Spring 2010 AguaClara Clear Well Design Calculations - Updated April 28 2010

(needs fluid functions)

Target Input:

$Q_{Plant} := 6.3\frac{L}{s}$ Plant Flow Rate

$N_{Filter} := 2$ Number of Granular Filters

$T_{BW} := 10min$ Backwash Time Required is 5 to 10 minutes

$T_{Expansion} := 30\%$ By what percent do you want to expand the media during backwash

Condition Input:

$V_{FilterRate} := 1.4\frac{mm}{s}$ Water Treatment Filtration Rate

Filter Characteristics:

$D_{Sand} := .45mm$ Diameter of the Sand

$L_{Sand} := 45cm$ Depth of Sand Filter

$\varepsilon_{Sand} := .4$ Porosity of Sand Filter

$SG_{Sand} := 2.65$ Specific Gravity of Sand

$d_{60Sand} := .55mm$

$D_{Gravel} := 5mm$ Diameter of the Gravel

$L_{Gravel} := 25cm$ Depth of Gravel, Gravel used solely to hold the sand filter

$\varepsilon_{Gravel} := 0.7$ Porosity of Gravel

$SG_{Gravel} := 2.65$ Specific Gravity of Gravel

Piping/Structure Parameter:

$D_{BWOrifice} := 6in$ Diameter of Backwash orifice

$D_{ClearWell} := 6m$ Diameter of the Backwash Water Clear Well

$D_{Pipe} := 8in$ Diameter of Pipe

$\varepsilon_{Pipe} := .0001\,mm$ Roughness Coefficient for PVC Pipe

$L_{Pipe} := 3 \cdot 120\,cm$ Assumption Piping Required to connect the filter bed with Clear Well- 3 x Filter Bed Height

Misc. Parameters:

$K_{vc} := 0.62$ Vena Contracta Constant

$k := 5$ Kozeny Constant = 5 for most filtration conditions

Water Input:

$\rho_{Water} := 1000\,\frac{kg}{m^3}$ density of water

$\mu := 0.00089 \cdot \frac{newton \cdot sec}{m^2}$ dynamic viscosity of water

$\nu := 10^{-6}\,\frac{m^2}{s}$ kinematic viscosity of water

Calculations:

Filter Calculations:

$L_{Filter} := L_{Sand} + L_{Gravel}$ Total Filter Depth

$Q_{Filter} := \frac{Q_{Plant}}{N_{Filter}} = 3.15 \cdot \frac{L}{s}$ Flow Rate going through individual filter bed

$A_{Filter} := \frac{Q_{Filter}}{V_{FilterRate}} = 2.25\,m^2$ Area of Individual Bed

$$S_{Filter} := \sqrt{A_{Filter}} = 1.5\,m$$

Side of Filter

$$h_{Sand} := L_{Sand} \cdot 36 \cdot k \cdot \frac{(1-\varepsilon_{Sand})^2}{\varepsilon_{Sand}} \cdot \frac{V_{FilterRate} \cdot \nu}{g \cdot D_{Sand}^{\,2}} = 51.394 \cdot mm$$

HL from Sand Bed

Carmen Kozeny Equation

$$h_{Gravel} := L_{Gravel} \cdot 36 \cdot k \cdot \frac{(1-\varepsilon_{Gravel})^2}{\varepsilon_{Gravel}} \cdot \frac{V_{FilterRate} \cdot \nu}{g \cdot D_{Gravel}^{\,2}} = 0.033 \cdot mm$$

HL from Gravel Bed

$$HL_{Filtration} := h_{Sand} + h_{Gravel} = 0.051\,m$$

This is the total headloss occurring through the bed during filtration.

Clear Well Calculation (Conservative Approach: V of BW is 10x the V of Filtration):

$$V_{BW1} := 10 \cdot V_{FilterRate} = 14 \cdot \frac{mm}{s}$$

For conventional back washing design considerations, back wash velocity is usually ten times the filtration velocity.

$$Q_{BW1} := A_{Filter} \cdot V_{BW1} = 31.5 \cdot \frac{L}{s}$$

Minimum flow rate required for back wash

$$A_{Pipe} := \frac{D_{Pipe}^{\,2}}{4} \cdot \pi$$

Area of Pipes

$$V_{BWPipe} := \frac{Q_{BW1}}{A_{Pipe}}$$

Velocity in pipes during back wash

$$A_{BWOrifice} := \frac{D_{BWOrifice}^{\,2}}{4} \cdot \pi$$

Area of Back Wash Orifice

$$A_{ClearWell} := \frac{D_{ClearWell}^{2}}{4} \cdot \pi = 28.274\,m^{2}$$

Area of Clear Well

Calculation of Space Between:

$$Re_1 := \frac{4 \cdot Q_{BW1}}{\pi \cdot D_{Pipe} \cdot \nu} = 1.974 \times 10^{5}$$

Friction Factor for the Darcy Equation

$$f_1 := \begin{array}{|l} f_1 \leftarrow \dfrac{64}{Re_1} \quad \text{if } Re_1 < 2100 \\ f_1 \leftarrow \dfrac{.25}{\left(\log\left(\dfrac{\varepsilon_{Pipe}}{3.7 \cdot D_{Pipe}} + \dfrac{5.74}{Re_1^{.9}}\right)\right)^{2}} \quad \text{if } Re_1 > 2100 \end{array}$$

Calculations of Headlosses:

Darcy Equation

$$HL_{Pipe} := \frac{8}{g \cdot \pi^{2}} \cdot L_{Pipe} \cdot \frac{f_1 \cdot Q_{BW1}^{2}}{D_{Pipe}^{5}} = 0.013\,m$$

HL from Pipe

$$HL_{Orifice} := \frac{\left(\dfrac{Q_{BW1}}{K_{vc} \cdot A_{BWOrifice}}\right)^{2}}{2 \cdot g} = 0.396\,m$$

HL from Orifice is also the distance that the orifice must be away from the bottom of the Clear Well Tank

$$H_{MinClearWell1} := HL_{Orifice}$$

Minimum Distance Required between Backwash Orifice located at the bottom of filter and the bottom of the Clear Well to achieve backwash velocity until the well is used out.

Okun, p. 161

HL through Expanded Sand

$$HL_{ExpSand} := L_{Sand} \cdot \left(1 - \varepsilon_{Sand}\right) \cdot \left(SG_{Sand} - 1\right) = 0.446\,m$$

HL through Expanded Gravel

$$HL_{ExpGravel} := L_{Gravel} \cdot \left(1 - \varepsilon_{Gravel}\right) \cdot \left(SG_{Gravel} - 1\right) = 0.124\,m$$

$$HL_{TotalExp} := HL_{ExpSand} + HL_{ExpGravel} = 0.569\,m$$

Total Expansion HL

$$HL_{Elbow} := \frac{V_{BW1}^{\;2}}{2\cdot g}\cdot.014\cdot30 = 4.197\times10^{-4}\cdot cm$$

HL Through Elbow

$$K_{Expansion} := \left(1 - \frac{A_{Pipe}}{A_{Filter}}\right)^2$$

"Minor Losses in Pipes Manual" p. 5

$$HL_{Expansion} := \frac{V_{BWPipe}^{\;2}}{2\cdot g}\cdot K_{Expansion} = 0.047\,m$$

HL of Sudden Expansion of flow from pipe to filter

$$D_{Filter} := \left(\frac{A_{Filter}}{\pi}\right)^{\left(\frac{1}{2}\right)}$$

Diameter of the Filter, if it was round. Needed to determine Kcontraction which is depend on ratio of diameters and velocity of flow

$$Ratio_D := \frac{D_{ClearWell}}{D_{Pipe}} = 29.528$$

$$K_{Contraction} := 0.485$$

When D1/D2= infinity and v2 is ~1m/s

$$HL_{Contraction} := \frac{V_{BWPipe}^{\;2}}{2\cdot g}\cdot K_{Contraction} = 0.023\,m$$

HL of Sudden Contraction of flow from clear well to pipes

$$H_{Gutter} := 1.1\left[\left(1 + T_{Expansion}\right)\cdot L_{Filter}\right] = 1.001\,m$$

Height of the Gutter based on how high the bed expands so sand does not wash away

$$SpaceBetween := HL_{Orifice} + HL_{Pipe} + HL_{Contraction} + HL_{Expansion} + HL_{TotalExp} + 2\cdot HL_{Elbow} = 1.$$

Space between top of the filter bed and the bottom of the clear well, is equal to all the headloss between those two levels.

$$H_{BW1} := \left| \begin{array}{l} t \leftarrow 1s \\ H_{BW1} \leftarrow SpaceBetween \\ \text{while } t < T_{BW} \\ \quad \left| \begin{array}{l} t \leftarrow t + 1s \\ H_{BW1} \leftarrow H_{BW1} + 1s \dfrac{K_{vc} \cdot A_{BWOrifice} \cdot \sqrt{2 \cdot g \cdot H_{BW1}}}{A_{ClearWell}} \end{array} \right. \\ \text{return } H_{BW1} \end{array} \right.$$

Height of the water needed in the clear well for the back wash to last 10 min

$$H_{BW1} = 2.415\,m$$

$$H_{ClearWell} := H_{BW1} - SpaceBetween = 1.367\,m$$

Height of Clear Well Required if back wash flow is not controlled. More water comes out in the beginning than necessary due to higher head when the well is full.

$$H_{ClearWellControl} := \frac{Q_{BW1} \cdot T_{BW}}{A_{ClearWell}} = 0.668\,m$$

Height of Clear Well Required if flow is controlled via valve and operator to produce the minimum flow rate required for back wash velocity.

$$H_{FilterControl1} := H_{ClearWellControl} + SpaceBetween + HL_{Filtration} + \left(HL_{Orifice} + HL_{Pipe} + HL_{Contraction} + HL_{Expansion} + 2 \cdot HL_{Elbow}\right) + H_{Gutter}$$

$$H_{Filter1} := H_{ClearWell} + SpaceBetween + HL_{Filtration} + H_{Gutter} + HL_{Orifice} + HL_{Pipe} + HL_{Contraction} + HL_{Expansion} + 2 \cdot HL_{Elbow}$$

The height of the filter walls must be high enough to in enable the recharging of the Clear Well so it must be include the height of:
1) The Clear Well itself
2) Take into account the space between the bottom of the Clear Well and the top of the unexpanded filter bed
3) Take into account the headloss which occurs during the recharging process.

Clear Well Calculation (Weber Equation Approach):

I. Determination of composite filter properties:

$$L_{filter} := L_{Sand} + L_{Gravel} = 0.7\,m$$

Depth of Filter

$$V_{Sand} := \left(1 - \varepsilon_{Sand}\right) \cdot S_{Filter}^{2} \cdot L_{Sand} = 607.5\,L$$

Volume of Sand, subtracting the pore space in the filter bed

$\rho_{Sand} := SG_{Sand} \cdot \rho_{Water}$ — Density of Sand

$M_{Sand} := V_{Sand} \cdot \rho_{Sand} = 1.61 \times 10^{3}\,kg$ — Mass of Sand

$\omega_{water} := \rho_{Water} \cdot g = 62.428 \cdot \frac{lbf}{ft^{3}}$ — Specific Weight of Water

$\omega_{msand} := \frac{M_{Sand}}{V_{Sand}} \cdot g = 2.599 \times 10^{4} \frac{kg}{m^{2} \cdot s^{2}}$ — Specific Weight of Sand

II. Determination of Ke and ne:

All below equations used are from Walter J. Weber, Jr., <u>Physicochemical Processes for Water Quality Control</u>, pages 172-173. *Note that* ω_m *applies only to sand.*

$$V_f = \frac{0.00381(d_{60})^{1.82}\{\omega_s(\omega_m - \omega_s)\}^{0.94}}{\mu^{0.88}}$$

Empiricial Formula - No Units!

$$V_{fsand} := \frac{0.00381 \cdot \left(\frac{d_{60Sand}}{mm}\right)^{1.82} \cdot \left[\frac{\omega_{water}}{\frac{lbf}{ft^{3}}} \cdot \left(\frac{\omega_{msand}}{\frac{lbf}{ft^{3}}} - \frac{\omega_{water}}{\frac{lbf}{ft^{3}}}\right)\right]^{.94}}{\left(\frac{\mu}{\frac{gm}{m \cdot s}}\right)^{.88}} \frac{gpm}{ft^{2}} = 3.669 \cdot \frac{mm}{s}$$

$$Re_0 := \frac{\rho_{Water} \cdot 8.45 \cdot V_{fsand} \cdot d_{60Sand}}{\mu} = 19.162$$

$$Re_0 = \frac{\rho_l \cdot 8.45 \cdot V_f \cdot d_{60}}{\mu}$$

$$Re_f := \frac{Re_0}{8.45} = 2.268$$

$$Re_0 = 8.45 \cdot Re_f$$

$$n_e := 4.45 \cdot \left(8.45 \cdot Re_f\right)^{-0.1} = 3.312$$

$$n_e = 4.45(8.45 \cdot Re_f)^{-0.1}$$

$$K_e := \frac{V_{fsand}}{\varepsilon_{Sand}^{n_e}} = 0.076\,\frac{m}{s}$$

$$K_e = \frac{V_f}{\varepsilon^{n_e}}$$

III. Fluidization Velocities required for Expansion:

All below equations used are from Walter J. Weber, Jr., <u>Physicochemical Processes for Water Quality Control</u>, pages 172-173.

Minimum Fluidization Velocity: $V_{fsand} = 3.669 \cdot \frac{mm}{s}$

Fluidization Velocity for X Expansion:

$$\frac{D_e}{D} = \frac{(1-\varepsilon)}{(1-\bar{\varepsilon})}$$

$$D := L_{filter}$$

$$D_e := \left(1 + T_{Expansion}\right) \cdot D = 91 \cdot cm$$

$$\bar{\varepsilon} = 1 - \frac{D}{D_e}(1-\varepsilon)$$

$$\varepsilon_{Exp} := 1 - \frac{D}{D_e} \cdot \left(1 - \varepsilon_{Sand}\right) = 0.538$$

$$V = K_e(\bar{\varepsilon})^{n_e}$$

$$V_{BW2} := K_e \cdot \varepsilon_{Exp}^{\;n_e} = 9.822 \cdot \frac{mm}{s}$$

Velocity Required to Fluidize Bed

IV. Determine Filtration Unit Dimensions:

$$Q_{BW2} := A_{Filter} \cdot V_{BW2} = 22.099 \cdot \frac{L}{s}$$

Minimum flow rate required for back wash

$$V_{BW2Pipe} := \frac{Q_{BW2}}{A_{Pipe}}$$

Velocity in pipes

$$HL_{Orifice2} := \frac{\left(\frac{Q_{BW2}}{K_{vc} \cdot A_{BWOrifice}}\right)^2}{2 \cdot g} = 0.195\,m$$

HL from Orifice is the distance that the orifice must be away from the bottom of the Clear Well Tank

Calculation of Space Between filter bed and clear well, and Headlosses:

$$Re_2 := \frac{4 \cdot Q_{BW2}}{\pi \cdot D_{Pipe} \cdot \nu} = 1.385 \times 10^5$$

$$f_2 := \left| \begin{array}{l} f_2 \leftarrow \dfrac{64}{Re_1} \;\; \text{if } Re_1 < 2100 \\ f_2 \leftarrow \dfrac{.25}{\left(\log\left(\dfrac{\varepsilon_{Pipe}}{3.7 \cdot D_{Pipe}} + \dfrac{5.74}{Re_1^{.9}}\right)\right)^2} \;\; \text{if } Re_1 > 2100 \end{array} \right.$$

$$HL_{Pipe2} := \frac{8}{g \cdot \pi^2} \cdot L_{Pipe} \cdot \frac{f_1 \cdot Q_{BW2}^2}{D_{Pipe}^5} = 6.534 \times 10^{-3}\,m$$

HL from Pipe

$$HL_{Elbow2} := \frac{V_{BW2}^2}{2 \cdot g} \cdot .014 \cdot 30 = 2.066 \times 10^{-4} \cdot cm$$

HL Through Elbow, there are 2

"Minor Losses in Pipes" Manual, p 5

$$HL_{Expansion2} := \frac{V_{BW2Pipe}^2}{2 \cdot g} \cdot K_{Expansion} = 0.023\,m$$

HL of Sudden Expansion of flo\
from pipe to filter

$$HL_{Contraction2} := \frac{V_{BW2Pipe}^2}{2 \cdot g} \cdot K_{Contraction} = 0.011\,m$$

HL of Sudden Contraction of flo\
from clear well to pipes

$$SpaceBetween_2 := HL_{Orifice2} + HL_{Pipe2} + HL_{Contraction2} + HL_{Expansion2} + HL_{TotalExp} + 2 \cdot HL_{Elbo}$$

Space between top of the filter bed and the bottom of the clear well, is equal to all the headloss between those two levels.

$$
H_{BW2} := \left|\begin{array}{l} t \leftarrow 1s \\ H_{BW2} \leftarrow SpaceBetween_2 \\ \text{while } t < T_{BW} \\ \quad \left|\begin{array}{l} t \leftarrow t + 1s \\ H_{BW2} \leftarrow H_{BW2} + 1s\dfrac{K_{vc}\cdot A_{BWOrifice}\cdot\sqrt{2\cdot g\cdot H_{BW2}}}{A_{ClearWell}} \end{array}\right. \\ \text{return } H_{BW2} \end{array}\right.
$$

Height of the water needed in the clear well for the back wash to last 10 min

$$H_{BW2} = 2.038\,m$$

$$H_{ClearWell2} := H_{BW2} - SpaceBetween_2 = 1.233\,m$$

Height of Clear Well Required if back wash flow is not controlled. More water comes out in the beginning than necessary due to higher head when the well is full.

$$H_{ClearWellControl2} := \frac{Q_{BW2}\cdot T_{BW}}{A_{ClearWell}} = 0.469\,m$$

Height of Clear Well Required if flow is controlled via valve and operator to produce the minimum flow rate required for back wash velocity.

$$H_{FilterControl2} := H_{ClearWellControl2} + SpaceBetween_2 + HL_{Filtration} + H_{Gutter} = 2.326\,m$$

$$H_{Filter2} := H_{ClearWellControl2} + SpaceBetween_2 + HL_{Filtration} + \left(HL_{Orifice2} + HL_{Pipe2} + HL_{Contraction2} + HL_{Expansion2} + 2\cdot HL_{Elbow2}\right) + H_{Gutter}$$

The height of the filter walls must be high enough to in enable the recharging of the Clear Well so it must be include the height of:
1) The Clear Well itself
2) Take into account the space between the bottom of the Clear Well and the top of the unexpanded filter bed
3) Take into account the headloss which occurs during the recharging process.

Design Parameters:

Conservative Design:

Dimensions for Square Filter:

The individual filtration unit has a square surface area with a side of: $S_{Filter} = 1.5\,m$

The Filtration unit's walls are of the following heights depending on whether or not the entire backwash process is controlled by a skilled operator:

$H_{Filter1} =$

$H_{FilterControl1} = 1.768\,m$

Dimensions for Cylinder Shaped Clear Well:

The Clear Well Storage Unit is cylindrical and has a diameter of : $D_{ClearWell} = 6\,m$

The Clear Well Storage Unit has the following height depending on whether or not the entire backwash process is controlled by a skilled operator:

$H_{ClearWell} = 1.367\,m$

$H_{ClearWellControl} = 0.668\,m$

Weber Equation Design:

Dimensions for Square Filter:

The individual filtration unit has a square surface area with a side of: $S_{Filter} = 1.5\,m$

The Filtration unit's walls are of the following heights depending on whether or not the entire backwash process is controlled by a skilled operator:

$H_{Filter2} = 1.325\,m$

$H_{FilterControl2} = 2.326\,m$

Dimensions for Cylinder Shaped Clear Well:

The Clear Well Storage Unit is cylindrical and has a diameter of : $D_{ClearWell} = 6\,m$

The Clear Well Storage Unit has the following height depending on whether or not the entire backwash process is controlled by a skilled operator:

$H_{ClearWell2} = 1.233\,m$

$H_{ClearWellControl2} = 0.469\,m$

	Conservative	Empirical
Filter Square Side	1.5m	1.5m
Filter Height	3.95m	2.56m
Clear Well Diameter	6m	6m
Clear Well Height	1.37m	1.23m

Conclusions

1) Our design based on simple hydraulics will work. However, it is a very large filter and will not be sustainable economically. The material cost for construction will be too high.

2) The design based on the empirical Weber equation (instead of the conservative approach) is smaller and less expensive. However, the validity of the empirical equations is not yet certain. Therefore testing needs to be done in bench and pilot scale models.

3) If the empirical equations are valid, then we can change parts of the design, by changing the sand parameters in the following equation:

$$V_f = \frac{0.00381(d_{60})^{1.82}\{\omega_s(\omega_m - \omega_s)\}^{0.94}}{\mu^{0.88}}$$

We can lower BW velocity by lowering the d60 and specific weight of the media.

048 m

w

ow

$w2 = 0.805$ m