StaRS Filter Sand Segregation, Spring 2015

Vicki Chou, Caitlin McKinley, Sharon Zhang

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Abstract

The StaRS Sand Segregation team's goal for the Spring 2015 semester was to quantify under what conditions sand segregation occurs by changing the H_{filter}/D ratio, expansion ratio, and sand size ratio. Using a water recycle system coupled with the filter experimental apparatus, experiments ran in the Fall 2014 semester were replicated and extended to gather more sand segregation data. Experiments were performed using two filters of different diameters and sand segregation was observed visually and by photo analysis software. Different parameters of the sand filter were tested, including the backwash velocity, the addition of a sloped surface, and the sand bed height, to see when sand segregation occurs and for the optimal backwash conditions that does not result in segregation. Results from testing and photo analysis suggest that with a sand size ratio of 1.4 (a sand size range of standard sieve no. 35-45), segregation occurs regardless of the H_{filter}/D ratio and expansion ratio. The addition of a sloped surface, however, yielded more mixing within the sand bed, providing a possible solution to preventing segregation during backwash.

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Introduction

An effective backwash is essential for a sand filter to function properly, but the design parameters that facilitate an effective backwash are not well understood. Fluidization of the sand bed is essential in removing particles during backwash, and it is governed by the distribution of sand sizes and the backwash velocity. Finding the right sand sizes and size distribution is needed to prevent segregation of the sand bed after backwash. A better backwash would impact the efficiency of the stacked rapid sand filters by more thoroughly cleaning the bed, allowing the sand grains to collect more colloids during each filtration run. An improved understanding of fluidization can also potentially save water by decreasing backwash time while still achieving sufficient backwash quality.

Literature Review

Sand Particle Size Ratio

Sand segregation occurs when sand separates at different levels in a fluidized sand bed. The particles can either separate when larger particles move to the bottom of a sand bed and smaller particles are on top, or when higher density particles end up at the bottom and lower density particles end up at the top of a sand bed. The ratio of the largest sand diameter to the smallest sand diameter in a sand bed is expressed by , d_R, the size ratio. This ratio affects the degree to which sand segregation occurs. According to Đuriš, et al. (2013) at a size ratio of less than 2, the maximum mixing intensity is at a porosity (ε) of about 0.7 in the fluidized bed during backwash, meaning that the composition of the sand at any part of the bed is about the same. Good mixing can be achieved by a ration of less than 1.5.

Minimum Fluidization Velocities of Multi-component Solid Mixtures

The expressions for predicting minimum fluidization velocities of multi-component solid mixtures in terms of mono-component values for the velocity and the bed voidage at incipient fluidization are discussed are listed below in Table 1.

$\overline{U_{mf}}$: The average of minimum fluidization velocities.

U_{mfi}: The minimum fluidization velocities of species *i.*

X_i : The volume fraction of the *i*th solid species

Table 1. Expressions for the prediction of minimum fluidization velocities of multi-component mixtures

Regime	Mixing state	Size-different mixture	Density-different mixture
Laminar flow	Mixed	$\frac{1}{\sqrt{\overline{U_{mf}}}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}}$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i \, U_{mf\,i}$
	Segregated	$\frac{1}{\overline{U_{mf}}} = \sum_{i=1}^{n} \left[\frac{X_i}{U_{mf\,i}} \right]$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i \, U_{mf\,i}$
Turbulent flow	Mixed	$\frac{1}{\overline{U_{mf}}^{2}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}^{2}}$	$\overline{U_{mf}}^{2} = \sum_{i=1}^{n} U_{mf\,i}^{2} \, X_i$
	Segregated	$\frac{1}{\overline{U_{mf}}^{2}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}^{2}}$	$\overline{U_{mf}}^{2} = \sum_{i=1}^{n} U_{mf\,i}^{2} \, X_i$

In turbulent flow or mixed or segregated, density-different mixtures the averaging procedure for mean fluidization velocity are the same. For both segregated and completely mixed beds the averaging procedures for size-different mixtures are also the same in turbulent flow.

For density-different solid mixtures, the mean fluidization velocities for a mixed bed and a segregated bed are the same in laminar flow. But, for size-different solid mixtures, the mean fluidization velocities for a mixed bed and a segregated bed are different in laminar flow.

The formula

$$\frac{1}{\sqrt{\overline{U_{mf}}}} = \sum_{i=1}^{n} \frac{x_i}{U_{mfi}}$$

is applicable if the sizes of the constituent species are not significantly different so that the volume contraction is relatively insignificant. The prediction of $\overline{U_{mf}}$ is significantly affected by the level of mixing; different values of $\overline{U_{mf}}$ will be obtained for segregated and mixed beds in laminar conditions. In this case, a mixed bed will possess a higher $\overline{U_{mf}}$ as compared to a segregated bed. On the other hand, if the size difference is large, the concomitant volume change of mixing will be significant. The $\overline{U_{mf}}$ of a mixed bed in this case could be smaller than that of a segregated bed. The reason for this is the fact that the lower porosity will cause a higher pressure drop in the mixed bed, which is ultimately reflected by the lower values of $\overline{U_{mf}}$ (Asif, 2013).

Measurement of particle size and size distribution by fluidization

A fluidization dependent method of particle size distribution measurement was developed in this paper by Obata, et al. (1982). This graphical method, which is theoretically derived in the paper, simply requires measurement of the pressure drop across the bed and of superficial velocity which can be calculated from flow rate, which is the independent variable in the experiments this method uses. The method was verified by measurements made by separating particles into multiple grades by particle size. As a result of comparing the size distributions found with their method and with screening, the researchers confirmed the validity of the method. They found that the size distributions observed for binary and the tertiary mixtures were in good agreement with those obtained by microscopic measurement. The researchers graphed pressure drop against superficial velocity to calculate particle size distribution, as seen in Figure 1.The need for further investigation into the characteristics of multi-component particles was acknowledged.

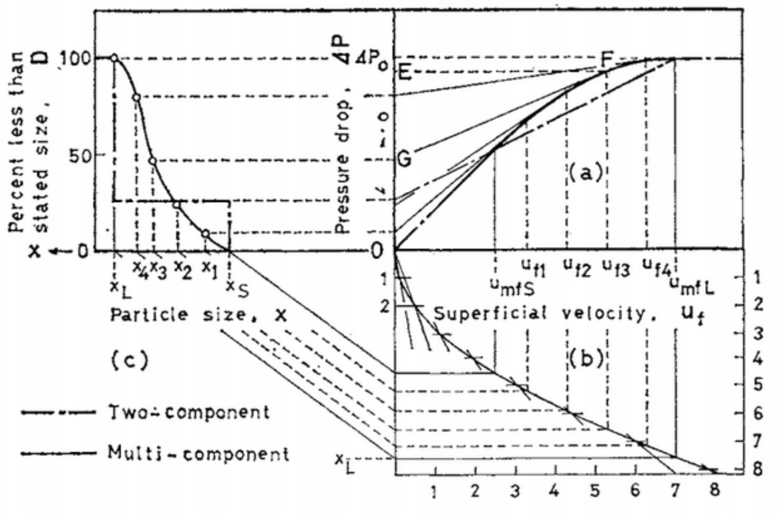

Figure 1: Construction to determine particle size distributions by plot of ΔP vs.u_f

The equations the author derived in this paper are listed below.

For two-component particles, the velocity is

$$u_s = \frac{u_{mfS}}{\left(1-\frac{u_{mfS}}{u_{mfL}}\right)\left(\frac{W_S}{W_O}\right)+\left(\frac{u_{mfS}}{u_{mfL}}\right)} = \left(\frac{W_S}{W_O}u_{mfS}+\frac{W_L}{W_O}u_{mfL}\right)^{-1}$$

u_s—The apparent minimum fluidizing velocity

u_{mfS}—Velocity of beginning of fluidization

u_{mfL}—Velocity of complete fluidization

W_S—The weights of the fine (small) particles

W_L—The weights of the coarse (large) particles

W_O—The weights of overall particles

For multi-component particles, the velocity is

$$u_s = (\Sigma W_i / W_O u_{mfi})^{-1}$$

u_{mfi}—The harmonic mean of the minimum fluidizing velocity

W_i—The weights of components i.

Air Dynamics Through Filter Media During Air Scour

Increasing the collision of particles can achieve a more thorough cleaning than using water fluidization alone to backwash filters, which can be limited low grain contact and abrasion. Air scour can improve the effectiveness of backwashing. This is related to the abrasion between sand grains. The effective stresses between grains and the magnitude of their relative movement affect the intensity of abrasion. A less fluidized bed can be achieved with a higher effective stress at low water flow rates. A more fluidized bed can be achieved by a greater movement at increasing water flow rates. This suggests that for cleaning effectiveness when using air scour there exists an optimum air-water rate combination (Hewitt and Amirtharajah, 1984).

Previous Work

The previous team was called the “StaRS Backwash Team” and mainly focused on finding the right sand size and distribution to stop the sand bed from segregating. The team listed three main specifications, namely that the largest sieve size to smallest sieve size ratio should be less than or equal to 1.5, no particle should be smaller than 0.2 mm, and the sand bed must fluidize with a nominal velocity of 11 mm/s. The team performed three trials of segregation testing by using two different colored sands for sand sizes of 30-35 for one color and 35-40 for another color. Experimental results indicated that above a threshold backwash velocity of 15 mm/s, the sand would segregated, but below this threshold velocity the sand would remain mixed. A density test was also performed to determine whether the segregation was actually caused by different sand particle sizes and not by different sand particle densities. The results indicated that the two sands, the natural laboratory sand and the colored craft sand, had the same density, and therefore segregation was due to the size difference. This semester’s initial research will be based on these previous results.

Methods

Water Recycle System & Experimental Setup

In order to fix the bubble issue faced by last semester’s team, a water recycle system was implemented as a part of the experimental apparatus. The recycle system consists of a 50 L bucket, which acts like a water source tank, and 12.7 mm (½”) tubing connecting the tank to a centrifugal pump and then to the bottom of the filter. Instead of the effluent water leaving through the sink, it is recycled back into the water tank, allowing reuse of the water. The water flow through the pump is regulated by a ball valve. By using the water tank, the water can equilibrate with the atmosphere, getting rid of any bubbles that may come from water straight from the tap. This new water recycle system setup is shown as a schematic in Figure 2 and in reality in Figure 3 below.

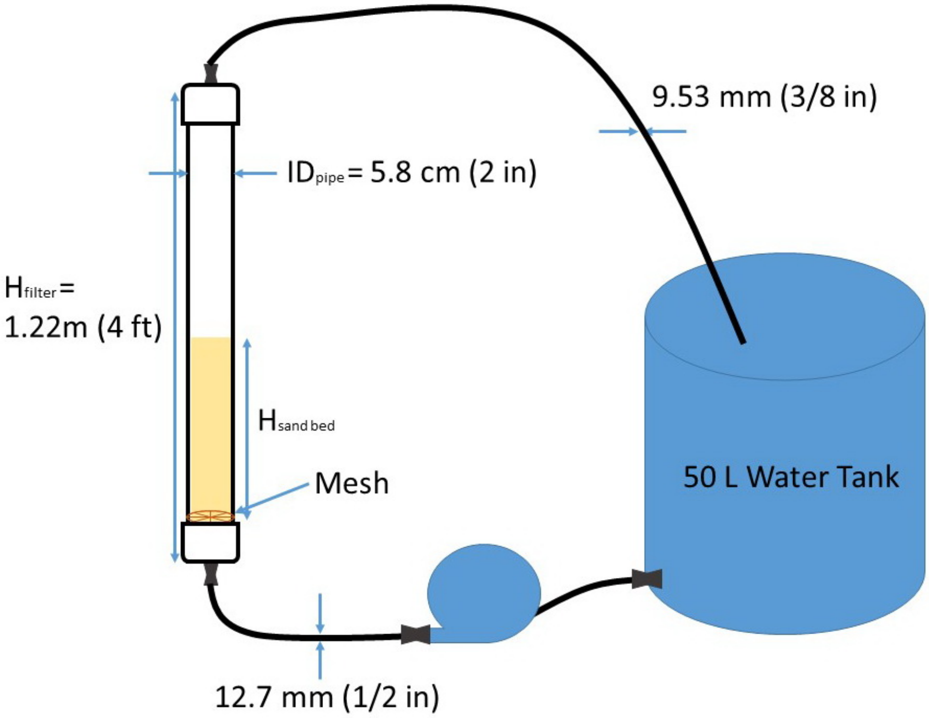

Figure 2: Water recycle system connected with the filter experimental apparatus

Figure 3: Experimental setup

Along with this new water recycle system, another filter apparatus (shown in Figure 3) was constructed to further test sand segregation characterization, particularly in respect to the H_{filter}/D ratio. The only change for the additional filter apparatus compared to the existing filter is the new filter is a 2.5 cm (1”) diameter PVC pipe. The sand size used in backwash velocity experimentation was also changed from the previous sand sieve sizes 30-40 to 35-45, as after sifting the craft sands obtained, it was found that there was not a sufficient amount of 30-35 sand to use.

Backwash Velocity Testing

The experimental procedure was the following for different backwash velocity experiments:

1) Ran the filter through backwash at a high velocity for a few minutes to allow for bubbles to escape and to adjust the column for vertical alignment, both visually and with the level.
2) Turned off the flow to allow the sand to settle.
3) Ran the backwash at a high velocity for a few seconds a couple of times to achieve good mixing (quantified visually).
4) Allowed the mixed sand to settle.
5) Ran the backwash at the desired backwash velocity.
6) Allowed the sand to fluidize to a constant height.
7) Took flow and bed height measurements.

8) Allotted a maximum of a minute of backwash after a stable fluidized bed height to quantitatively test for segregation.
9) Repeated steps 2-7 for different backwash velocities.

The main purpose of testing different backwash velocities is to see if there is a certain range of velocities where the sand bed will not segregate and to quantify at what expansion ratio a sand bed will segregate.

A series of experiments were done using the 5.1 cm (2”) diameter filter to see the effect of a slanted surface on mixing. A steel bar, 2 cm wide x 0.3 cm thick x 34.3 cm long was placed in the sand bed. It rested on the bottom of the filter and sat at a 86.7 degree slant, as shown in Figure 4 below. Experiments were then conducted at different backwash velocities following the same procedure as the original experimental design. Comparisons were then made by examining the mixing of the sand bed at equivalent backwash velocities in the 5.1 cm (2”) filter with and without the slanted steel bar.

Figure 4: Steel bar placed within the filter to act as a slanted slope

Another set of experiments were done with a H_{filter}/D ratio of 1 to 1 by filling the 5.1 cm (2”) filter with 100 mL total of sand, 50 mL of each color. This H_{filter}/D ratio was tested because

AguaClara plant filters use this ratio. Experiments were then conducted at different backwash velocities using the same procedure as previously described.

Sand Segregation Testing

Segregation was tested through visual observations; if the two colored sands stratified, the majority of the colored smaller sized sand was on top, and the larger sand sizes settled to the bottom. Segregation was defined as occurring if it was detectable by the human eye qualitatively and if segregation was noticeable after a minute had passed.

Previously sand segregation has been assessed visually, as described above, largely just determining sand segregation as a yes or no. This semester the team began using pictures and computer technology to assess the degree of segregation in experiments. The LabView program analyzed the RGB values of images by looking at the color distribution of the pixels making up the image and comparing the colors to a calibration photo.

In order to assess the degree of mixing, the team photographed the sand inside the experimental ‘tube’ filters while the sand bed was completely segregated and completely mixed. Using these images as baseline calibration photos, the team was able to qualitatively assess the behavior of the sand during future experiments. This quantitative photo analysis also allowed the team to communicate what is happening during the backwash experiments more effectively.

The baseline reference images were taken of 0% (no green sand), 50% (half green and half pink sand), 75% (25% green, 75% pink and vice versa) and 100% (purely green sand) sand ratios. Due to the difficulties in deconstructing the existing filters, another clear pvc tubing with a 3.81 cm (1.5”) diameter was found and used as the filter column for taking reference pictures.

After the reference images were taken, the filters (both 1” and 2”) were fluidized one at a time at a variety of velocities and allowed to reach steady state, where pictures were taken of the sand segregation within the columns. The filters displayed varying amounts of mixing. The corresponding velocities were recorded, and the images were saved to be quantified later by the photo analysis program.

Results & Discussion

Preliminary Testing

After implementing the water tank, there were no longer any bubbles in the water. The new system was left running for fifteen minutes and as seen in Figure 5, no bubbles remained in the water to attach to smaller sand particles at the top of the fluidized bed.

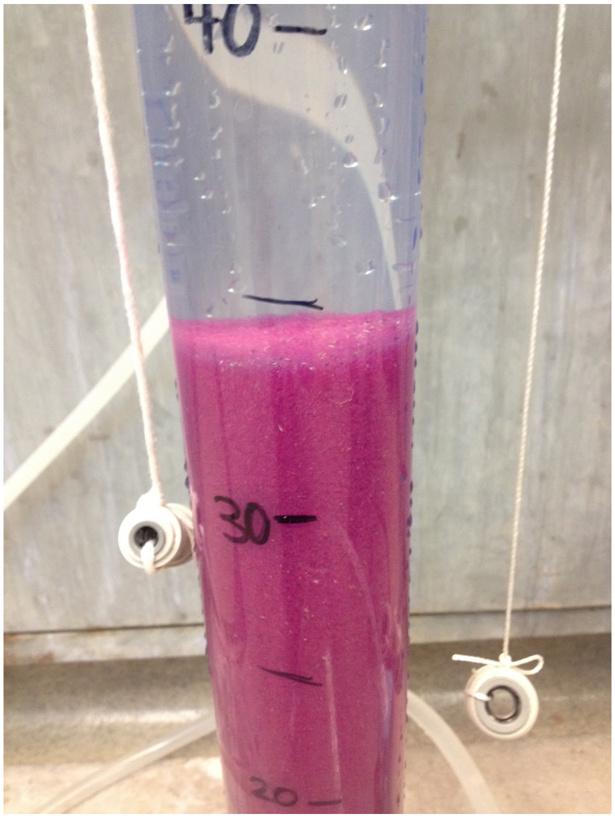

Figure 5: No bubbles collected at the top of the fluidized bed

The team ran a few segregation tests with the setup to try and replicate the past semester's experiments. Three preliminary tests were ran at different velocities to see if the new recycle system without bubbles in the influent water had a large effect on the segregation and fluidization of the sand bed. Table 1 below summarizes the new tests compared with tests ran by the past semester ran at a similar backwash velocity.

Table 1: Comparison of expanded bed height at similar velocities

Initial Bed Height (cm)	Exp Bed Height (cm)	Velocity (mm/s)	Previous Exp Bed Height (cm)	Velocity (mm/s)
18	40	30.3	52	30.2
18	34	25.2	44	25.9
18	30	21.2	39	21.4

As can be seen from these few comparisons in Table 1, the bubbles that were in the water last semester played a large role in expanding the sand bed. All of the new tests had a significantly lower expanded bed height during fluidization, by more than 20% each. In the previous semester, all three of these backwash velocities resulted in very obvious sand segregation, while this semester the team observed that the segregation was not as obvious since the top few centimeters of the fluidization were very pink, but the rest of the fluidized bed was partially mixed. These few preliminary results show that more replications of work done in the previous semester must be done in order to get more accurate results concerning sand bed segregation and fluidization because the bubbles in the water previously did have a large effect on the results.

After changing the sand particle size from 30-40 to 35-45 and reconstructing the 1” diameter filter, it was found that there were a lot of large bubbles appearing in the filter. The bubbles interfered with the results of the velocity test as it was very hard to get the sand level in the filter to stabilize. The team as yet is unable to identify where the bubbles may have appeared from. The bubbles could be in the water source or could be produced by the pump. When the bubbles flow through the sand bed, the larger sand particles at the bottom of the bed attach to the bubbles and then remain within the fluidized bed, as they are too heavy to rise up and exit with the effluent. The sand was also unable to mix properly and settle at the initial level (10 cm) when not fluidized, also due to the bubbles causing the sand bed to be slightly expanded, even when settled.

The pump was also noted to have some issues, for instance the flow of water was very irregular, which resulted in extremely uneven sand segregation. This irregular water input also affected the level of sand expansion which resulted in an expansion difference of 10 to 20 cm. The maximum expansion of the sand changed during each experimentation due to this irregular flow. The pump also made strange sounds during experimentation, although this disappeared after it was unplugged.

Backwash Velocity Testing

Eight trials were run on the smaller filter to test different backwash velocities and the expansion ratio. Equal parts of 30 mL pink and green sand were used at an initial sand bed height of 10 cm. As can be seen from Figure 6 below, there is a power relationship between expansion ratio and backwash velocity, where the expansion ratio increases more at higher backwash velocities. In these eight trials, all sand beds segregated after a minute of backwash. The first backwash velocity tested at 2 mm/s was the minimum velocity where the sand bed was completely fluidized. Even at this low velocity, the sand bed segregated, which contradicts the findings from last semester where low velocities resulted in a mixed bed and higher velocities (above 15 mm/s) resulted in segregated beds.

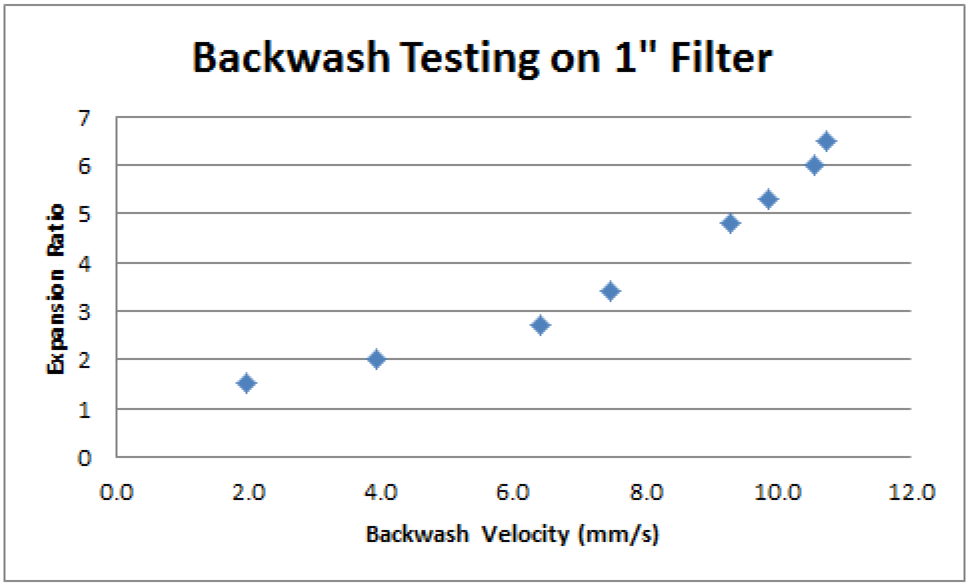

Figure 6: Expansion ratio as a function of backwash velocity on the smaller filter

Seven trials were run on the larger filter with equal parts of 200 mL pink and green sand. The initial sand bed height was 20 cm, which is double the 10 cm height of the smaller filter to keep the same H/D ratio, accounting for the doubled diameter. All of the trials resulted in segregation, similarly to the results of the smaller filter. As shown in Figure 7, both filters had similar curves comparing the backwash velocity with the expansion ratio.

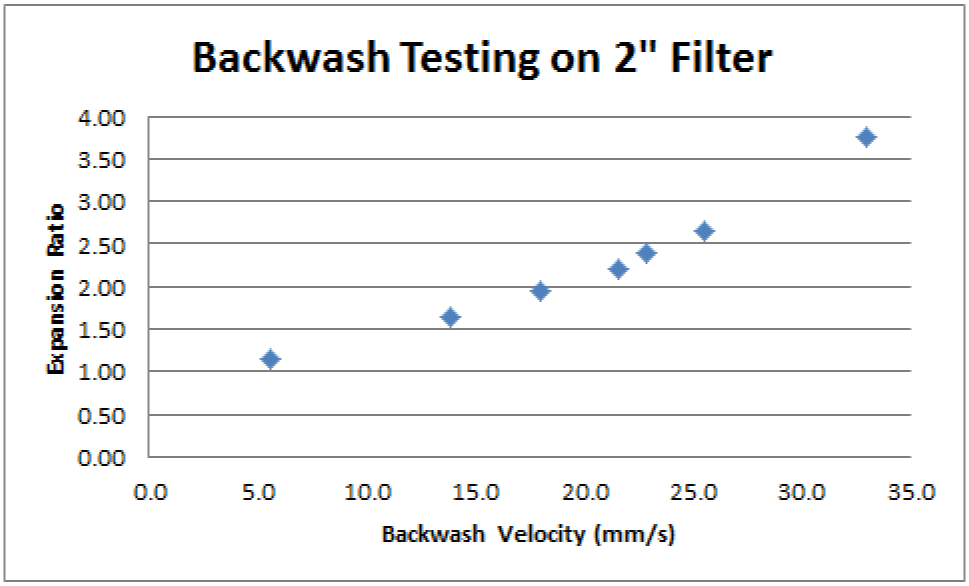

Figure 7: Expansion ratio as a function of backwash velocity on the larger filter

Because the segregation testing was qualitative, there were some discrepancies as to whether or not a sand bed is segregated and the degree of the segregation. The team observed that most sand beds resulted in three distinct zones: pink, green, and mixed. The two colors of sand would distinctly be segregated where the top of the bed is all one color and the bottom of the bed is the other color, but there would be a transition zone in between where the two sands were mixed. As shown in Figure 8, the three zones are distinct, but where they start and stop is not as clear. The team also observed that at higher backwash velocities, the transition zone was larger and accounted for a larger proportion of the fluidized bed. A possible explanation for this observed phenomenon could be that at higher backwash velocities it is much easier for the smaller particles to fluidize and move to the top of the sand bed, while the middle-sized particles remain near the middle. The higher velocity causes each of the three zones to expand, but also creates more mixing for the middle-sized particles since the small and large particles immediately go to the top and bottom, respectively.

In order to better quantify segregation and take out human subjectivity to judging the segregation, photo imaging and analysis was done on images taken of the filter column at different velocities. The imaging software on LabView extracted the colors from the image and quantified how much of one color is in each section of the photo. With this software, the team was able to numerically quantify the level of segregation, as well as the percentage of the bed that is within each of the three zones, as described previously.

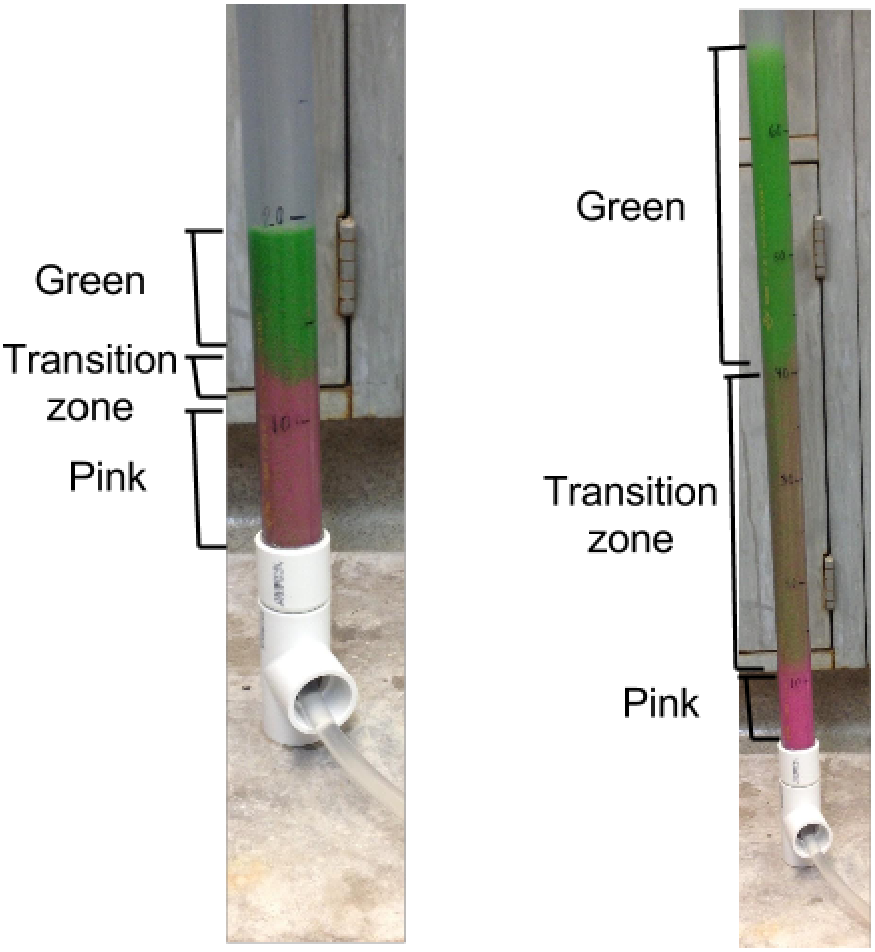

Figure 8: The three zones in a fluidized bed for backwash velocities of 3.9 mm/s (left) and 10.6 mm/s (right)

Slanted Slope Testing Comparison to Baseline

Twelve different trials were run with the slanted bar within the sand bed. Of these twelve trials, five were matched with trials of similar backwash velocities without the slanted bar. Graphs showing the experimental data are presented below in Figure 9, where the base represents experiments ran without the slanted bar within the sand bed.

Figure 9: Comparison of the sand segregation with and without the slanted bar, where the base is in blue and slanted slope is in orange. The data is presented with the height from the bottom of ROI (cm) as the independent variable and the percentage of sand that is green as the dependent variable.

In all of the experiments except for the 5.5 mm/s trial, the slanted slope experiments were quite consistently more mixed than the base. The slanted slope percentage of green centers close to around 50% for the experiments, while the base experiment had a large range of percentages, starting with close to 0% green at the bottom of the filter to close to 100% at the top of the filter, which indicates clear segregation. The 5.5 mm/s trial may have yielded different results since at this backwash velocity, the bed is just fluidized and the entrance configuration could have more of an impact on sand segregation and mixing than the backwash.

From observing visually, it was very obvious that the sand bed was well mixed with the slanted bar in the filter. The mixing seemed to be caused by increased velocity around the bar, due to the bar constricting the flow and effectively making the diameter of the filter smaller where it was placed. A lot more mixing was observed with the slanted bar. When backwash velocities were higher, however, the sand bed that fluidized above where the bar was placed (up to 34 cm) would still segregate, with only green sand above the bar, as shown in Figure 10.

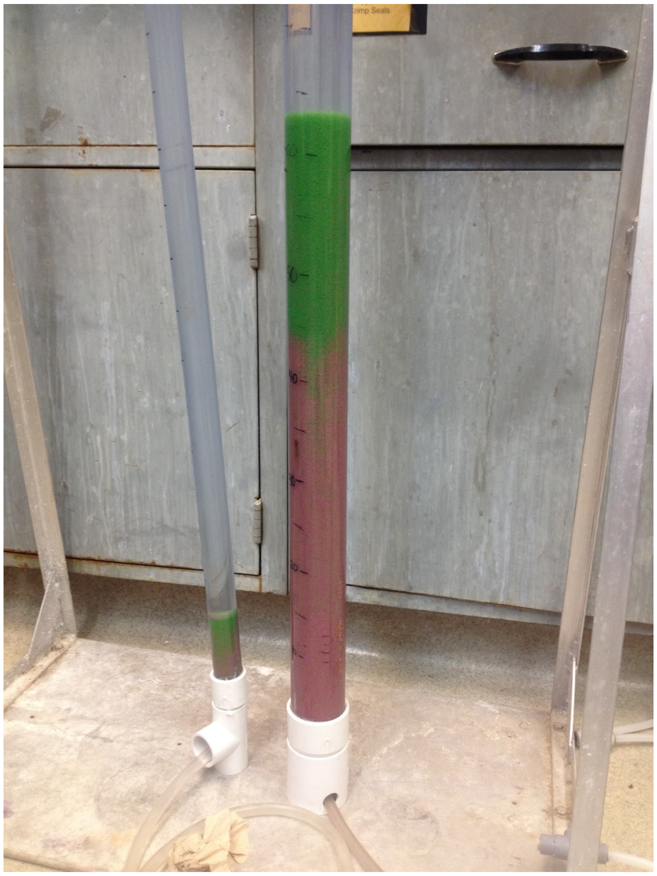

Figure 10: Segregation is clear above where the slanted bar was placed.

This observed phenomena can be seen in the graphs in Figure 9, with how the slanted bar curve would increase dramatically at higher heights. The segregation that occurs above the slanted bar supports the fact that the slanted bar helps to induce mixing within the sand bed.

Problems/Concerns

Due to the filter design, the first 3 cm of the sand bed are not visible during experiments. Because of the available PVC needed to construct the filter, this problem was unavoidable. As a result, the behavior of the sand at the waters entrance cannot not be fully seen and some speculation was employed as to what exactly occurred within the bottom 3 cm of the column. If there was clear segregation at the top of the sand bed and if the bottom of the sand bed was primarily one color, the team assumed that the bottom of the sand bed behaved similarly as the area right above the PVC cap.

One area of concern regarding the team’s experiments is the water injection into the filter cylinders. Water enters through a push-to-connect opening in the bottom center of each filter. This design was intended to equally distribute flow into the cylinder. However, at low flow, it was clear that water was flowing unequally, causing some sand to fluidize in the first few inches of the cylinder and some sand to remain un-fluidized. The uneven fluidization was observed visually, as some sand on one side of the filter would be moving upward while other sand would remain still. The flow and fluidization of sand becomes uniform a few inches from the bottom of the cylinder. This unequal fluidization does not appear to be a problem at high flow rates.

This phenomenon may be caused by the flexible tubing used to deliver water into the filter since the tubing is bent almost 90 degrees immediately before entering the bottom of the filter. The problem may be solved by adjusting the design so the flexible tubing is not bent as much approaching the entrance, for instance increasing the length of the apparatus holding the filter up so that the tubing enters the bottom of the filter vertically. The inconsistencies with flow in the entrance seems to be a problem regardless of the filter angle.

Another issue is that sand sorting is limited using sieves, so the team can only see two different size ranges in the sand bed. Typically when the sand segregates, there are three relatively distinct zones, as described previously. It is very possible that the sand is actually sorting itself to a more distinct degree in sizes than the team can measure using the available technology. If the team could have different color sand for every 1 um measurement, versus the available every 5 um sieve range, then the team might be able to confirm this behavior of the sand.

In using the LabView software to analyze the sand segregation, sometimes it was difficult to get the region of interest (ROI) to exactly fit the column, so there may be small variabilities with where the analysis started and stopped in regard to the height of the filter. There were also some lighting differences between pictures that could have affected the analysis, as well as differences in the PVC filters used. Both of the filters have black markings on the outside to indicate the height of the filter, which could also have altered the analysis slightly. The output of some analyses also indicated negative percentages of green or over 100% green, which is not possible, showing slight errors in the analysis itself and from the issues previously described. Because of the variabilities in the photos as well as the analysis, the data gathered through this method should only be used as support with what was observed visually.

Conclusions

Over the range of backwash velocities used for experiments, the sand seemed to segregate into three layers of green, transition, and pink sand zones. All experiments followed a common pattern of segregation behavior regardless of the backwash velocity or diameter of the filter, although the segregation was more prominent at higher backwash velocities. Even though the sand size ratio in the experiments were below the 1.5 ratio suggested by Đuriš et al., segregation still occurred. In the transition zone, however, the sand seemed to be well-mixed, suggesting that an even smaller sand size ratio could result in a well-mixed bed.

The addition of a slanted surface to the filter generally served to create a more uniformly mixed sand bed, possibly providing an easy solution to creating a mixed bed after backwash.The addition of slanted surfaces to the injection sites of AguaClara sand filters may result in less sand segregation during backwash and a more evenly distributed sand bed throughout the filter layers.

Sand filters in AguaClara plants have H_{filter}/D ratios of 1. The mixing at a ratio of 1 in the experimental filter indicate that sand still segregated, based on the behavior in the sand visible in the top portion of the sand bed. The bottom of the sand bed was not visible so there is some speculation in regards to these conclusions. This suggests that Aguaclara filters behave similarly to our other experiments in regards to H_{filter}/D ratios.

Even for a relatively small range of sand particles, significant segregation was observed. This study indicates that the initial assumption of sand ratios of less than 1.5 not segregating may be incorrect. Observation of the tendency of the sand to segregate into three general ‘zones’ suggests that segregation occurs among sand particles at a very small size difference. The transition zone observed in most experiments suggests that larger particles in the grouping of smaller sand particles were inclined to mix primarily with the smaller particles of the larger sand group. Due to limitations in sand supply, it was determined to be too difficult to sort sand into more narrow size groups to confirm this theory.

Future Work

In future semesters, the work done by this team could be expanded and built upon by incorporating designs from the actual filters used by AguaClara. This semester’s research has established a basic idea of how sand segregation can be measured and quantified, but in order for the values to be of functional relevance to the work done by AguaClara, more testing should be done with real filter parameters. For instance, the AguaClara filters are square, which could be significant to the experimental results as the filters used in previous experiments are all circular. The work done by this team was based on an isolated system only looking at sand segregation parameters and limited to the laboratory environment due to certain constraints on size, pump speeds, and sand sizes. For example, the sand sizes used in experimentation (35-45) were not the same as the ones used in the AguaClara filters (30-40), as the team was not able to obtain those sand sizes in enough quantity. This difference between laboratory testing and real filters could mean that in order to have more direct results for AguaClara filters, future teams should attempt to mimic the field conditions more closely. Having different layers of injection, like real sand filters, would also be helpful to determine the different ways sand segregation could occur in the actual filters. In the filter design used by this team, it was not possible to have more than one layer of injection, which meant that the condition of multiple layers of injection could not be tested. The new injection configuration with the sloped wings could also have a large effect on the behavior of the sand during backwash since the wings may act like a sloped surface to increase mixing within the bed. Testing backwash with the use of the sloped wings would be very useful in testing the hypothesis that they will help in mixing the sand. In future semesters, working closely with the other filter teams could be helpful in further quantifying sand segregation specific to AguaClara filters.

Another suggestion for future work is to incorporate clay injection and turbidity measuring to test the forward filtration of the filters to see if the degree of segregation truly inhibits the functionality of the filters. Experiments done previously were not sufficient to prove this since only backwash with clean water and clean sand was tested. If some amount of sand segregation does not have a greatly detrimental effect on filter effectiveness, it may be unnecessary to continue exploring the sand segregation issues related to AguaClara.

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