Cornell University

CEE 4561

Spring 2016

Team Baffle Final Report

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February 26, 2016

Introduction

Over the course of January 9th to January 23rd, 2016, Josiah Hinterberger, Tanvi Naidu, and William Pennock, known as Team Baffle, engaged in several projects and studies to help improve AguaClara flocculation design and operation in Honduras. These activities are described in the following sections.

Minor Loss of a Baffle

When the AguaClara team traveled to Honduras in January of 2016, one of the goals for the team was to better measure the head loss attributable to a single baffle in an AguaClara vertical hydraulic flocculator. This had been recognized as a need on the 2015 trip, and the 2016 trip was seen as an opportunity to gather this information.

The head loss due to a baffle is mathematically characterized by the coefficient K_e in the equation

$$h_e = K_e \frac{V^2}{2g}, \tag{1}$$

where h_e is the head loss due to an expansion (in this case as a result of a baffle), V is the average velocity of the flow before it reaches the baffle, and g is the gravitational constant (Granger, 1995). Equation 1 is useful in flocculator design, because AguaClara flocculators are designed in order to achieve a minimum value of the product $\theta\bar{\varepsilon}^{1/3}$, where θ is the hydraulic residence time of the flocculator and $\bar{\varepsilon}$ is the mean energy dissipation rate (spatially and temporally) of the flocculator. The mean energy dissipation rate, $\bar{\varepsilon}$, is found for a flocculator according to

$$\bar{\varepsilon} = \frac{g h_e}{\theta}, \tag{2}$$

and so the calculation of head loss due to baffles by Equation 1 is essential to designing AguaClara baffled hydraulic flocculators.

In applying Equation 1 for flocculator design, there has remained some uncertainty about the selection of K_e for baffles. As a first estimate, it is possible to calculate the coefficient K_e from first principles, using the equation for a sudden expansion, which is derived from the conservation of mass and of momentum as

$$K_e = \left(\frac{A_{\text{Out}}}{A_{\text{In}}} - 1 \right)^2, \tag{3}$$

where A_{In} is the area of the constricted flow (due to the vena contracta formed in the flow after the bend) and A_{Out} is the unconstricted area of the flow (Granger, 1995). The value of A_{Out} can be taken as 1, and the value of A_{In} can be taken as the contraction coefficient of a 180° bend. A 180° bend can be considered two 90° bends as a first approximation (Haarhoff, 1998). Using the contraction coefficient of a sluice gate (90$\circ$ bend) of 0.61, the value of A_{In} can be estimated as 0.37 (Kim, 2007). Using this value results in a theoretical prediction of K_e of 2.85.

Values in the literature vary considerably from this estimate. Haarhoff (1998) predicted the value of K_e to be 2.0. He noted, however, that measured values tend to be higher (Haarhoff, 1998). Kawamura (1991) found the value to be between 3.2 and 3.5, and the textbook *Water Treatment Principles and Design* (1985) recommends a design value of 3.2. Given the range in variables, it was determined that a study by the AguaClara team was warranted.

Baffle Bending Strength

Previous AguaClara flocculator designs operated under a mean energy dissipation rate constraint to prevent flocs from breaking up, but as recent research has demonstrated that concern to be a much smaller issue than previously thought, investigations are being made into the feasibility of greatly increasing the energy dissipation rate by increasing head loss and decreasing residence time (see Equation 2).

This would permit the use of a smaller and less expensive flocculator, however it would also add stresses to the baffle material that go far beyond its previously tested stress levels. The head losses over a single baffle in the plants visited were on the order of a millimetres or less, and proposals for new head loss amounts were on the order of up to a centimeter. Verifying that excessive deformation, bending, or fracture did not occur under conditions of high head loss was necessary so that flocculator design could evolve further.

Ojojona

One of the AguaClara plants visited by the team in Honduras, the plant serving Ojojona, no longer had a fully-functioning flocculator or sedimentation tank. Lack of maintenance had allowed both to fall into a state of disrepair. Among other issues, the plant was built entirely with non-community money at the outset, and popular support for the water project had not grown with time enough to ensure the plant's upkeep.

A partner organization to AguaClara, Agua Para el Pueblo (APP), is in dialogue with the community of Ojojona about the situation at the treatment plant, and the members of team baffle recorded data about the state of the flocculator in order to better assist APP in potentially improving the quality of water in Ojojona.

Methods

Minor Loss of a Single Baffle:

Experimentally determining the minor loss coefficient K_e of a single baffle was done by measuring the variables upon which K_e depends: velocity, head loss, and number of baffles (Equation 1).

Velocity was not measured directly, because no velocity-measuring equipment was available, instead the equation for continuity,

$$V = \frac{Q}{WS}, \tag{4}$$

where Q is the flow rate, W is the width of the flocculator, and S is the spacing between baffles, was used to obtain velocity from flow and width measurements. Unevenness in the concrete, especially near both ends, interfered with accurate measurement, so channel width was taken as the average of several measurements near the center of the flocculator. Flow rate values were obtained by measuring the height of water in the Linear Flow Orifice Meter (LFOM), a perforated pipe which roughly provides a linear relation between flow and measurable head above the its base. Flow (Q) was calculated by multiplying the maximum flow capacity of the plant (Q_{max}) by the ratio of measured water on the LFOM (h_{test}) to height of water when plant is running at full capacity (h_{max}).

$$Q = Q_{max} \frac{h_{test}}{h_{max}} \tag{5}$$

Utilizing this Q and the measured widths, S and W, in Equation 1 gave the velocity values for the calculations. These values were treated as estimates since the LFOM is itself an approximation.

Head loss was measured using a flexible tube water level across the entirety of the flocculator, from entrance to exit, as well as across channels or sections of channels. Oscillation in the water level due to vibrations in the plant, parallax (since level could not be perpendicularly observed), as well as occasional bubbles in the water level tube made error in these measurements an important consideration. Due to this, after measuring head loss across the entire flocculator, head loss of a single flocculator channel or section was measured and multiplied by the number of channels or sections as a check. If the head loss across the full flocculator were far removed from the single-section estimate, the water level tube was checked for bubbles and the measurement was repeated. Head loss across the orifices between flocculator channels was also recorded, however the values were so small that measurement error rendered their legitimacy suspect.

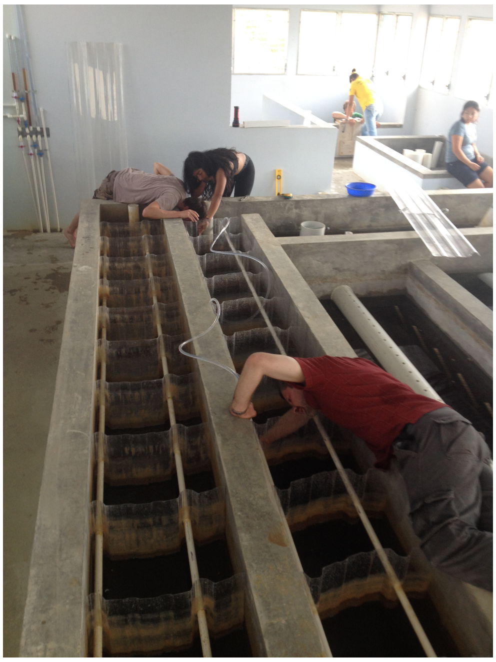

Figure 1: The team measured sections of the flocculator with a water level to check if the full flocculator value obtained was reasonable.

The number of baffles was initially obtained by counting the baffles visible from the surface, using a flashlight to find submerged baffles. Due to concerns about the accuracy of the recorded number of baffles, the number of baffles was later obtained from each plant's schematics.

Baffle Bending Strength:

A full sheet of flocculator baffle material was tested by fabricating a mount that inserted into the end of the flocculator in San Matías. The mount was made of another sheet of baffle material held against the wall of the final flocculator channel and two clamps to attach to the test sheet.

Clamping the test sheet in place on the mount blocked nearly all of the flow area at the flocculator exit, causing substantial head loss to develop across the test specimen, reaching steady state at 3 cm of head loss and causing deflection of the sheet.

Results and Discussion

Minor Loss of a Single Baffle

Following the procedure described previously, head loss across baffles was measured at all four plants studied. This included both measurements of head loss across channels (or portions of channels) as well as measurements of head loss across the entire flocculator. The results of these measurements are reported in Table 1.

Table 1: Head Loss Measurements and Flow Rates for Plants Studied

Plant Name	**Flow Rate** (LFOM Estimate)	**Head Loss Measurements**			
		ΔH Channel	Baffles per Channel	ΔH Flocculator	Total Baffles
San Nicolás	25.6 L/s	1.6 cm	9*	8.8 cm	42*
Jesús de Otoro	12 L/s	0.7 cm	11	3.0 cm	43
Morocelí	11.8 L/s	0.8 cm	12**	3.3 cm	49
San Matías	5.25 L/s	0.1 cm	14**	3.4 cm	53

* In San Nicolas, the first baffle was not considered in measurements because it was covered with a board while measurements were being taken.

**In Morocelí and San Matías, the tube used as a water level was not long enough to span the entire channel, so 12 and 14 baffles were considered as opposed to the full channel for each.

The data from Table 1 was then used along with plant measurements to obtain velocities for the flow through the flocculators from Equation 4 and the resulting head loss coefficient from Equation 1. In calculating the head loss coefficient with Equation 1, the resulting value of K_e was normalized by the number of baffles plus the number of orifices (for the entire flocculator calculations), since orifices are sized to have roughly the same minor loss as baffles according to Equation 3. Thus, the calculation had the form of

$$K_{\mathrm{B}} = \frac{2gh}{N_{\mathrm{B}}V^2}, \tag{6}$$

where N_{B} is the number of baffles plus the number of orifices. The results of these calculations are shown in Table 2.

Table 2: Flocculator Geometry and Calculated Velocity and K values

Plant Name	**Channel Width**	**Baffle Spacing**	**Orifices**	**Velocity**	**K_{B}** Channel	**K_{B}** Entire
San Nicolás	53.5 cm	52.5 cm	3	0.09 m/s	3.78	4.62
Jesús de Otoro	53.5 cm	36.5 cm	3	0.06 m/s	3.31	3.39
Morocelí	47.8 cm	36.1 cm	1	0.07 m/s	2.82	2.80
San Matías	50.0 cm	20 cm	1	0.05 m/s	5.08	4.48

As can be seen in Table 2, the value for K_{B} showed considerable variation and was in several cases higher than expected (San Matías and San Nicolás). This variation was not anticipated, given the similar geometry of the plants, and neither were the high values, based on the predictions given in the Introduction section. One possibility to account for these discrepancies was a significant effect of major losses in the flocculators.

The major loss for each flocculator was estimated by using the $\mathtt{h_{frect}}$ function in the AguaClara Fluids Functions Mathcad file, which evaluates the head loss in a rectangular channel. In applying this function, the absolute roughness was taken to be the weighted average (based on the proportion of H to W) of the absolute roughness of concrete (0.3 mm) and the absolute roughness of plastic (0.005 mm) as given by Engineering Toolbox. The length for the friction loss was estimated as the length of a single baffle times the number of spaces between the baffles. The results of these calculations are shown in Table 3.

Table 3: Flocculator K values Corrected for Friction Losses

Plant Name	**Baffle Length,** L	**Absolute Roughness** ε	**Channel Major Loss**	**Entire Major Loss**	**Adjusted** $\mathbf{K_B}$ **Channel**	**Adjusted** $\mathbf{K_B}$ **Entire**
San Nicolás	1.064 m	0.15 mm	0.21 mm	0.86 mm	3.73	4.57
Jesús de Otoro	1.314 m	0.12 mm	0.17 mm	0.68 mm	3.22	3.54
Morocelí	1.505 m	0.13 mm	0.28 mm	1.09 mm	2.73	2.76
San Matías	1.543 m	0.09 mm	0.32 mm	1.19 mm	4.92	4.41

As can be seen in Table 3, accounting for major loss only slightly lowered the measured values of K_{B}. Another thought was that measurement errors might be responsible for the different readings. Based on this, an error of 2 mm was put into each of the corrected calculations and compared to the calculation without the error. This was based on the assumption that the measurement error should be likely no more than 2 mm from the actual measurement. The percent differences found in this sensitivity analysis were never greater than 6 percent, suggesting that the likely measurement error also did not account for the variability in the data. Based on these findings, the value of 3.54 from Jesús de Otoro most closely agrees with Kawamura (1991), and the value of 2.76 from Morocelí most closely agrees with the calculation made using Equation 3. The data remain inconclusive.

Baffle-bending Test:

The baffle material did not experience significant bending even when subjected to a head loss of 3.0 cm, which is higher than the suggested value for head loss for this study, i.e. 1.0 cm.

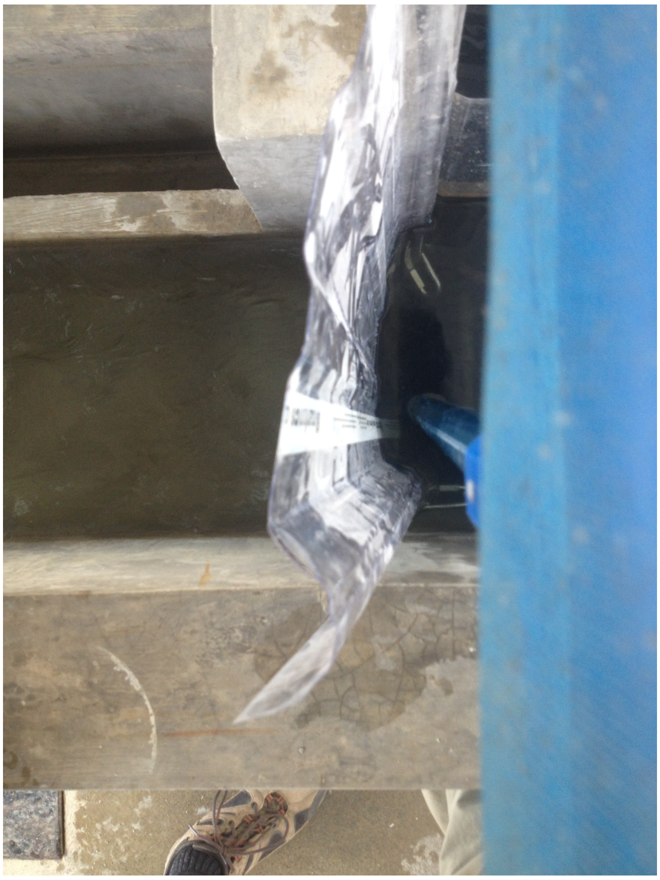

Figure 2: The test baffle installed in the mount at the flocculator's end. 3 cm of head loss and the minimal resulting deflection is shown.

Ojojona

The measurements taken at Ojojona were as follows:

Vertical Flocculator

- Length: 297 cm
- Width: 81.5 cm
- Exit Depth: 224 cm (water level of 197 cm at the time)
- Entrance Depth: 228 cm (water level of 201 cm at the time)
- 36 baffles currently in place

Horizontal Flocculator (2 channels, never used)

- Length: 515 cm
- Width: 100 cm (channel connecting has 14 cm wide)

- Depth: 63 cm
- Walls of channels were 10.5 cm thick

Conclusions and Recommendations

Baffle bending-strength test:

The test demonstarted that the baffle material, i.e., polycarbonate sheet, experiences very minor bending with up to to 3.0 cm of head loss built up on one side. The goal of this study was to test whether the flocculator modules could withstand up to 1.0 cm of head loss per baffle, which would provide insight on whether or not the lower baffles could be extended to within distance S from the water surface, where S represents the horizontal distance between baffles. The results of this test thus show that the baffle material can withstand far more than the suggested amount of head loss, indicating that the design modifications could easily be feasible.

Extending the lower baffle height in the manner described above will be helpful to AguaClara projects because it will help maintain the same head loss through the flocculator even in periods of low flow, since the lower baffles will then act as a submerged weir. This could also then help reduce the formation of 'dead zones' above the lower baffles, which are regions of low shear, circulating fluid with very low collision potential for floc formation. This translates to an overall more efficient use of space in the plants. Likewise, the strength of the baffle material indicates that the average energy dissipation rate through AguaClara flocculators can be raised, allowing them to be smaller and more cost-effective. Before this is done, further study should be conducted on other possible failure mechanisms of flocculator modules subjected to higher pressure differences.

Minor Loss of a Single Baffle

Based on the measurements taken at the newer plants in Honduras, the minor loss value of a single baffle seems to be higher than expected. The theoretical value, 2.85, is lower than all except one calculated value of K_{B}. The calculated values range from 2.76 to 4.57. This would suggest that the theoretical value used for calculations in AguaClara plant designs might be too low, and may need to be re-evaluated. However, there are some potentially significant sources of error in the data obtained and hence the calculations. Firstly, the oscillations of the water height in the flocculator made it difficult to obtain accurate head loss measurements, which were usually on the order of millimetres. Using the entire flocculator measurements (more baffles, higher head loss), as opposed to the channel measurements, lessened the influence of measurement error, because the measurement error was a smaller percentage of the total measurement for these larger measurements, but did not eliminate the error completely. Secondly the flow rate values were fairly rough estimations since they were from LFOM, an error that is compounded since the V term, derived from flow rate, is second order. Finally, measuring very small head loss values using a water level was subject to human error which could have affected the data, particularly due to parallax and in finding the meniscus. Further studies and calculations with a more accurate method to measure flow rate will provide a better understanding of the true value of minor loss associated with a single baffle. Without further measurements, it is difficult to make a clear recommendation. Tentatively, 3.5 seems to be in agreement with literature, so it may be a suitable value.

Ojojona

The provided measurements make possible the design of a retrofit of the currently malfunctioning flocculator in Ojojona. Along with fixing the coagulant dosing system, a new set of modules in a potentially new configuration could vastly improve flocculation performance. In order for this to have the desired effect, changes will need to be made to the sedimentation tanks, as well. Likewise, systemic changes are needed in the operation and maintenance of the plant to make its performance suitable for drinking water treatment. Additionally, it will need more sources to achieve a flow rate that can adequately supply Ojojona with water. Provided there is funding to make these changes, these improvements to the plant in Ojojona could be highly visible in the tourist center of Ojojona, and might serve to promote the adoption of AguaClara plants in other parts of Honduras.

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