 
- Entrance region 
- Floc blankets 

- Floc resuspension 
- Floc Hoppers 
- Delivering flocs 

Extras!

- Minimum channel width 
- Scour velocity 

## Conventional Surface Water Treatment




## Evolution of Sedimentation

- Uses gravity to separate particles from water
- Often follows flocculation
- Traditionally a big tank where particles settle
- Combined processes including
  - Flocculation
  - Sedimentation
  - Sludge consolidation (reduce waste stream)

## Sedimentation: Particle Terminal Fall Velocity

$$\sum F = ma$$

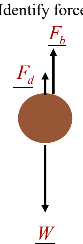
$$F_d + F_b - W = 0$$

$$W = \cancel{V}_{Floc}\rho_{Floc}g$$

$$F_b = \cancel{V}_{Floc}\rho_{H_2O}g$$

$$F_d = C_D A_{Floc}\rho_{H_2O}\frac{V_t^2}{2}$$

Identify forces




$\cancel{V}_{Floc}$ = particle volume

$A_{Floc}$ = particle projected cross sectional area

$\rho_{Floc}$ = particle density

$\rho_{H_2O}$ = water density

$g$ = acceleration due to gravity

$C_D$ = drag coefficient

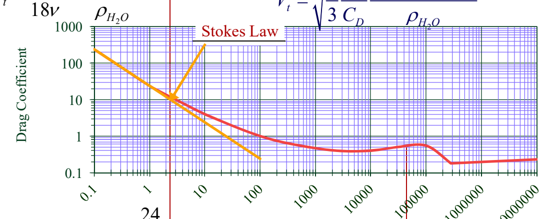
$V_t$ = particle terminal velocity

$$V_t = \sqrt{\frac{4}{3}\frac{gd}{C_D}\frac{(\rho_{Floc}-\rho_{H_2O})}{\rho_{H_2O}}}$$

## Drag Coefficient on a Sphere

$$V_t = \frac{d^2 g}{18\nu}\frac{\rho_{Floc}-\rho_{H_2O}}{\rho_{H_2O}}$$

$$V_t = \sqrt{\frac{4}{3}\frac{gd}{C_D}\frac{(\rho_{Floc}-\rho_{H_2O})}{\rho_{H_2O}}}$$

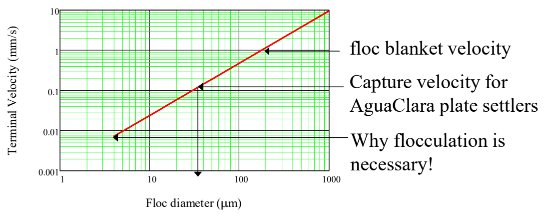



$C_d = \frac{24}{Re}$ laminar

$Re = \frac{V_t d}{\nu}$ turbulent

turbulent boundary

## Floc Terminal Velocity $V_t = \frac{gd^2}{18\nu_{H_2O}}\frac{\rho_{Floc}-\rho_{H_2O}}{\rho_{H_2O}}$

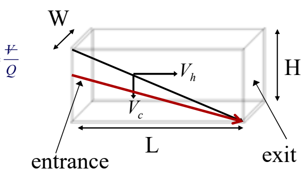



$$V_t = \frac{gd_0^2}{18\Phi\nu_{H_2O}}\frac{\rho_{Floc_0}-\rho_{H_2O}}{\rho_{H_2O}}\left(\frac{d}{d_0}\right)^{D_{Fractal}-1} \quad D_{Fractal} = 2.3 \text{ and } d_0 = 4\ \mu m$$

The model takes into account the changing density of flocs

## Horizontal Flow Sedimentation Tank

- How much time is required for water to pass through the tank? $\theta$ $\quad \theta = \frac{\forall}{Q}$
- How far must a particle fall to reach the bottom of the tank (worst case)? H
- How fast must the particle fall?




$$V_c = \frac{H}{\theta} = \frac{HQ}{\forall} = \frac{Q}{LW} = \frac{Q}{A_s}$$

Will it remove any smaller particles? Yes

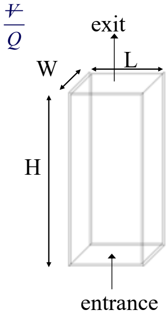
Settle Capture velocity: Property of the sedimentation tank. The slowest settling particle that the sedimentation tank captures reliably.

## Vertical Flow Sedimentation Tank

- How much time is required for water to pass through the tank? $\theta$ $\quad \theta = \frac{\forall}{Q}$
- How far must a particle fall relative to the fluid to not be carried out the exit? H
- How fast must the particle fall (relative to the fluid)?

$$V_c = \frac{H}{\theta} = \frac{HQ}{\forall} = \frac{Q}{LW} = \frac{Q}{A_s}$$

Will any smaller colloids be captured? Only if they collide and grow so they have a sed velocity > $V_c$




## Settle Capture Velocity Guidelines

- Based on tube settlers
  - 0.12 – 0.36 mm/s http://www.brentwoodprocess.com/tubesystems_main.html
- Based on Horizontal flow tanks
  - 0.24 to 0.72 mm/s **Surface Water Treatment for Communities in Developing Countries.** Christopher R. Schulz, Daniel A. Okun
- AguaClara adopted 0.12 mm/s in an effort to reduce effluent turbidity as much as possible because AguaClara wasn't using filters
- We'd like to know the performance curve. How does settled water turbidity change with the capture velocity? More research is needed!
- Save plastic by increasing the capture velocity

## Vertical Flow Sedimentation Tanks

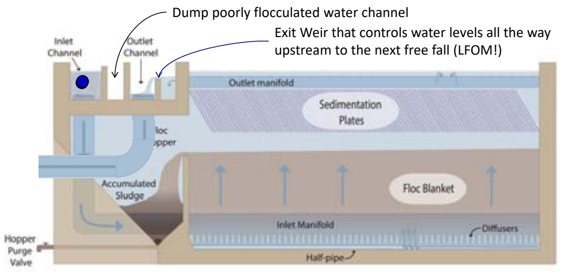
- Have lower velocities and hence turbulence levels might be lower (plan view area is larger than width x height
- Require **careful** attention to delivery and extraction of water
- AguaClara uses channels at one end of the tanks that are connected to pipes to deliver and extract water – other geometries would be possible

## Stagnant Water (or Ripe for Innovation?)

extra

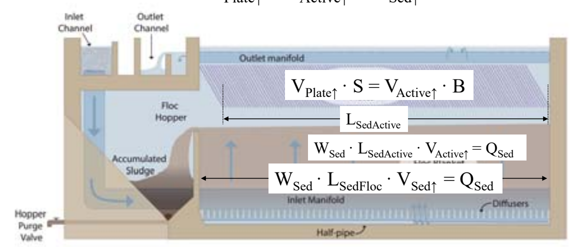
- State of the art in sedimentation…
  - Empirical guidelines
  - No understanding of scaling effects
- Last significant paper on tube settlers was published in 1978
- No significant revisions to Ten State Standards section on sedimentation in the past 30 years

## AguaClara Sedimentation Tank




## Sedimentation Tank Geometry: plate settlers have a lost triangle

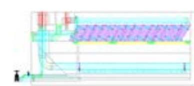
$$V_{Plate\uparrow} > V_{Active\uparrow} > V_{Sed\uparrow}$$

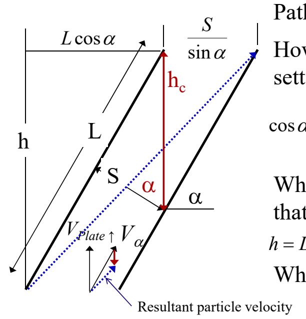



## 3 Steps to Sedimentation Success

- The floc must be able to **settle** unto the surface of a plate or tube settler
  - Settle capture velocity
- It must **slide** down the incline to reach the lower section of the sedimentation tank
  - Slide capture velocity
- Finally the floc must be **removed** from the lower section of the sedimentation tank
  - Floc hopper

## Settle Capture Velocity for Plate (and Tube) Settlers






Path for critical particle?

How far must particle settle to reach lower plate?

$$\cos\alpha = \frac{S}{h_c} \qquad h_c = \frac{S}{\cos\alpha}$$

What is total vertical distance that particle will travel?

$$h = L\sin\alpha$$

What is net vertical velocity?

$$V_{net} = V_{Plate\uparrow} - V_c$$

## Compare Times

Time to travel distance $h_c$ = Time to travel distance h

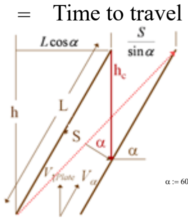
$$\frac{h_c}{V_c} = \frac{h}{V_{Plate\uparrow} - V_c}$$

$$\frac{S}{V_c\cos\alpha} = \frac{L\sin\alpha}{V_{Plate\uparrow} - V_c}$$

$$SV_{Plate\uparrow} - SV_c = L\sin\alpha V_c\cos\alpha$$

$$SV_{Plate\uparrow} = (L\sin\alpha\cos\alpha + S)V_c$$

$$V_c = \frac{SV_{Plate\uparrow}}{L\sin\alpha\cos\alpha + S} \qquad \boxed{\frac{V_{Plate\uparrow}}{V_c}} = 1 + \frac{L}{S}\cos\alpha\sin\alpha$$




$$h_c = \frac{S}{\cos\alpha}$$

$$h = L\sin\alpha$$

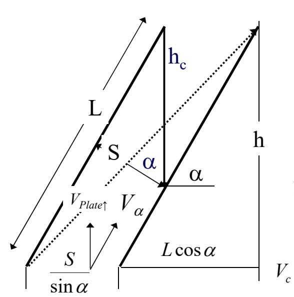
α := 60deg   sin(α)·cos(α) = 0.433

5 parameters… how do we choose?

## Comparison with Q/$A_s$

extra

$A_s$ is horizontal area over which particles can settle




$$Q = V_\alpha SW$$

$$\frac{V_{Plate\uparrow}}{V_\alpha} = \sin\alpha \qquad Q = \frac{V_{Plate\uparrow}SW}{\sin\alpha}$$

$$A = \left(L\cos\alpha + \frac{S}{\sin\alpha}\right)W$$

$$V_c = \frac{Q}{A} = \frac{V_{Plate\uparrow}SW}{\sin\alpha}\frac{1}{\left(L\cos\alpha + \frac{S}{\sin\alpha}\right)W}$$

$$V_c = \frac{V_{Plate\uparrow}S}{L\cos\alpha\sin\alpha + S}$$

Same answer!

## Equation for capture velocity

$$V_c = \frac{SV_{Plate\uparrow}}{L\sin\alpha\cos\alpha + S} \qquad V_{Plate\uparrow} = \frac{Q_{Plant}}{N_{Plate}W_{Plate}\frac{S}{\sin\alpha}}$$

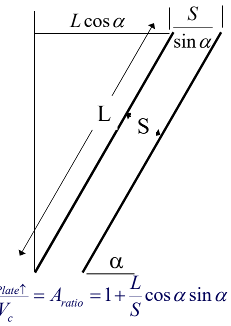
$$V_c = \frac{Q_{Plant}}{N_{Plate}W_{Plate}\left(L\cos\alpha + \frac{S}{\sin\alpha}\right)}$$

$$V_c = \frac{V_\alpha}{\left(\frac{L}{S}\cos\alpha + \frac{1}{\sin\alpha}\right)} \qquad L = \frac{S}{\cos\alpha}\left(\frac{V_\alpha}{V_c} - \frac{1}{\sin\alpha}\right)$$

## Performance ratio (conventional to plate/tube settlers)

extra

- Compare the area on which a particle can be removed
- Use a single plate settler to simplify the comparison




Conventional capture area

$$A_{conventional} = W\frac{S}{\sin\alpha}$$

Plate/tube capture area

$$A_{plate} = W\frac{S}{\sin\alpha} + WL\cos\alpha$$

$$\frac{V_{Plate\uparrow}}{V_c} = A_{ratio} = 1 + \frac{L}{S}\cos\alpha\sin\alpha$$

## Settle Capture Velocity Confusion

extra

$$\frac{V_{Plate\uparrow}}{V_c} = \frac{L}{S}\cos\alpha\sin\alpha + \sin^2\alpha$$

Surface Water Treatment for Communities in Developing Countries, Schulz and Okun (1984)

Consistent, but no one uses this geometry **except in labs**

Water Quality and Treatment (1999)

inconsistent

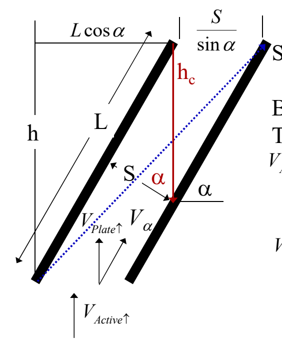
$$\frac{V_{Plate\uparrow}}{V_c} = \frac{L}{S}\cos\alpha\sin\alpha + 1$$

Weber-Shirk

Assume that the geometry is

## Thick Plate Settlers

extra




S Distance between plate settlers

B Center to center distance

T Plate settler thickness

$V_{Active\uparrow}$ Vertical velocity component **beneath** the plate settlers

$V_{Plate\uparrow}$ Vertical velocity component **between** the plate settlers

## Thick Plate Settlers

extra

$V_{Plate\uparrow} \cdot S = V_{Active\uparrow} \cdot B$ Mass Conservation

$B = S + T$ Geometry

$$V_{Plate\uparrow} = V_{Active\uparrow}\frac{S+T}{S}$$

$$V_c = \frac{SV_{Plate\uparrow}}{L\sin\alpha\cos\alpha + S}$$

$$V_c = \frac{S}{L\sin\alpha\cos\alpha + S}\left(V_{Active\uparrow}\frac{S+T}{S}\right)$$

$$B = \frac{L\sin\alpha\cos\alpha - T}{\frac{V_{Active\uparrow}}{V_c} - 1}$$

$$L = \frac{\boxed{B}\left(\frac{V_{Active\uparrow}}{V_c} - 1\right) + T}{\sin\alpha\cos\alpha}$$

$$L = \frac{\boxed{S}\left(\frac{V_{Active\uparrow}}{V_c} - 1\right) + T\frac{V_{Active\uparrow}}{V_c}}{\sin\alpha\cos\alpha}$$

## Plate Settler Design (AguaClara approach)

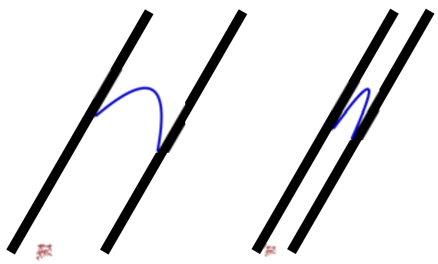
$$\frac{V_{Plate\uparrow}}{V_c} = 1 + \frac{L}{S}\cos\alpha\sin\alpha$$

- Upflow velocity (determines size of tanks) (1 mm/s) $V_{Sed\uparrow}$
  - If floc blanket is a goal then needs to be approximately 1 mm/s*
- Capture velocity (0.12 mm/s) $V_c$
  - target turbidity
  - particle size distribution after floc blanket Needs research!
- Plate angle (60 deg) $\alpha$
  - self cleaning (60 deg works well)
- Spacing (2.5 cm) $S$
  - Clogging (not a problem at 2.5 cm)
  - floc roll up: Will the floc slide down? (next topic in the notes!)
- Length of the plate settlers $L$
  - will be the parameter that we calculate

* Active research topic!

2011 AguaClara design

## Plate Settler Spacing Constraints Floc Rollup



## Floc Roll Up Solution Scheme: Another failure mode

- Find the velocity gradient next to the plate
- Find the fluid velocity at the center of the floc
- Find the terminal velocity of the floc down the plate (for the case of zero velocity fluid)
- Set those two velocities equal for the critical case of no movement
- Find the floc sedimentation velocity that can be captured given a plate spacing ($V_{Slide}$)

## Infinite Horizontal Plates: Boundary Conditions

extra

No slip condition

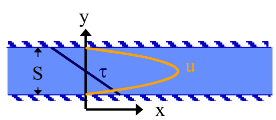
u = 0 at y = 0 and y = S

$$\cancel{\frac{y^2}{2}\frac{dp}{dx}} + \cancel{Ay} + B = \cancel{\mu u}$$

$$B = 0$$

$$\frac{S^2}{2}\frac{dp}{dx} + AS = 0 \qquad A = \frac{-S}{2}\frac{dp}{dx}$$

$$\frac{y^2}{2}\frac{dp}{dx} - \frac{S}{2}\frac{dp}{dx}y = \mu u$$




let $\frac{dp}{dx}$ be negative

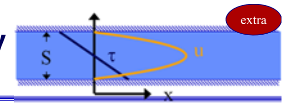
What can we learn about τ?

$$\mu\left(\frac{du}{dy}\right) = y\frac{dp}{dx} + A$$

$$\tau = \left(y - \frac{S}{2}\right)\frac{dp}{dx}$$

## Navier Stokes Flow between Plates

extra




$$u = \frac{y(y-S)}{2\mu}\frac{dp}{dx} \longrightarrow V_\alpha = \frac{q}{S} = \frac{1}{S}\int_0^S u\,dy = \frac{1}{S}\int_0^S\left(\left(\frac{y^2 - Sy}{2\mu}\right)\left(\frac{dp}{dx}\right)\right)dy$$

$$V_\alpha = -\frac{S^2}{12\mu}\frac{dp}{dx} \qquad \frac{dp}{dx} = -\frac{12\mu V_\alpha}{S^2}$$

Integrate to get average velocity

$$\mu\left(\frac{du}{dy}\right) = y\frac{dp}{dx} + A \qquad A = \frac{-S}{2}\frac{dp}{dx} \qquad \frac{du}{dy} = \frac{1}{\mu}\left(y - \frac{S}{2}\right)\frac{dp}{dx}$$

$$\left.\frac{du}{dy}\right|_{y=0} = -\frac{S}{2\mu}\frac{dp}{dx}$$

$V_\alpha$ is average velocity between plates

$$\left.\frac{du}{dy}\right|_{y=0} = \frac{6V_\alpha}{S}$$

We have velocity gradient as a function of average velocity

## Laminar Flow through Circular Tubes: Equations no gravity

extra

$$v_l = \frac{r^2 - R^2}{4\mu}\frac{dp}{dx}$$

R is radius of the tube

$$v_{max} = -\frac{R^2}{4\mu}\frac{dp}{dx}$$

Max velocity when $r = 0$

$$V = -\frac{R^2}{8\mu}\frac{dp}{dx}$$

Velocity distribution is paraboloid of revolution therefore average velocity ($V$) is 1/2 $v_{max}$

$$Q = -\frac{\pi R^4}{8\mu}\frac{dp}{dx}$$

$Q = VA = V\pi R^2$

## Velocity gradient at the wall

extra

$$v_\alpha = \frac{r^2 - R^2}{4\mu}\frac{dp}{dx} \qquad \frac{dp}{dx} = -\frac{8\mu Q}{\pi R^4}$$

$$v_\alpha = -2Q\frac{r^2 - R^2}{\pi R^4}$$

Where dp/dx is the pressure gradient in the direction of flow NOT due to changes in elevation

$$\left.\frac{dv_\alpha}{dr}\right|_{r=R} = \frac{-4Q}{\pi R^3}$$

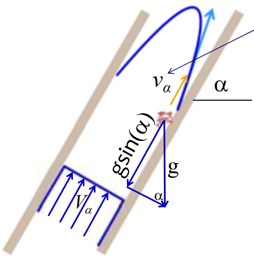
Tube geometry $\left.\frac{dv_\alpha}{dy}\right|_{y=0} = \frac{8V_\alpha}{D}$

Average velocity

Plate geometry $\left.\frac{dv_\alpha}{dy}\right|_{y=0} = \frac{6V_\alpha}{S}$

extra

## Floc Rollup Constraint




Velocity at center of floc

$$v_\alpha \approx \left(\frac{6V_\alpha}{S}\right)\frac{d}{2}$$ floc diameter

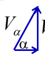
Linearized (plates)

$$v_\alpha \approx \frac{3V_{Plate\uparrow}d}{S\sin\alpha} \qquad V_\alpha = \frac{V_{Plate\uparrow}}{\sin\alpha}$$

Failure point (floc stationary)

Terminal velocity

$$v_\alpha = V_{t\alpha} = V_t \sin\alpha$$




$$V_\alpha = \frac{V_{Plate\uparrow}}{\sin\alpha} \qquad V_t\sin\alpha \approx \frac{3V_{Plate\uparrow}d}{S\sin\alpha} \qquad S \approx \frac{3V_{Plate\uparrow}d}{V_t\sin^2\alpha}$$

extra

## Spacing as a function of floc terminal velocity

$$S \approx \frac{3V_{Plate\uparrow}d}{V_t\sin^2\alpha}$$

But terminal velocity and floc diameter are related!

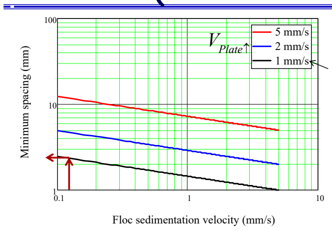
$$d = d_0\left(\frac{18V_t\Phi\nu_{H_2O}}{gd_0^2}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)^{\frac{1}{D_{Fractal}-1}}$$

Sedimentation velocity solved for diameter

$$S \approx \frac{3}{\sin^2\alpha}\frac{V_{Plate\uparrow}}{V_t}d_0\left(\frac{18V_t\Phi\nu_{H_2O}}{gd_0^2}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)^{\frac{1}{D_{Fractal}-1}}$$

This is the smallest spacing that will allow a floc with a given settling velocity to remain stationary on the slope (and not be carried upward)

## Minimum Plate Settler Spacing (function of Floc $V_t$)




Fewer, but longer plate settlers due to higher upflow velocity in the sed tank

Current AguaClara design for $V_{Plate\uparrow}$

$$S \approx \frac{3}{\sin^2\alpha}\frac{V_{Plate\uparrow}}{V_t}d_0\left(\frac{18V_t\Phi\nu_{H_2O}}{gd_0^2}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)^{\frac{1}{D_{Fractal}-1}}$$

What happens if a floc forms from organic matter rather than clay?

Plate settler spacing of 5 mm or larger should be adequate if the capture velocity is 0.12 mm/s

extra

## Slide Capture Velocity

$$V_{Slide} \approx V_{Plate\uparrow}\left[\left(\frac{3d_0}{S\sin^2\alpha}\right)^{D_{Fractal}-1}\left(\frac{18\Phi V_{Plate\uparrow}\nu_{H_2O}}{gd_0^2}\frac{\rho_{H_2O}}{\rho_{Floc_0}-\rho_{H_2O}}\right)\right]^{\frac{1}{D_{Fractal}-2}}$$

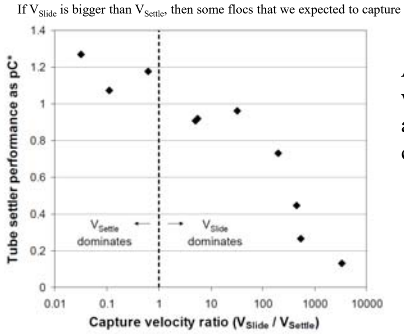
$V_{Slide}$ is the terminal sedimentation velocity ($V_t$) of the slowest-settling floc that can slide down an incline. Flocs with this terminal velocity (the slide velocity) will be held stationary on the incline because of a balance between gravitational forces and fluid drag. Flocs with a terminal velocity lower than $V_{Slide}$ will be carried out the top of the tube (i.e., "roll up") even if they settle onto the tube wall. Thus, the slide terminal velocity represents a constraint on the ability of plate settlers to capture flocs.

What happens if the primary particles are less dense? $V_{Slide}\uparrow$

extra

## Experimental Evidence that the Slide Capture Velocity Matters

If $V_{Slide}$ is bigger than $V_{Settle}$, then some flocs that we expected to capture will slide out the top




All experiments were performed at the same settle capture velocity

Floc Roll-up and its Implications for the Spacing of Inclined Settlers Matthew W. Hurst, Michael J. Adelman, Monroe L. Weber-Shirk, Tanya S. Cabrito, Cosme Somogyi, and Leonard W. Lion. Journal of Environmental Engineering, submitted (2012)

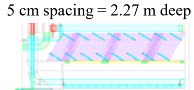
## Plate Settler Spacing effects

- Plate settler spacing has a strong influence on sedimentation tank depth
- Diminishing effect for small S
- Reduced spacing results in increased pressure drop through plate settlers*
- Which plate settlers will have more uniform flow distribution?

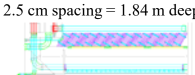
Small S

*proof coming up…

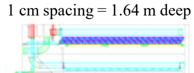
5 cm spacing = 2.27 m deep



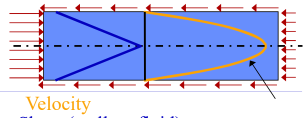
2.5 cm spacing = 1.84 m deep



1 cm spacing = 1.64 m deep



## Pressure drop (from head loss) through plate settlers



Velocity

Shear (wall on fluid)

$$2\tau LW = \Delta PWS \qquad \text{Force balance} \qquad \Delta P = \frac{2\tau L}{S}$$

$$\tau = \mu \frac{du}{dy} \qquad \text{Viscous shear} \qquad \tau = \mu\left(\frac{6V_{Plate\uparrow}}{S\sin\alpha}\right)$$

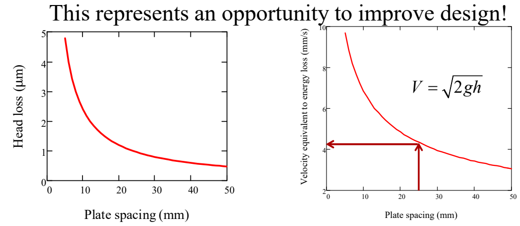
$$V_c = \frac{SV_{Plate\uparrow}}{L\sin\alpha\cos\alpha + S} \qquad \text{Change L to maintain capture velocity} \qquad L = \frac{S\left(\frac{V_{Plate\uparrow}}{V_c}-1\right)}{\sin\alpha\cos\alpha}$$

$$\Delta P = 2\mu\left(\frac{6V_{Plate\uparrow}}{S\sin^2\alpha\cos\alpha}\right)\left(\frac{V_{Plate\uparrow}}{V_c}-1\right) \qquad h_f = \frac{\Delta P}{\rho g}$$

## Plate Settler Head Loss

$$h_f = 2\frac{\mu}{\rho g}\left(\frac{6V_{Plate\uparrow}}{\boxed{S}\sin^2\alpha\cos\alpha}\right)\left(\frac{V_{Plate\uparrow}}{V_c}-1\right)$$

This represents an opportunity to improve design!




Head loss is tiny! We need some head loss to get reasonable flow distribution between (and within) plates. This lack of head loss may be one of the reasons for poor performance of full scale plate settlers. The velocity of any turbulent eddies or mean flow needs to be less than 4 mm/s to achieve uniform flow through plate settlers. The floc blanket will end up helping us here!

## Plate Settler Conclusions…

- Laminar flow
- Parabolic velocity profile is established
- Very low head loss (and thus flow distribution between plates is difficult to ensure)
- Designed to capture flocs with sedimentation velocities greater than the settle capture velocity
- Spacing determines the ability of the flocs to roll down the incline (slide capture velocity)

## Plate Settler Confusions…

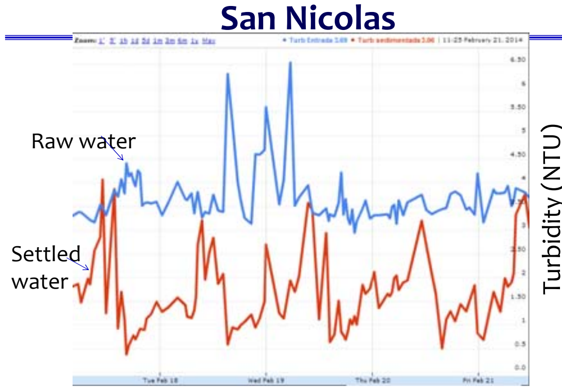
- We need a basis for choosing a settle capture velocity based on overall plant performance*
- Smaller spacings have diminishing returns in terms of sedimentation tank depth. So for now we are using 2.5 cm.
- Flocs made from natural organic matter may be less dense, more prone to floc rollup, and require larger spacing between plate settlers

* Predictive performance model for hydraulic flocculator design with polyaluminum chloride and aluminum sulfate coagulants. Karen A. Swetland, Monroe l. Weber-Shirk, and Leonard W. Lion. Journal of Environmental Engineering, submitted (2012)

## Floc Volcanoes

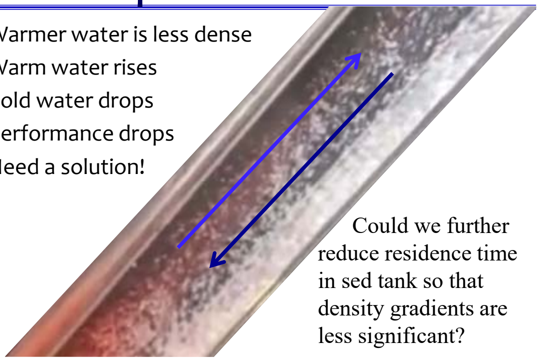
- Intermittent floc volcanoes in the sedimentation tanks at San Nicolas
- Flocs rise preferentially on one side of the sed tanks
- Raw water turbidity = 4 NTU
- PACl dose = 3.5 mg/L
- Settled water turbidity varies between 0.5 and 4 NTU
- Brainstorm! What is happening? Why does our plant do so poorly?

## Settled Turbidity at San Nicolas



## Plate Settler Problems: Temperature Gradients

- Warmer water is less dense
- Warm water rises
- Cold water drops
- Performance drops
- Need a solution!

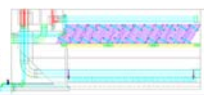


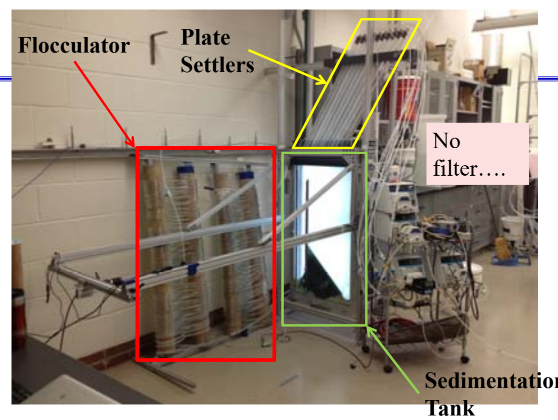
Could we further reduce residence time in sed tank so that density gradients are less significant?

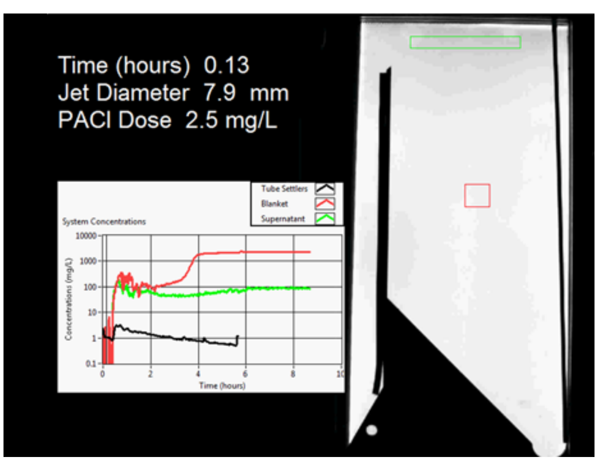
## Floc blankets reduce settled water turbidity

- Research required to determine optimal upflow velocity
- Floc blanket formation requires
  - All flocs be returned to the bottom of the sedimentation tank (plate settlers)
  - All settled flocs must be resuspended by incoming water (jet reverser)
- We don't have a model for floc blanket performance

## Floc Blanket Research






## Density of the floc blanket

$$\rho_{FB} = 0.687 C_{FlocSolids} + \rho_{H_2O}$$

Density of the floc blanket is approximately equal to the volume weighted average of the density of clay and water

$$m_{Clay} = C_{Clay} V_{FB} \qquad m_{H_2O} = \left(1 - \frac{C_{Clay}}{\rho_{Clay}}\right)\rho_{H_2O} V_{FB}$$

$$\rho_{FB} = \frac{m_{H_2O} + m_{Clay}}{V_{FB}}$$

$$\rho_{FB} = \left(1 - \frac{C_{Clay}}{\rho_{Clay}}\right)\rho_{H_2O} + C_{Clay}$$

$$\rho_{FB} = \left(1 - \frac{\rho_{H_2O}}{\rho_{Clay}}\right)C_{Clay} + \rho_{H_2O}$$

## Flocculation in a floc blanket due to shear from suspended flocs

$$\frac{h_{L_{FB}}}{H_{FB}} = \frac{\rho_{FB}-\rho_{H_2O}}{\rho_{H_2O}}$$

See filtration notes for derivation
Head loss in a fluidized bed

$$\frac{h_{L_{FB}}}{H_{FB}} = \left(\frac{1}{\rho_{H_2O}} - \frac{1}{\rho_{Clay}}\right) C_{Clay}$$

Density of fluidized bed

$$\rho_{FB} = \left(1-\frac{\rho_{H_2O}}{\rho_{Clay}}\right)C_{Clay} + \rho_{H_2O}$$

Porosity of floc blanket

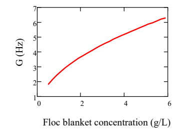
$$G=\sqrt{\frac{\varepsilon}{\nu}} \qquad \varepsilon = \frac{gh_L}{\theta} \qquad \theta=\frac{H_{FB}\phi_{FB}}{V_{Up}} \qquad \varepsilon = \frac{gV_{Up}}{\phi_{FB}}\frac{h_L}{H_{FB}}$$

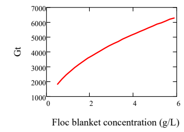
$$G=\sqrt{\frac{gV_{Up}}{\nu\phi_{FB}}\frac{h_L}{H_{FB}}} \qquad G=\sqrt{\frac{gV_{Up}}{\phi_{FB}\nu}\left(\frac{1}{\rho_{H_2O}}-\frac{1}{\rho_{Clay}}\right)C_{Clay}}$$

$\phi_{FB}$ is approximately = 1 and is a function of $C_{Clay}$

## Fluidized flocs provide a collision potential of a few thousand

$$G=\sqrt{\frac{gV_{Up}}{\phi_{FB}\nu}\left(\frac{1}{\rho_{H_2O}}-\frac{1}{\rho_{Clay}}\right)C_{Clay}} \qquad G\theta$$

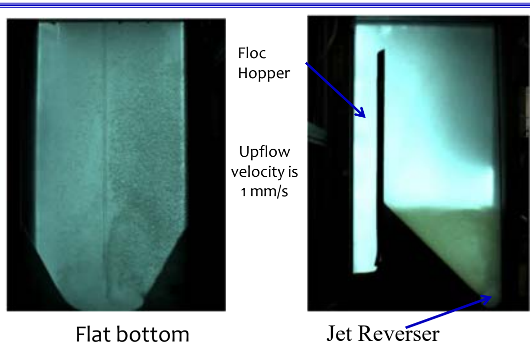


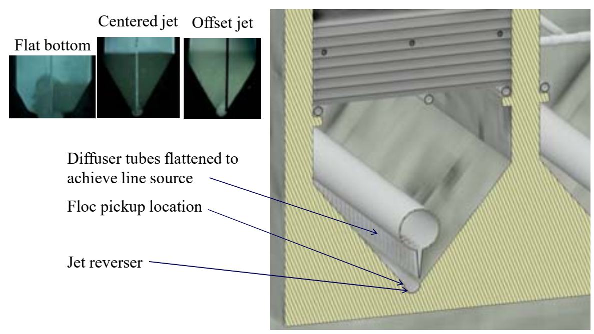

Assuming: 1 mm/s upflow velocity, 1000s residence time

How does a small Gθ cause a large reduction in turbidity?

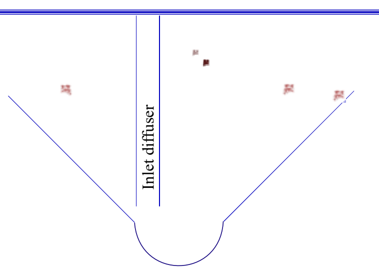
## Sedimentation Tank Bottom Geometry determines if floc blanket builds




## Floc Blanket Resuspender



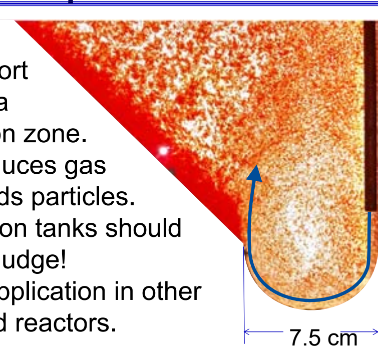

## Floc Blanket Resuspender




How does this animation violate the laws of physics?

## The jet reverser creates a vertical jet that resuspends settled flocs

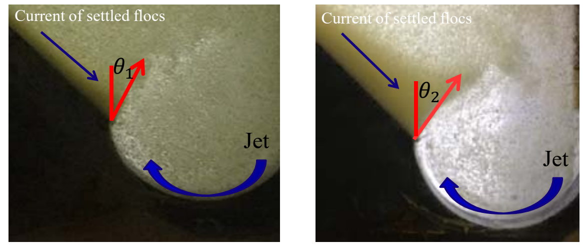
- All surfaces must transport particles to a resuspension zone.
- Sludge produces gas that suspends particles.
- Sedimentation tanks should have zero sludge!
- May have application in other fluidized bed reactors.



## Floc Blanket Resuspension

- All surfaces in the sed tank with a horizontal component must return settled flocs to a resuspension zone.
- Floc resuspension geometry works by having a flocculated water jet with a high vertical velocity component that returns settled flocs to the floc blanket

## The jet deflects more when it has less momentum




3.9 mm Jet Diameter

$\theta_1 < \theta_2$

8.9 mm Jet Diameter

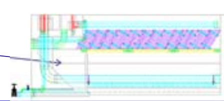
## Floc Blanket Conclusions

- Perhaps (low G) flocculation to provide rapid growth of the flocs coming from the flocculator
- Reduces the turbidity after sedimentation
- Requires a mechanism to keep the flocs suspended
  - Upflow velocity of approximately 1 mm/s
  - Settled flocs must return to a resuspension point where they are carried upward by a vertical jet

## Floc Blanket Questions

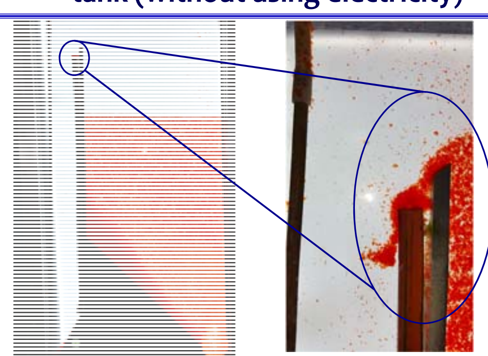
- How deep should it be?
- How do you design for flow rate variability including turning off a sedimentation tank?
- Can a settled floc blanket be resuspended?
- What is the optimal velocity of the incoming jet? (high velocity is better for resuspension and breaks more flocs)
- How will the operator observe the floc blanket?

## Floc Hopper Requirements



- Control the depth of the floc blanket
- Allow time for floc blanket overflow to concentrate (consolidate and dewater)
- Floc blanket solids concentration decreases as coagulant dose increases (2 g/L is reasonable estimate)
- Floc blanket flow into the floc hopper is a function of the mass flux of particles into the sed tank
- We need to characterize the consolidation rate of the flocs to optimize the floc hopper design

## Self-cleaning, sludge-free sedimentation tank (without using electricity)

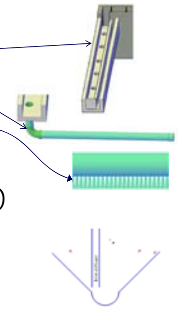


## Consolidation Questions

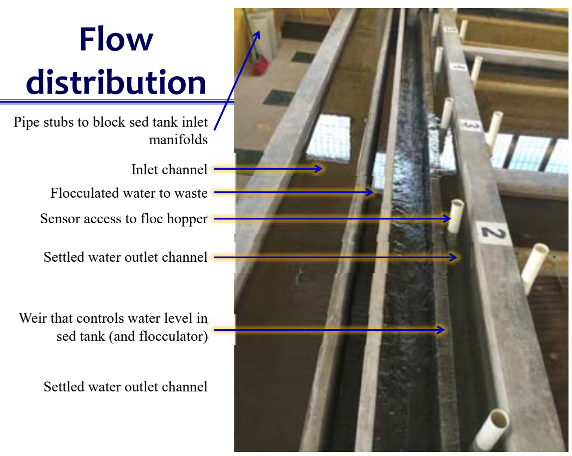
- AguaClara built our first successful floc hoppers at Atima in Honduras. We have much to learn about this design. (and they work!!!!)
- Floc consolidation in the floc hopper results in less water waste from the sedimentation tank.
- Zero sludge sed tank design reduces need to clean sedimentation tank
- We don't yet have a method to guide the operation of the floc hopper. How will the operator know if the floc hopper valve should be opened further?

## Delivering Flocs to the Sedimentation Tank

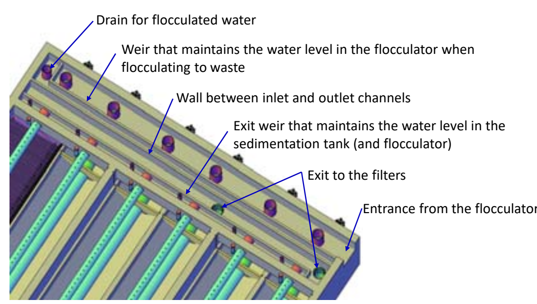
- It is necessary to design the inlet channel, inlet manifold, and diffusers so that they
  - Min V — Don't drop the flocs (0.15 m/s)
  - Max V — Distribute the water uniformly (section on manifold hydraulics)
  - Min V — Create a jet that resuspends settled flocs



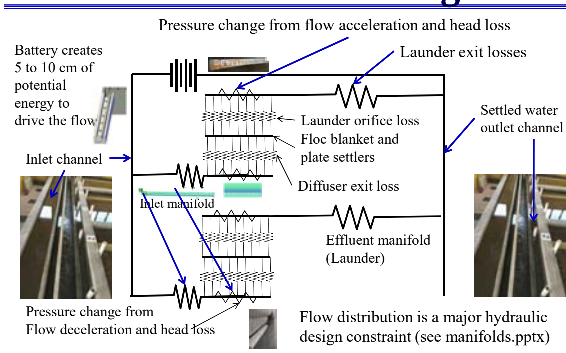
## Flow distribution



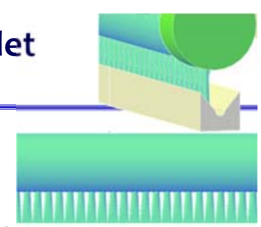

## Sedimentation tank controls




## Sed Tank as a Circuit: Flow Distribution Challenge

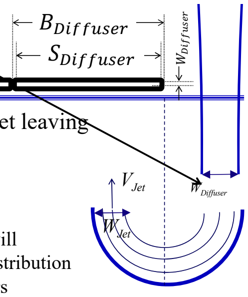



## Design of the Inlet Diffuser



- If a sedimentation tank has a length of 6 m, a width of 1 m, a depth of 2 m, an upflow velocity of 1 mm/s, and a diffuser spacing ($B_{Diffuser}$) of 5 cm…
- What is the port flow rate?
  (50 mm)(1 m)(1 mm/s) = 50 mL/s

## Diffuser Slot Width




Proposed constraint is head loss in jet leaving the jet reverser (perhaps 1 cm)

$$Q_{Diffuser} = V_{Jet} W_{Diffuser} S_{Diffuser} = V_{Sed} W_{Sed} B_{Diffuser}$$

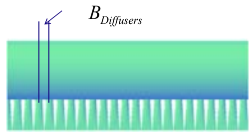
$$W_{Diffuser} = \frac{V_{Sed} W_{Sed} B_{Diffuser}}{V_{Jet} S_{Diffuser}}$$

$$h_{Jet} = \frac{V_{Jet}^2}{2g} \qquad V_{Jet} = \sqrt{2gh_{Jet}}$$

This head loss will improve flow distribution between diffusers

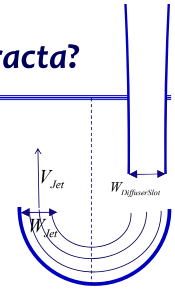
$$W_{Diffuser} = \frac{V_{Sed} W_{Sed} B_{Diffuser}}{S_{Diffuser}\sqrt{2gh_{Jet}}}$$

Minimum width to not exceed target head loss



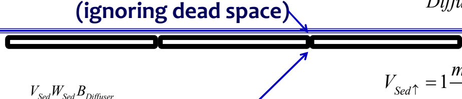

## Is there a *Vena Contracta*?

- *Vena contracta* is associated with a change in pressure that causes an acceleration of the fluid
- The change in pressure is supported by an enclosed flow space
- What is the energy of the water leaving the diffuser pipe?
- Prove that the flow can't contract!




## Diffuser Width
### (ignoring dead space)

$W_{Diffuser}$



$$W_{Diffuser} = \frac{V_{Sed} W_{Sed} B_{Diffuser}}{S_{Diffuser}\sqrt{2gh_{Jet}}}$$

$$B_{Diffuser} \approx S_{Diffuser}$$

$$V_{Sed\uparrow} = 1\frac{mm}{s}$$

$$h_{Jet} = 1cm$$

$$W_{Sed} = 1m$$

$W_{Diffuser} = 2.7mm$ Round up to 1/8” mold

$$V_{Jet} = \frac{V_{Sed} W_{Sed} B_{Diffuser}}{W_{Jet} S_{Diffuser}}$$

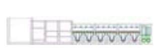
$V_{jet}$ is about 380 mm/s!

Compare jet velocity with head loss through plate settlers. The momentum of this jet must be attenuated through jet expansion and floc blanket.

## Sed Tank Inlet design Post 2014

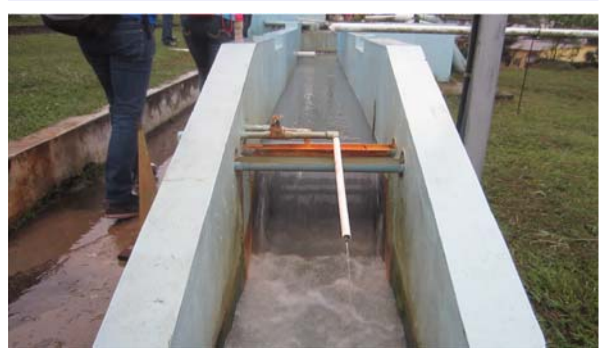
- Floc break up is likely not a constraint for delivery of water to the sedimentation tanks.
- Flow distribution will be the primary constraint
- Floc hopper needs design algorithms (highlighted by design of 1 L/s plant)

## Design Review



- Comparing designs
  - Pan-American Health Organization (CEPIS)
  - Superpulsator®
  - AguaClara
- What is good?
- What can be improved?
- What could (or did) fail?

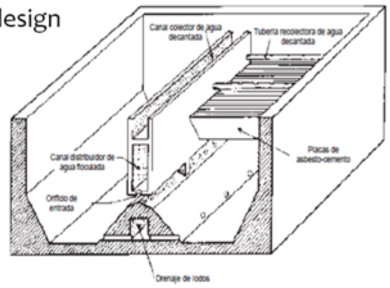
## Santa Rosa de Copan: CEPIS Plant Tour



## CEPIS/OPS designs – Vertical Flow

Centro Panamericano de Ingeniería Sanitaria y Ciencias del Ambiente CEPIS/OPS

- Critique this design
  - Orifices are small – will they break flocs?
  - Sludge will accumulate on the flat tank bottom
  - How are plate settlers suspended?
  - Inaccessible channels




## CEPIS Sed

- Plate settlers and effluent launders
- Launders must be perfectly level using this system
- Submerged launders are better

## AguaClara Evolution

- Ojojona - Vertical Flow Sedimentation (2 m)
- Tamara and Marcala - sloped bottoms of the tanks (2 m)
- 4 Comunidades - Inlet manifold below the sloped bottoms (1.55 m) and no elevated platforms
- Agalteca – Inlet manifold pipe with orifices

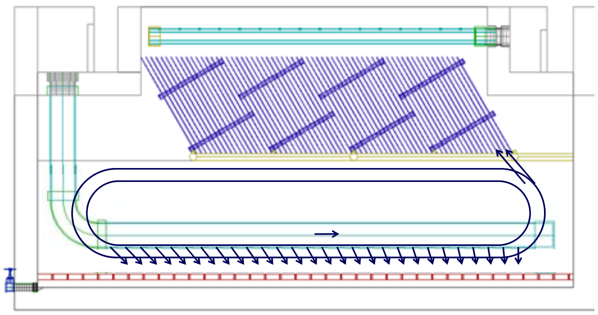
## Cuatro Comunidades

## Cuatro Comunidades Sludge

## Brainstorm

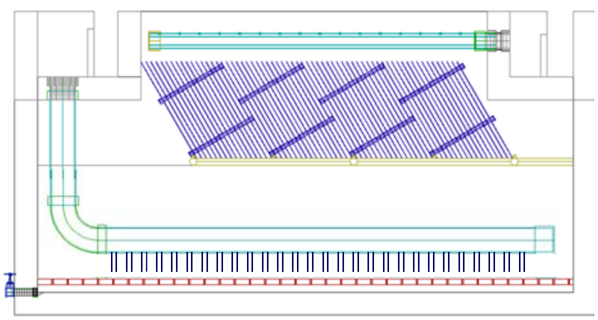
- Why is this problem occurring?
- How would you fix this problem?
- What concepts might be important in obtaining a solution?
- What are some of the other constraints that must be considered?

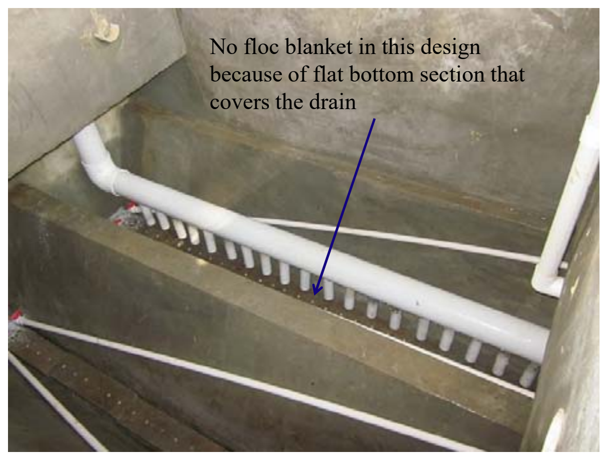
## Large scale circulation and poor performance



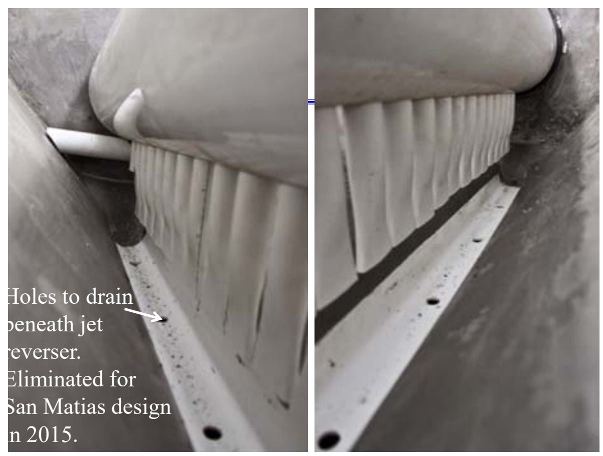
## Floc escape at Agalteca (2009)

## Flow Straightening Tubes to Eliminate Circulation

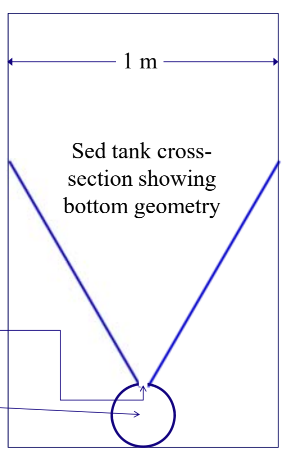





## Moroceli – Fall 2014



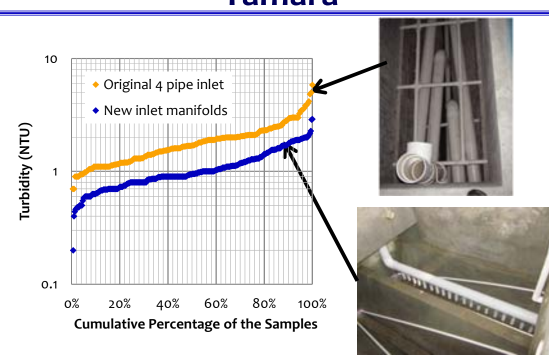

Identify the failure modes for this geometry



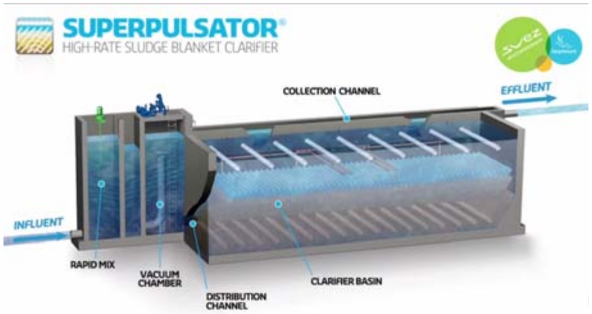

Slot that runs the length of the sed tank

Inlet manifold/drain

## Inlet Manifold Improvements at Tamara

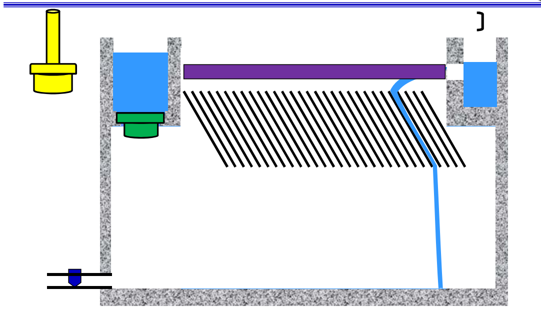


## Optimized Treatment? SUPERPULSATOR® Clarifier




https://www.youtube.com/watch?v=UNhygQov69Q Suez environment

## How can you drain and then refill a sedimentation tank?



## Questions

- Why do horizontal flow sedimentation tanks perform much worse than theory predicts? (eliminate inlet manifold?)
- Why do we use plate settlers?
- What is the failure mechanism for plate settlers for small spacing?
- What helps the flow divide evenly between the sed tanks? (hint… flow resistance)

## Sedimentation Conclusions

- 3 processes in one tank: flocculation, sedimentation, consolidation
- Eliminate the need for mechanized sludge removal by using hydraulic sludge removal
- Provide the operator with options for dumping poorly treated water
- Make the sedimentation tank easy to operate and maintain

## Sedimentation Conclusions

- Plate settlers make it possible to significantly reduce sedimentation tank area
- Reduced plate spacing for shallower tanks
- Floc blankets improve performance and provide a method to remove sludge
- Flow distribution is VERY important
- Hydraulic residence time of 24 minutes is sufficient for efficient sedimentation

## More sedimentation tank failure modes

- Buoyant flocs
  - Anaerobic sludge
  - Dissolved air flotation from compressed air in the transmission line or from increased temperature
- Collapsing floc blankets from bad bottom geometry
- Floc volcanoes from temperature increases
- Curtains on windows to block sunlight
- Slime from iron oxidizing bacteria