A COMPARISON OF LABORATORY TESTING AND THEORETICAL ANALYSES OF SEDIMENT PROCESSES IN A SEPARATOR UNIT

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1 INTRODUCTION

Laboratory testing is the best method to determine the effectiveness of a manufactured stormwater separator unit at removing suspended sediment, as well as its propensity to scour and resuspend already settled material. It allows significant variables to be kept constant and provides the ability to isolate the true settling rate of the particulate relative to flow. Additionally, much work has been done in the field of sediment transport to develop equations which theoretically describe complicated sediment transport and settling processes. These processes include sedimentation and reentrainment of a sediment bed, both of which can typically be found occurring within a separator unit. This study ventures to determine if some of these equations can successfully be applied to stormwater separators. To see how well it can predict the sediment behavior, the results of the theoretical analysis are compared with experimental results from a separator unit tested at Alden Research Laboratory. The results are both a better understanding of the sediment processes occurring within a manufactured stormwater separator unit and the applicability of certain sediment transport formulas in the stormwater field.

2 TEST UNIT

For this study, a Terre Kleen 18 (TK18) by Terre Hill Stormwater Systems was tested and analyzed. The TK18 is a rectangular separating device which has a plan area of approximately 6 feet by 6.5 feet. The test unit is approximately 9 feet high and consists of two chambers separated by a baffle wall containing an internal flow through duct. Figure 1 and Figure 2 show simplified drawings of the test unit and how water flows through it. The primary chamber, which measures 2 feet by 6 feet, is designed to capture trash and debris as well as coarse sediment particles. Flow then passes through a screened opening in the baffle wall to the internal flow through duct. Under high flow conditions, water can flow up through the internal flow through duct in the baffle wall and bypass the secondary chamber. Under most flow conditions however, flow passes through orifices to the secondary chamber. The secondary chamber measures 3.5 feet by 6 feet and is designed to capture the majority of the sediment. It contains a series of 18 inclined lamella plates to enhance settling surface area. Lamella plates are a type of laminar settlers which increase the horizontal settling area within a given footprint and therefore decrease the design settling velocity, allowing the unit to capture smaller particles with a smaller plan area. The idea of settling area is explained further in Section 4. The lamella plates also encourage countercurrent settling of the solids whereby solids slide down the plate in the opposite direction of the flow.[1] In addition, the TK18 is designed so the direct flow path of the water is more than 1.5 feet off the bottom of the device to minimize disturbance of the sediment bed and further improve settling at the base of the plates. The test unit has an 18-inch influent pipe with an invert located 75 inches above the wetted floor. The effluent pipe is 24 inches in diameter and has an invert of approximately 72.5 inches.

3 LABORATORY METHODS

The TK18 was brought to Alden Lab for verification testing based on a protocol developed by the New Jersey Corporation for Advanced Technology (NJCAT) and the New Jersey Department for Environmental Protection (NJDEP). This method is accepted by California, Illinois, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, and Virginia under the Technology Acceptance and Reciprocity Partnership (TARP.)[2] NJCAT protocol for sediment removal efficiency requires testing to be carried out at 5 flow rates and 3 concentrations, for a total of 15 tests. The flow rates required are 25%, 50%, 75%, 100% and 125% of the maximum hydraulic operating rate (MHC). The concentrations for the tests are 100 mg/L, 200 mg/L and 300 mg/L. During the tests, the unit is required to be preloaded with a sediment bed to 50% of the unit's capture capacity. A weighted efficiency, based on to the results of these tests, is then calculated. The procedure for the calculation is as follows. At each flow rate, the efficiencies from the three tests, with varying influent concentrations, are averaged. The result is multiplied by a weighting factor based on the flow rate, and then all weighted efficiencies are summed. The weighting factors are: 0.25 for 25%, 0.30 for 50%, 0.20 for 75%, 0.15 for 100% and 0.10 for 125% (see also Table 6 and Table 7 for further clarification on this calculation.) The protocol also requires 2 reentrainment tests, utilizing clean water (no sediment injected), and with the unit preloaded to 50% and 100% of the unit's capture capacity to check for resuspension and washout. Finally, the NJCAT protocol specifies a particle size distribution (PSD) of the sediment to be used during all tests. The PSD requirements specified by NJCAT can be found in Table 1. Alden has developed a sediment mix utilizing three grades of readily available silica sand, all with a specific gravity of 2.65. The historic average baseline particle size distribution for tests carried out at Alden Lab is shown in Table 2 and Figure 3. The historic average baseline d_{50} is 70 µm.[3]

The TK18 was installed in Alden's closed test loop which is depicted in Figure 4. Water was supplied to the unit with three pumps which draw water from a 50,000-gallon, heated sump. The sump was maintained at 70°F ± 5°. Water then passes through one of 6 calibrated flow meters (connected to a differential pressure cell and a data acquisition computer) to a section of influent piping and then to the unit itself. After the unit, the water is returned to the sump through effluent piping. During sediment removal efficiency testing, sediment is introduced through a tee, approximately 10 diameters upstream of the test unit, in the influent pipe, using a volumetric screw feeder and attached hopper. This provides a constant supply of dry sediment and an even injection throughout the test. In addition, by using dry sediment, the injection rate can be ensured and maintained throughout the test, and in conjunction with the real time flow measurement, the target concentration can be calculated. Alden uses this calculated concentration for determining the unit efficiency since it is the most accurate influent concentration available. Isokinetic samplers (example shown in Figure 5) were used in the effluent piping to collect the effluent sediment concentration and particle size distribution samples. The size and number of tubes was chosen for each test and the tube array was adjusted vertically to ensure the full cross section of flow was sampled. Particle size distribution samples were sent to a third party lab for analysis using the Coulter Counter Method. Sediment concentration samples were filtered and analyzed by Alden in accordance with Method B of ASTM D 3977-97, "Standard Test Methods for Determining Sediment Concentration in Water Samples."[4] The required silica sand used in the sediment testing did not result in any dissolved solids in the samples and therefore, simplified the process. This process is known as Suspended Sediment Concentration (SSC) and Alden has found it to be the most accurate method for determining the effluent sample concentrations.

Background concentrations do have the potential to increase in the sump during testing because the water is circulated and reused. Since the effluent concentrations are determined through sampling and would include the background levels and the influent concentrations are based on the injection and flow rates and would not include the background levels, background concentrations would show up in the analysis by artificially increasing effluent concentrations. Baffle walls have been installed in the sump to minimize this potential by maximizing the flow path. Additionally, the particles that would contribute to background levels are quite small and are only those not captured by the unit or not settled in the sump itself. Still, in order to ensure the test is accurate, background samples are taken throughout each test at the pump intake and analyzed using the SSC method. The concentrations are accounted for in the overall efficiency determination by subtraction from the effluent concentrations.

After determining the influent, effluent and background sediment concentrations in milligrams per liter, the removal efficiency can be calculated using the following equation:

$$Efficiency(\%) = \frac{(MeanInfluentConcentration - MeanEffluentConcentration)}{(MeanInfluentConcentration)} * 100$$

EQUATION 1

In coordination with Alden Lab, Terre Hill set the MHC or 100% flow rate for the TK18 at 2070 gpm or 4.61 cfs. The corresponding flow rates tested were 2587 gpm or 5.76 cfs for the 125%, 1552 gpm or 3.46 cfs for the 75%, 1035 gpm or 2.31 cfs for the 50% and 517 gpm or 1.15 cfs for the 25%. During the course of testing, Terre Hill revised the unit's capture capacity. For this reason, the sediment removal efficiency tests were carried out at 100% of the unit's capacity instead of the 50% specified by NJCAT. The 100% sediment loading level (depth of the sediment bed) was set at 16.5 inches or 31.3 cubic feet and the 50% level is 8.25 inches or 15.6 cubic feet. In addition to the tests required by NJCAT, Terre Hill also decided to conduct three low flow efficiency tests at approximately 300, 200 and 100 gpm. These tests were done at 200 mg/L with a sediment loading level of 50%.

The procedure used for reentrainment testing is similar to sediment removal efficiency testing. The unit was preloaded to either 50% or 100% capacity. It was then slowly filled and allowed to sit for a minimum of 24 hours. Testing was conducted by incrementally increasing the flow to the target flow rates (25%, 50%, 75%, 100% and 125% MHC.) Four effluent samples were taken at each flow rate over a 15 minute period and background samples were taken throughout. Effluent and background concentration samples were analyzed using the SSC method and effluent PSD samples were analyzed using the Coulter Counter method. The effluent concentrations in mg/L were adjusted for background and then plotted versus time. All 18 sediment removal efficiency tests, as well as the 2 reentrainment tests, will be included in this analysis.

4 ANALYTICAL METHODS

In order to see if an equation or set of equations could help predict the lab results for the TK18, the basic principles of sedimentation were first considered and evaluated. Sedimentation is the process by which solids denser than water are removed from a portion of that water due to the forces of gravity.[5] The way to determine if a particle will settle in any situation is to calculate the settling velocity and compare that with the flow. To determine if a particle will settle within a certain area, such as basin or gravity separator, the size of the basin must also be taken into account. The basic equation for the settling velocity of spherical particle which is freely and discretely settling is,

$$\boldsymbol{V_S = [\frac{4g\,(S-1)d}{3C_D}]^{1/2}}$$

EQUATION 2

Where S is the specific gravity of the particle, d is the diameter of the particle and C_D is the drag coefficient. The drag coefficient is dependent on the flow regime immediately surrounding the particle. Small particles will produce laminar flow and as the particle size increases, so will the turbulence of the flow around it. The way to describe the flow around the particle is the by calculating the Reynolds Number, N_{RE}, shown here,

$$\boldsymbol{N_{RE} = \frac{V_S d}{v}} \qquad \textbf{EQUATION 3}$$

Where v is the kinematic viscosity of the water which varies with temperature. When the Reynolds number for the particle is less than one, the flow is laminar, and the drag coefficient can be expressed as,

$$\boldsymbol{C_D = \frac{24}{N_{RE}}} \qquad \textbf{EQUATION 4}$$

Substituting the drag coefficient and the Reynolds number into Equation 2, the settling velocity for a particle with a Reynolds number less than one is,

$$\boldsymbol{V_S = \frac{g}{18v}(S-1)d^2} \qquad \textbf{EQUATION 5}$$

This equation is also known as Stokes' Law. There have been many misconceptions about whether or not Stokes' Law is valid in stormwater so it is important to remember the basis of it. Stokes' law is based on the assumptions that the particles are spherical, the particles settle freely and discretely and do not interact with other particles and the particles are small enough that the flow around them in laminar. Stokes' law can be used solely to describe some wastewater treatment processes since the particles all fall within the laminar range. In stormwater however, many of the particles are larger and other equations need to be used for these regions. The next region is when the Reynolds number is greater than 1 but less than 10,000. Here the flow around the particle is considered transitional and the drag coefficient can be expressed as,

$$\boldsymbol{C_D = \frac{24}{N_{RE}} + \frac{3}{\sqrt{N_{RE}}} + 0.34} \qquad \textbf{EQUATION 6}$$

In this case the settling velocity can only be determined by trial and error using Equations 2, 3 and 6. Some discrepancy does exist as to when the flow stops being transitional and changes to turbulent but as stated previously, 10,000 was used as the threshold in this study.[6,7] Finally, for the region where the Reynolds number is greater than 10,000, the flow around the particle is turbulent and the drag coefficient is,

$$\boldsymbol{C_D = 0.4} \qquad \textbf{EQUATION 7}$$

Substituting the drag coefficient and the Reynolds number into Equation 2, the settling velocity becomes,

$$\boldsymbol{V_S = \sqrt{3.3g(S-1)d}} \qquad \textbf{EQUATION 8}$$

The purpose of this partial derivation of the equations for settling velocity is to remind ourselves what is really driving the sedimentation process and the assumptions which are made in applying these formulas. Gravity (*g*) and the difference between the specific gravity of the particle and specific gravity of water (*S-1*) appear in all formulas and are the driving forces behind the settling. The settling velocity is also a function of the particle diameter. The velocity increases as particle size increases, and so does the turbulence of the flow regime around the particle. Finally, the temperature of the water also has an effect on settling since it changes the viscosity of the water.[8]

In a paper published in 1997, Nian-Sheng Cheng developed a formula based on empirical data to describe settling velocity throughout the range of particle sizes and therefore throughout the flow regimes. The formula is simple and explicit and is presented below. It was also used in this analysis to determine settling velocity and removal efficiency.[9]

$$V_S = \frac{\nu}{d}\left(\sqrt{25 + 1.2{d_*}^2} - 5\right)^{1.5} \quad \text{EQUATION 9}$$

Where the dimensionless particle parameter d_* is defined as,

$$d_* = \left(\frac{(S-1)g}{\nu^2}\right)^{1/3} d \qquad \text{EQUATION 10}$$

The settling velocity analysis using Equations 2 through 8 is presented in Table 3 and the analysis using Equations 9 and 10 is shown in Table 4. The NJCAT sediment mix was divided into 7 ranges and the average particle size for that range was used. In addition, sediment much larger than was used in testing of the TK18 is included to demonstrate the results in all flow regimes. A comparison of the two settling velocity analysis methods is presented in Figure 6 which shows that Cheng's Formula plots very closely to Stokes' and the other standard formulas. In addition, as particle diameter increases settling velocity increases most in the laminar region and least in the turbulent region.

As stated at the beginning of this section, the settling velocity must be compared with the flow rate and area to determine the removal efficiency of the test unit. This is based on the ideal basin theory which shows that the sediment removal is a function of the area of the basin not the depth. The flow rate divided by the plan area is called the overflow rate and is shown here,[10]

$$Vo = \frac{Q}{A} \qquad \text{EQUATION 11}$$

All sediment with a settling velocity greater than the overflow rate will be removed by the stormwater separator. Some sediment with a smaller velocity will also be removed. As stated in Section 2, the TK18 is designed with laminar settling plates. Since sediment removal is based on the area, angled plate settlers increase the area by providing more horizontally projected surface. Using the horizontal area, Equation 11 predicts the upward velocity in the laminar settling plates. According to the theory, all particles with a settling velocity greater than the upward velocity will settle out. Most particles with a lesser velocity will remain with the flow and travel out.

Finally, to determine efficiency, the overflow rate for the unit was substituted into Equations 9 and 10 to determine the diameter of the particle associated with this settling velocity. Then, the particle diameter was plotted on the particle size distribution graph, shown in Figure 7, to determine the percentage of particles greater than it and therefore the percentage of particles removed. Results of this analysis are presented and discussed in Section 5.

In addition to sedimentation, reentrainment or resuspension of already settled materials was also occurring in the TK18 during laboratory testing and therefore also considered here in the theoretical analysis. The horizontal velocity in the tank, along with the properties of the sediment, are the determining factors as to whether reentrainment will occur. The critical horizontal velocity was described by Camp as,

$$V_H = \left[\frac{8k(S-1)gd}{f}\right]^{1/2} \qquad \text{EQUATION 12}$$

Where k is a unitless constant that depends on the nature of the sediment (0.04 for least interlocking sediment and 0.06 for the most) and where f is the unitless Darcy-Weisbach friction factor (0.02 to 0.03).[11] The analysis for the critical horizontal velocity, using Equation 12, is presented in Table 5. Once again, the sediment was broken into 7 particle ranges. The average diameter for each range was used to calculate the critical horizontal velocity. The value for *k* was estimated to be 0.04 and the value for *f* was estimated to be 0.025. Next, the horizontal velocity in the unit was calculated using the flow rate and an estimated area of 78 inches by 24 inches or 13 ft^2 (the plan area of the primary chamber.) Then, the velocity at each flow rate was compared with the critical velocity for each particle range. If the velocity was greater than the critical velocity, all or a portion of that particle range was assumed to scour. Finally, the percentage of the mix associated with the particle range assumed to scour was subtracted from the theoretical sediment removal efficiency curve. The intent is to try and account for reentrainment and hopefully match the lab results more closely. It should be noted that the theoretical sediment removal efficiency curve developed earlier was adjusted up by 15% before subtracting the theoretical reentrainment. This was based on a calculation of the additional percentage which is removed beyond the particles with settling velocities greater than the internal velocity in the settling plates. The results of this analysis are presented and discussed in Section 5.

5 RESULTS AND COMPARISON

The results of the sediment removal efficiency laboratory testing are presented in Table 6. The efficiencies for the TK18 cover a wide range from 9.2% at the highest flow of 2587 gpm to almost 80% at the lowest flow of 100 gpm. Additionally, the efficiencies at the same flow rate vary with different concentrations, however, the 200 mg/L test efficiencies fall in the middle of the range of efficiencies for each flow rate. This is consistent with Alden's past experience on other separator units and shows that the 100 and 300 mg/L tests may not be necessary. The weighted removal efficiency based on NJCAT weighting factors is 50.3% (with the PSD between 2 and 1000 µm and the d_{50}=70 µm.)

The results of the theoretical analysis for sediment removal efficiency are presented in Table 7. The range of efficiencies from the theoretical analysis is much smaller than the range for laboratory testing. They vary from 32% at the highest flow of 2587 gpm to 61% at the lowest flow of 100 gpm. Concentration, and a variation of the concentration, was not accounted for in the theoretical analysis. The theoretical weighted removal efficiency is 43.6%.

A comparison of the laboratory and analytical methods is presented in Figure 8. The two efficiency curves have slightly different shapes and cross around the mid range of the testing which corresponds to a flow rate of about 1550 gpm or 75% MHC. Beyond that, the theoretical analysis over predicts the efficiency at higher flows and under predicts the efficiency at lower flows. One thing to remember is that the theoretical analysis only accounts for particle sizes which have a settling velocity greater than the overflow rate. It did not account for any particles which have a slightly smaller velocity but may have entered the plates near the bottom and had time to settle out. Also, the theoretical analysis is based on an average velocity in the unit (the overflow rate) and the actual velocity distribution may not be uniform. In addition, this analysis does not account for any reentrainment which was likely occurring during the laboratory tests and occurred most at the highest flows.

One interesting result from the lab testing that is hard to account for is the particle size distribution analysis of the effluent samples (not included graphically but discussed here.) According to the theoretical analysis, the unit should be able to capture down to about 30 µm at 100 gpm. The particle size distribution analysis shows that at this flow, 98% was less than 47 µm and 96% was less than 31 µm. This is very close to the theoretical. However, as the flows increase, it would be expected that the size of some of the particles in the effluent would increase. This was not the case. Even at 2587 gpm, 100% of the particles were less than 49 µm and 95% were less than 30 µm.

The theory tells us that at this flow rate only particles 170 µm in diameter will be 100% captured and therefore a range of particles less than that should show up in the effluent. Since the theoretical analysis is based on the idea that as flow increases, the size of particle captured decreases, and since this does not seem to be the case in the lab testing, perhaps this shows the theoretical analysis is not valid for the TK18.

The results for the reentrainment laboratory testing are presented in Table 8, Table 9, Figure 9 and Figure 10. For the 50% loading test, little to no reentrainment occurred at the 25% and 50% flow rates. Effluent concentrations did increase for the 75% and 100% flow rates with a maximum average of 25.3 mg/L at 100%. The concentrations then decreased slightly for the 125% flow. The results were similar for the 100% loading test. Little to no reentrainment occurred at the 25% flow rate and effluent concentrations increased for the 50% and 75% flow rates with a maximum average of 43.6 mg/L at 75%. The concentrations decreased slightly for the 100% and 125% flow rates. It is important to remember that the NJCAT protocol requires preloading with sediment that has particles less than 30 µm. As discussed above, this particulate does not settle in the test unit and therefore is not representative for scour analysis. It is also not representative for sediment removal efficiency testing and therefore contributes to an understatement of the devices removal efficiency.

The results of the theoretical analysis for reentrainment are presented in Table 10. The analysis predicted that no scour would occur for 100, 200 and 300 gpm. Then at 517 gpm, the smallest particle range would scour representing about 5% of the sediment mix. The next particle range would start to scour for 1035 gpm for a total of about 20%. Finally, for 1552 gpm through 2587 gpm, portions of the third particle range would scour up to a total of about 44% reentrainment. This method is likely an overestimate of the reentrainment occurring since it assumes that the full percentage of the mix is available to scour; however the sediment is compacted on the bottom of the unit in a bed and consequently not all is available to move. Also, the theoretical analysis does not account for differing sediment bed heights and only takes into account average velocity in the unit. Finally, it is hard to compare this analysis directly with the lab results because lab results are presented as a concentration in mg/L and the theoretical results are a percentage. It is possible to look at general trends however and there is one major difference. The theoretical predicts the reentrainment rates increasing with the flow rate but the lab results show a drop off in reentrainment rates at the highest flows. Perhaps as the reentrainment test progresses, the sediment particles move to fill in spaces and bed becomes more stable. Another possible reason is that the smaller particles on the surface of the sediment bed may reentrain early on in the testing leaving only larger particles on the surface which are too large to reentrain. This can be seen at each flow rate by the decreasing concentrations over time and likely also occurs throughout the test and throughout the varying flow rates (see Figure 9 and Figure 10.)

A plot of the lab results versus the theoretical sediment removal adjusted for reentrainment is shown in Figure 11. While the results match better for the higher and lower flows than when reentrainment was not accounted for, the shape of the curves are quite different. For the middle flows, the efficiencies do not match well at all.

Once again, for the reentrainment tests, the results of the particle size distribution analysis (not included graphically but discussed here) show a slightly different picture than the theory would suggest. The idea behind the theoretical approach is that as flow rate increases, so will the size of the particles being reentrained. For the 25% flow rate, particles should be less than about 2 µm, for the 50% flow rate, particles should be less than about 10 µm, for the 75% flow rate, particles should be less than about 45 µm, for the 100% flow rate, particles should be less than about 100 µm and for the 125% flow rate, particles should be less than about 140 µm. According to the PSD analysis for the 50% loading test, about 95% of the particles are less than 48 µm for both 25% and 50% flow rates. For the 75% through 125% flow rates, about 95% of the particles are less than 95 µm. So, the size of the particles in the effluent does make one step increase; however the size of particles should be much smaller at the

the lower flows and should increase gradually with each sample. For the 100% loading test, the particle sizes in the effluent remain relatively constant and never go above 57 µm. The size of the particles in the effluent never increased. Again, something must be happening during the course of the reentrainment test that makes the bed more stable as the testing goes on. One final anomaly of the particle sizes is that, the sizes in the effluent during reentrainment were much larger than particle sizes in the effluent during sediment removal efficiency testing for the same flow rate. Perhaps this is caused by the active settling below the settling plates which is significant during sediment removal efficiency testing. The large amounts of particles settling and sloughing off the bottom of the plates cause a "sinking curtain" which may help temper the scour effect. The presence of such a "sinking curtain" was clearly observed in the viewing windows during testing. Overall, the PSD results of the lab testing are very hard to explain or rationalize. Either the PSD results are faulty or the complicated sediment processes that are occurring in the TK18 seemingly cannot be accounted for in this theoretical analysis.

6 CONCLUSION

In conclusion, it is important to remember the basic sediment processes which occur within a stormwater unit during laboratory testing. Gravity drives the sedimentation process and removal efficiencies and reentrainment amounts are a function of the particle size. However, there is much that is occurring within the units that still cannot be accounted for. The theoretical results were not able to be matched up with the laboratory results. Perhaps if this theoretical analysis was applied to more stormwater units some trend could be found. However, with the exception of the basic effective settling area, the configurations of all stormwater units are so different that a lamella plate unit like the TK18 will likely not match up with a circular unit that relies on vortex separation or any other type unit. Again, remembering that for all units, removed sediment still ends up on the unit floor as a result of gravity.

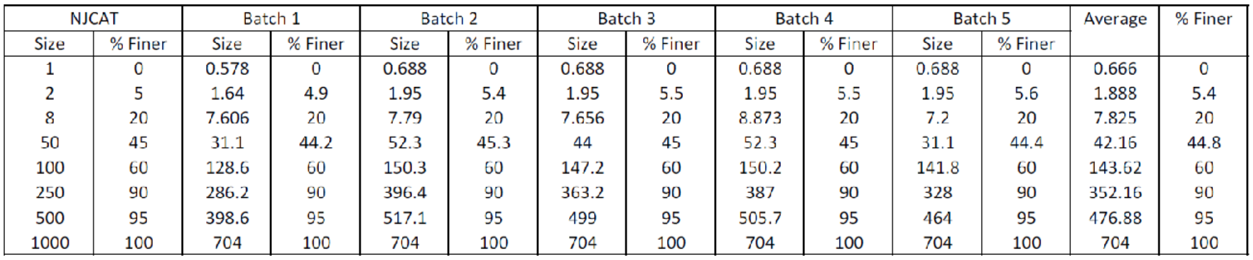
The best method for determining the efficiencies of stormwater units is still in the laboratory where conditions and variables can be controlled as much as possible and measurement of the results can be done more accurately. Formulas give some understanding about the relationships, but most likely there are many more complicated processes occurring that have to be corrected for at each condition and in each device.

Tables and Figures

TABLE 1 NJCAT SPECIFIED PARTICLE SIZE DISTRIBUTION

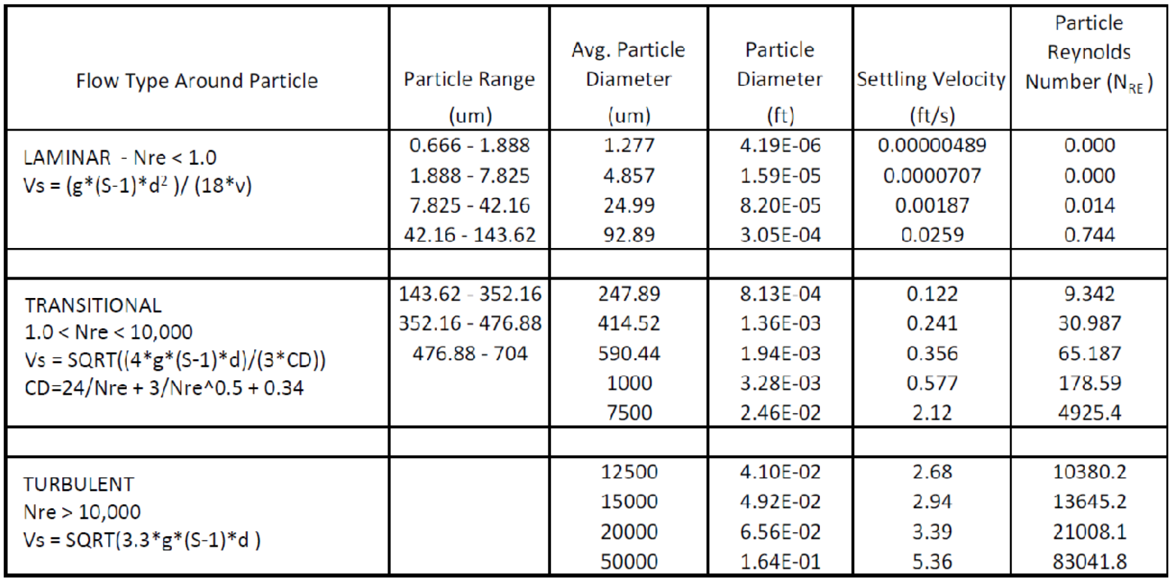
Particle Size (microns)	Sandy Loam (percent by mass)
1-2 (clay)	5.0
2-8 (very fine/fine silt)	15.0
8-50 (silt)	25.0
50-100 (very fine sand)	15.0
100-250 (fine sand)	30.0
250-500 (medium sand)	5.0
500-1000 (coarse sand)	5.0

TABLE 2 HISTORIC BASELINE PARTICLE SIZE DISTRIBUTIONS USED AT ALDEN LAB



NJCAT		Batch 1		Batch 2		Batch 3		Batch 4		Batch 5		Average	% Finer
Size	% Finer	Size	% Finer	Size	% Finer	Size	% Finer	Size	% Finer	Size	% Finer		
1	0	0.578	0	0.688	0	0.688	0	0.688	0	0.688	0	0.666	0
2	5	1.64	4.9	1.95	5.4	1.95	5.5	1.95	5.5	1.95	5.6	1.888	5.4
8	20	7.606	20	7.79	20	7.656	20	8.873	20	7.2	20	7.825	20
50	45	31.1	44.2	52.3	45.3	44	45	52.3	45	31.1	44.4	42.16	44.8
100	60	128.6	60	150.3	60	147.2	60	150.2	60	141.8	60	143.62	60
250	90	286.2	90	396.4	90	363.2	90	387	90	328	90	352.16	90
500	95	398.6	95	517.1	95	499	95	505.7	95	464	95	476.88	95
1000	100	704	100	704	100	704	100	704	100	704	100	704	100

TABLE 3 SETTLING VELOCITY CALCULATIONS



Flow Type Around Particle	Particle Range (um)	Avg. Particle Diameter (um)	Particle Diameter (ft)	Settling Velocity (ft/s)	Particle Reynolds Number (N_{RE})
LAMINAR - Nre < 1.0 Vs = (g*(S-1)*d^2)/ (18*v)	0.666 - 1.888	1.277	4.19E-06	0.00000489	0.000
	1.888 - 7.825	4.857	1.59E-05	0.0000707	0.000
	7.825 - 42.16	24.99	8.20E-05	0.00187	0.014
	42.16 - 143.62	92.89	3.05E-04	0.0259	0.744
TRANSITIONAL 1.0 < Nre < 10,000 Vs = SQRT((4*g*(S-1)*d)/(3*CD)) CD=24/Nre + 3/Nre^0.5 + 0.34	143.62 - 352.16	247.89	8.13E-04	0.122	9.342
	352.16 - 476.88	414.52	1.36E-03	0.241	30.987
	476.88 - 704	590.44	1.94E-03	0.356	65.187
		1000	3.28E-03	0.577	178.59
		7500	2.46E-02	2.12	4925.4
TURBULENT Nre > 10,000 Vs = SQRT(3.3*g*(S-1)*d)		12500	4.10E-02	2.68	10380.2
		15000	4.92E-02	2.94	13645.2
		20000	6.56E-02	3.39	21008.1
		50000	1.64E-01	5.36	83041.8

TABLE 4 SETTLING VELOCITY CALCULATIONS USING CHENG'S METHOD

Flow Type Around Particle	Particle Diameter Range (um)	Avg. Particle Diameter (um)	Particle Diameter (ft)	D*	Settling Velocity (ft/s)
$V=v/d * (SQRT(25+1.2d_*^2)-5)^{1.5}$ $d_*= ((S-1)*g/v^2)\text{^}(1/3)*d$	0.666 - 1.888	1.277	4.19E-06	0.03265	0.00000366
	1.888 - 7.825	4.857	1.59E-05	0.1242	0.0000529
	7.825 - 42.16	24.99	8.20E-05	0.6390	0.00139
	42.16 - 143.62	92.89	3.05E-04	2.375	0.0176
	143.62 - 352.16	247.89	8.13E-04	6.338	0.0874
	352.16 - 476.88	414.52	1.36E-03	10.60	0.165
	476.88 - 704	590.44	1.94E-03	15.10	0.235
		1000	3.28E-03	25.57	0.367
		7500	2.46E-02	191.8	1.26
		12000	3.94E-02	306.8	1.62
		15000	4.92E-02	383.5	1.82
		20000	6.56E-02	511.4	2.11
		50000	1.64E-01	1278	3.37

TABLE 5 CRITICAL HORIZONTAL VELOCITY CALCULATIONS

$V_H = [(8k(S-1)gd)/f]\text{^}0.5$	Particle Range (um)	Avg. Particle Diameter (um)	Particle Diameter (ft)	Critical Velocity (ft/s)	Percentage of Mix (%)
	0.666 - 1.888	1.277	4.19E-06	0.053	5.38
	1.888 - 7.825	4.857	1.59E-05	0.104	14.62
	7.825 - 42.16	24.99	8.20E-05	0.236	24.78
	42.16 - 143.62	92.89	3.05E-04	0.455	15.22
	143.62 - 352.16	247.89	8.13E-04	0.744	30
	352.16 - 476.88	414.52	1.36E-03	0.962	5
	476.88 - 704	590.44	1.94E-03	1.148	5

TABLE 6 TK18 SEDIMENT REMOVAL EFFICIENCIES DETERMINED BY LABORATORY TESTING

% MHC	Flow gpm	Concentration mg/L	Influent mg/L	Effluent mg/L	Efficiency %	Avg. Efficiency %	Weight Factor	Weighted Efficiency
	298.8	200	202.0	50.0	75.3			
	200.5	200	203.0	46.7	77.0			
	99.9	200	202.9	40.9	79.8			
125.0	2587.9	300	292.4	256.2	12.4			
124.9	2585.3	200	201.6	179.0	11.2			
125.0	2588.0	100	101.1	97.1	4.0	9.2	0.10	0.9
100.4	2078.2	300	295.7	213.7	27.8			
100.3	2075.4	200	196.2	147.8	24.7			
100.1	2072.3	100	96.9	79.7	17.8	23.4	0.15	3.5
74.5	1543.1	300	301.5	150.5	50.1			
74.2	1535.7	200	207.1	109.6	47.1			
74.4	1539.5	100	101.8	60.8	40.3	45.8	0.20	9.2
49.9	1033.9	300	296.4	111.1	62.5			
49.9	1033.7	200	204.9	75.9	63.0			
49.8	1030.8	100	98.4	37.0	62.4	62.6	0.30	18.8
25.0	517.9	300	302.8	82.6	72.7			
25.0	517.4	200	196.0	55.2	71.9			
24.9	516.1	100	97.4	28.8	70.4	71.7	0.25	17.9
								50.3

TABLE 7 THEORETICAL REMOVAL EFFICIENCIES FOR THE TK18

Flowrate (gpm)	Flowrate (cfs)	Velocity (Vo) (ft/s)	Associated Particle Diameter (from Cheng) (ft)	Particle Diameter (um)	% Finer (from PSD graph)	% Removed	Weight Factor	Weighted Removal
100	0.22	0.0019	9.69E-05	29.54	39.4	60.6		
200	0.45	0.0039	1.38E-04	42.07	44.0	56.0		
300	0.67	0.0058	1.70E-04	51.83	46.7	53.3		
517.5	1.15	0.0100	2.25E-04	68.60	50.3	49.7	0.25	12.43
1035	2.31	0.0201	3.27E-04	99.70	55.1	44.9	0.3	13.47
1552.5	3.46	0.0301	4.11E-04	125.30	58.0	42.0	0.2	8.39
2070	4.61	0.0401	4.87E-04	148.48	61.1	38.9	0.15	5.83
2587.5	5.76	0.0501	5.59E-04	170.43	65.7	34.3	0.1	3.43
								43.6

TABLE 8 TK18 50% REENTRAINMENT RESULTS DETERMINED BY LABORATORY TESTING

Flowrate (gpm)	**517**		**1036**		**1556**		**2076**		**2586**	
Effluent Sample (mg/L)	1	2.82	3	4.50	7	15.59	11	33.50	15	21.96
	2	3.03	4	3.56	8	12.92	12	28.02	16	19.75
			5	3.72	9	11.00	13	20.09	17	14.36
			6	2.73	10	11.53	14	19.51	18	10.52
Average Effluent (mg/L)		**2.93**		**3.63**		**12.76**		**25.28**		**16.65**

TABLE 9 TK18 100% REENTRAINMENT RESULTS DETERMINED BY LABORATORY TESTING

Flowrate (gpm)	**523**		**1060**		**1557**		**2086**		**2598**	
Effluent Sample (mg/L)	1	0	3	22.63	7	48.02	11	37.18	15	36.63
	2	0.56	4	16.94	8	45.09	12	48.50	16	37.67
			5	10.78	9	39.28	13	34.22	17	23.97
			6	7.88	10	41.96	14	20.58	18	24.28
Average Effluent (mg/L)		**0.28**		**14.56**		**43.58**		**35.12**		**30.64**

TABLE 10 THEORETICAL REENTRAINMENT AMOUNTS FOR THE TK18

V = Q / Ac	Flowrate (gpm)	Flowrate (cfs)	Critical Area (ft^2)	Velocity (ft/s)	Approx Amount of Scour (%)
	100	0.22	13	0.017	No Scour
	200	0.45	13	0.034	No Scour
	300	0.67	13	0.051	No Scour
	517.5	1.15	13	0.089	5
	1035	2.31	13	0.177	20
	1552.5	3.46	13	0.266	28
	2070	4.61	13	0.355	32
	2587.5	5.76	13	0.443	44

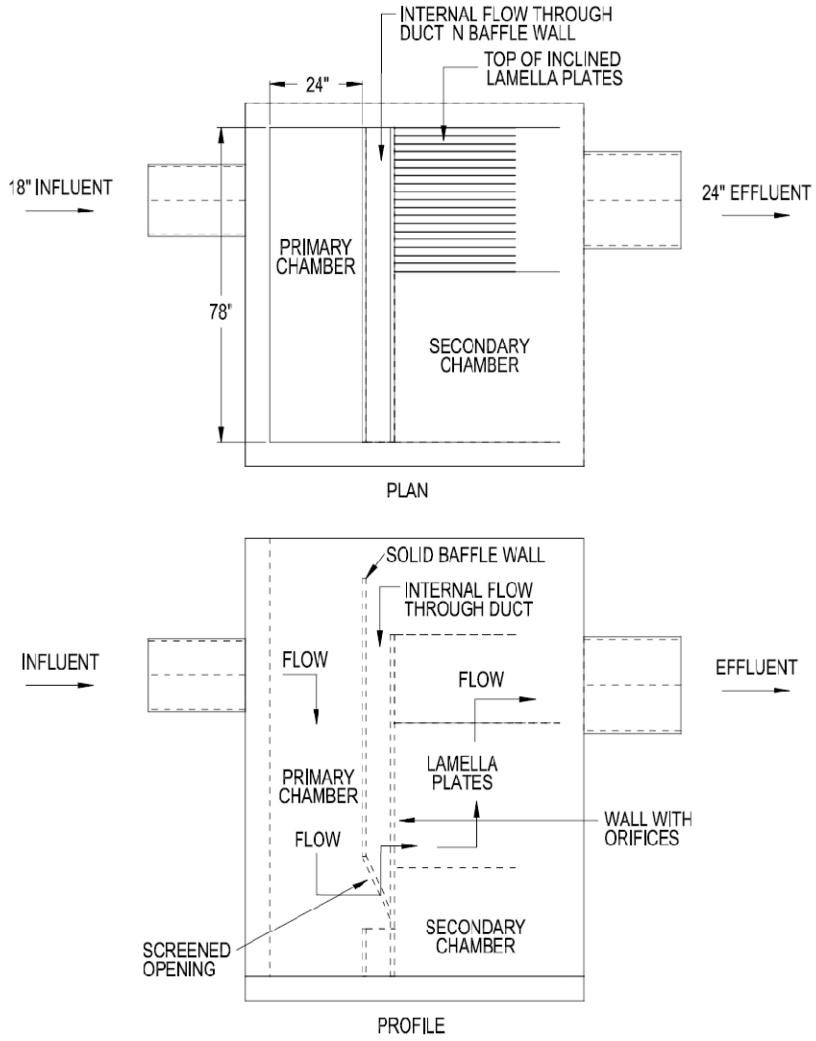


FIGURE 1 SIMPLIFIED PLAN AND PROFILE OF TK18 TEST UNIT

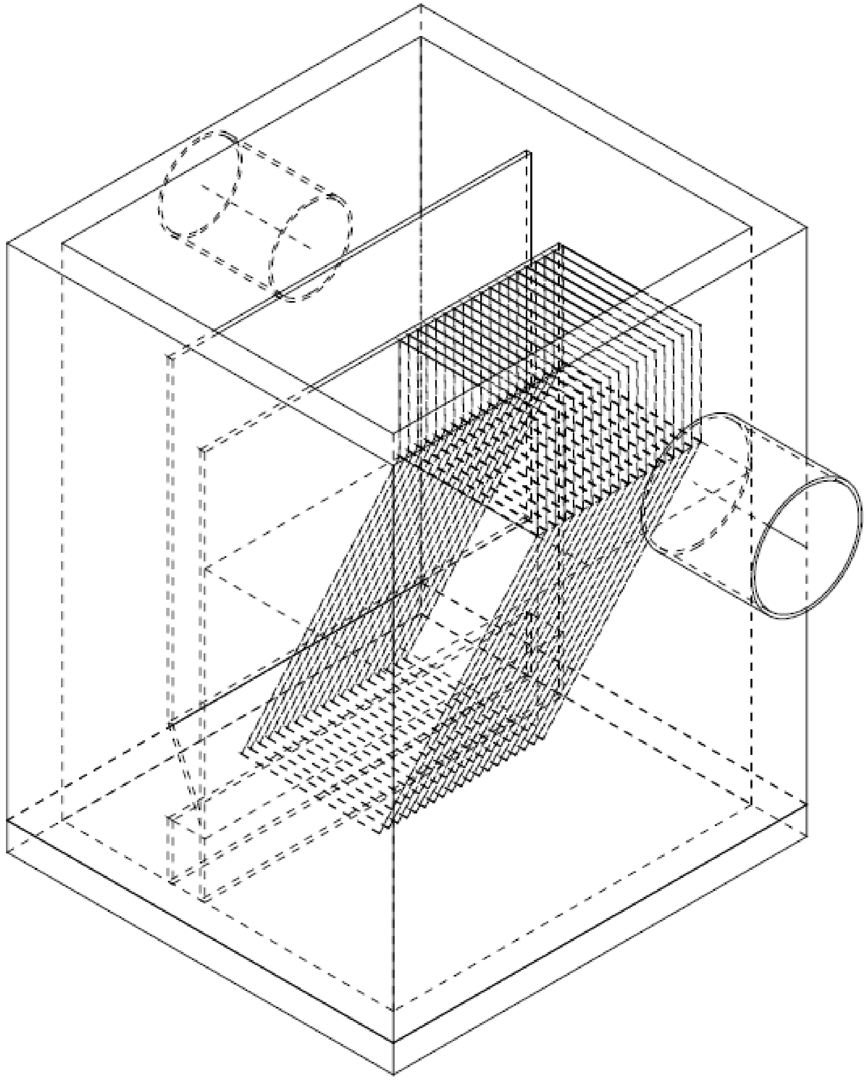


FIGURE 2 ISOMETRIC VIEW OF TK18 TEST UNIT

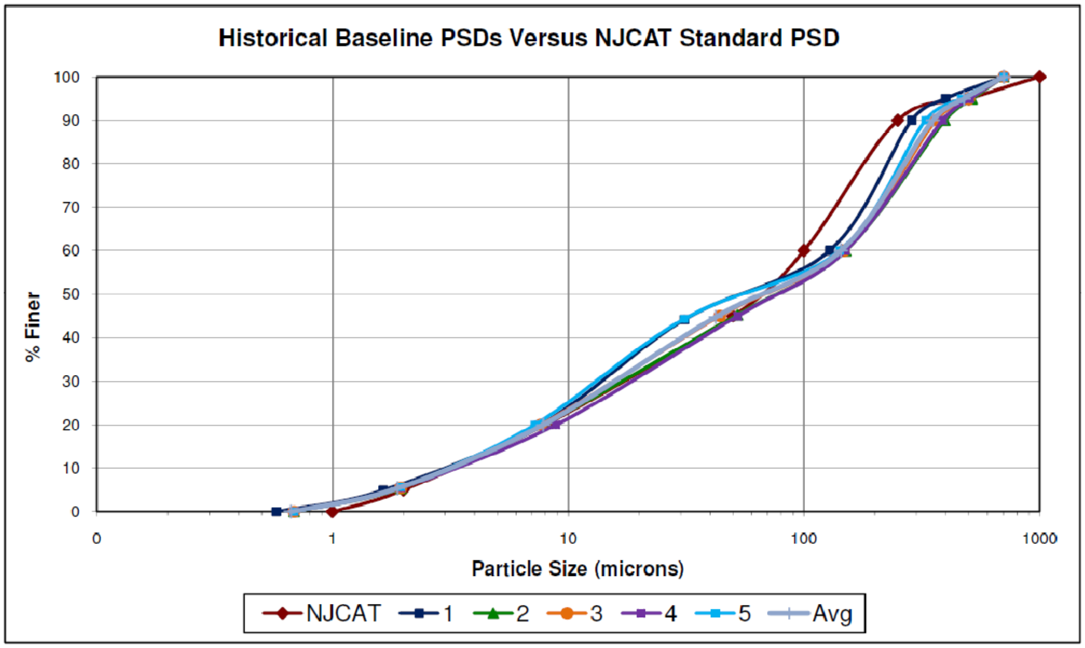


FIGURE 3 GRAPH OF HISTORICAL BASELINE PARTICLE SIZE DISTRIBUTIONS USED AT ALDEN

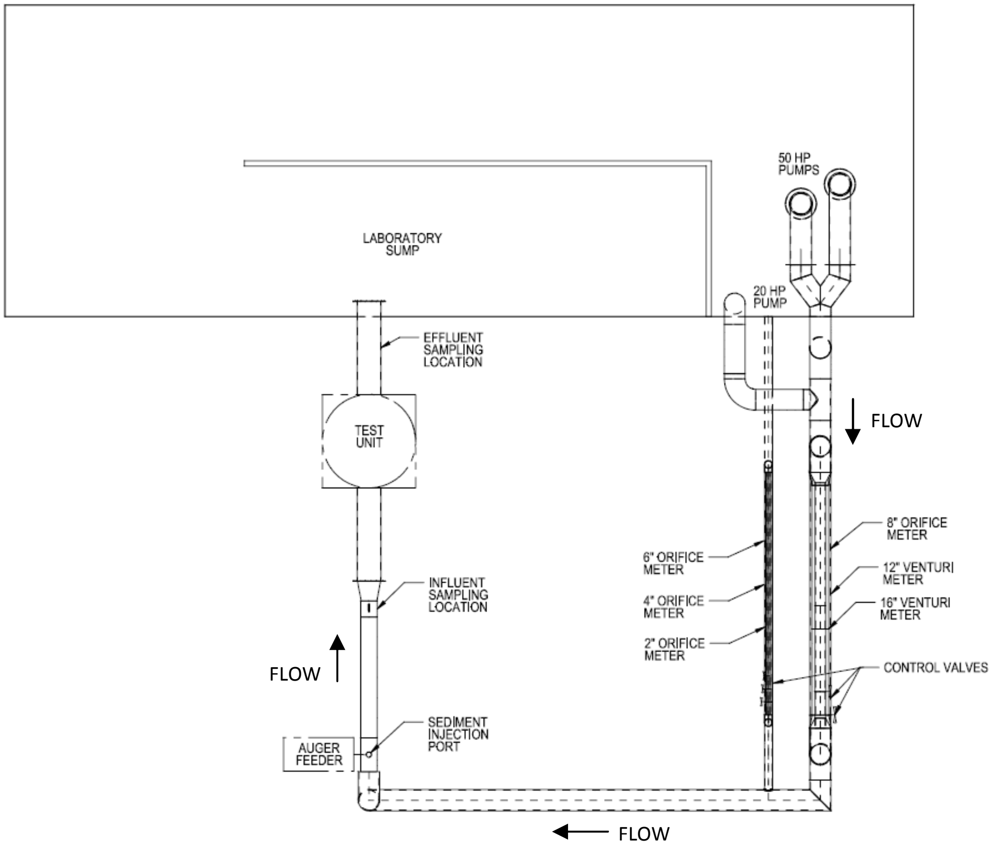


FIGURE 4 ALDEN TEST FLOW LOOP

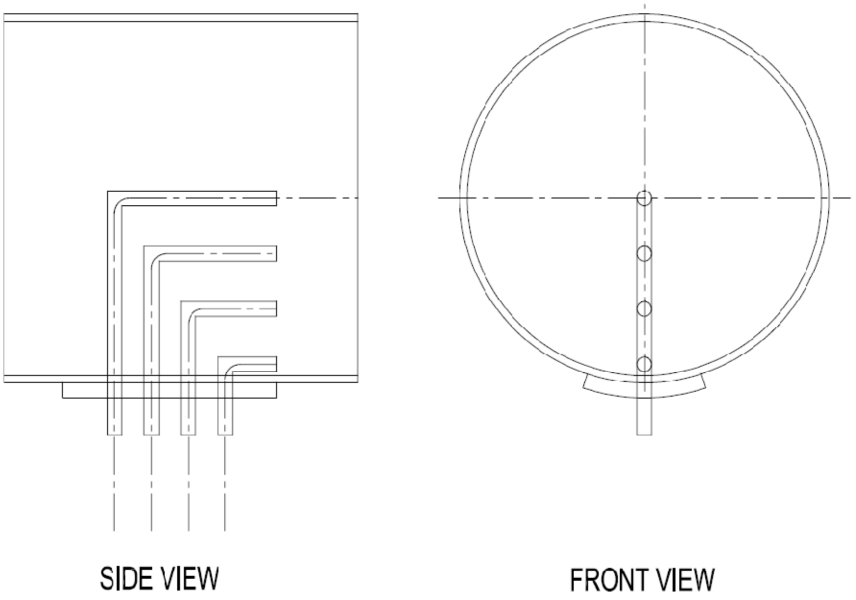


FIGURE 5 ISOKINETIC SAMPLING TUBES IN A PIPE

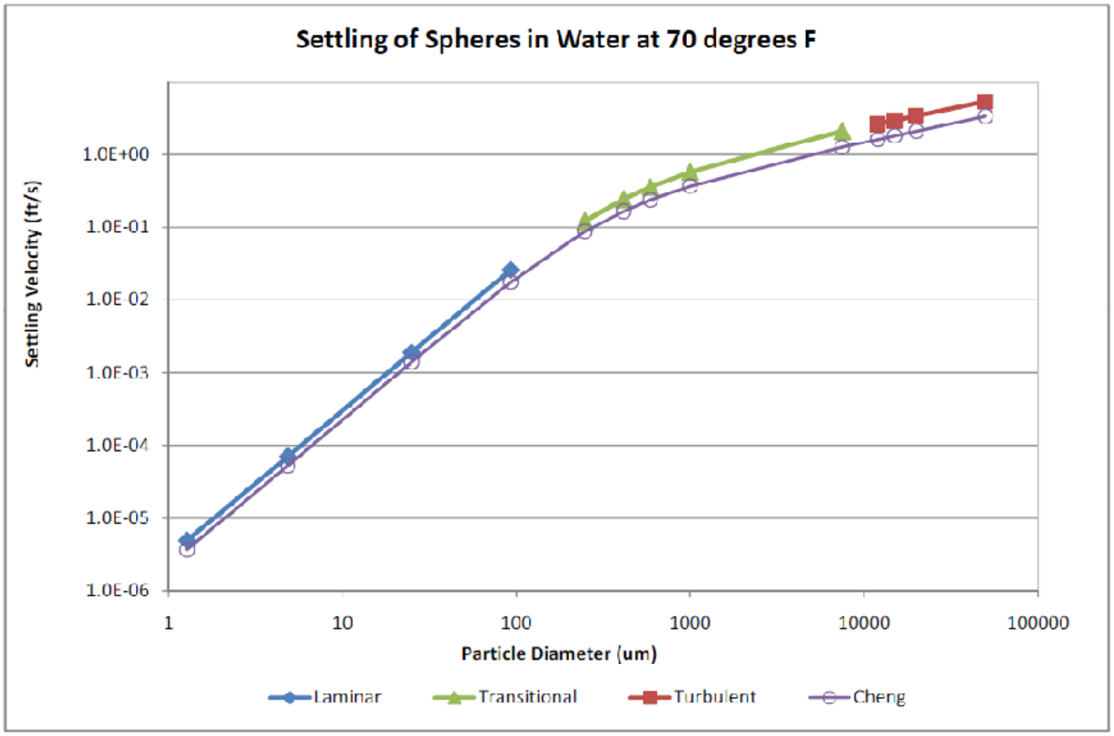


FIGURE 6 SETTLING VELOCITIES OF NJCAT SEDIMENT MIX AND LARGER

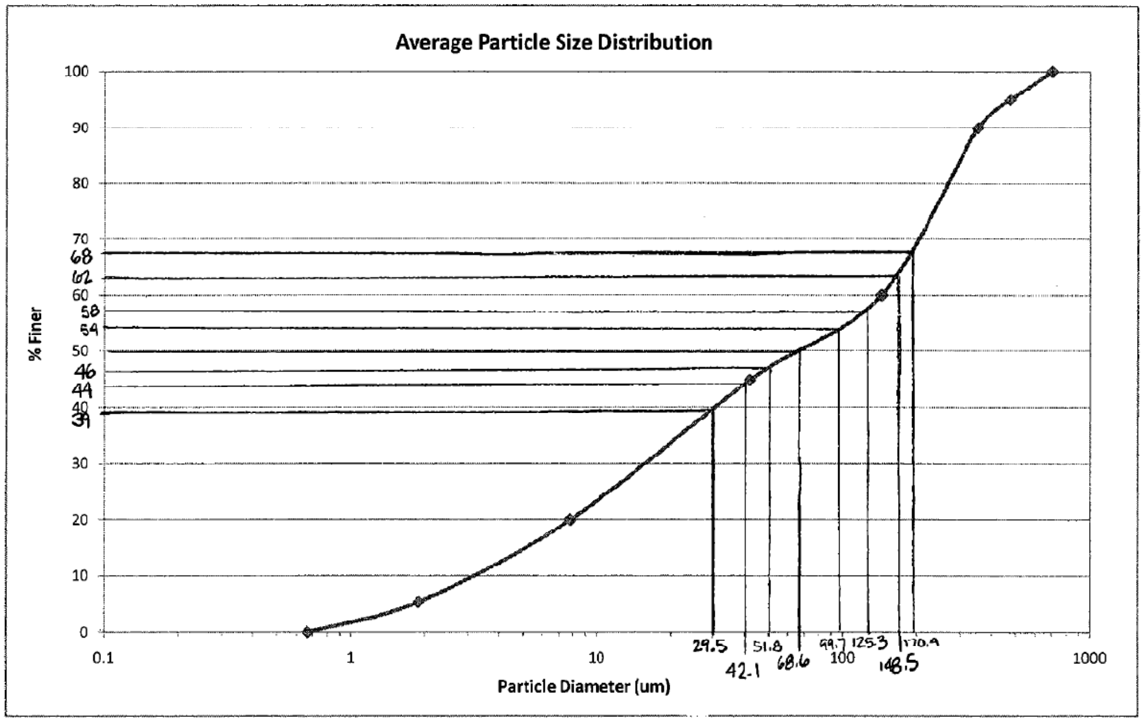


FIGURE 7 DETERMINATION OF THEORETICAL REMOVAL EFFICIENCIES FOR THE TK18

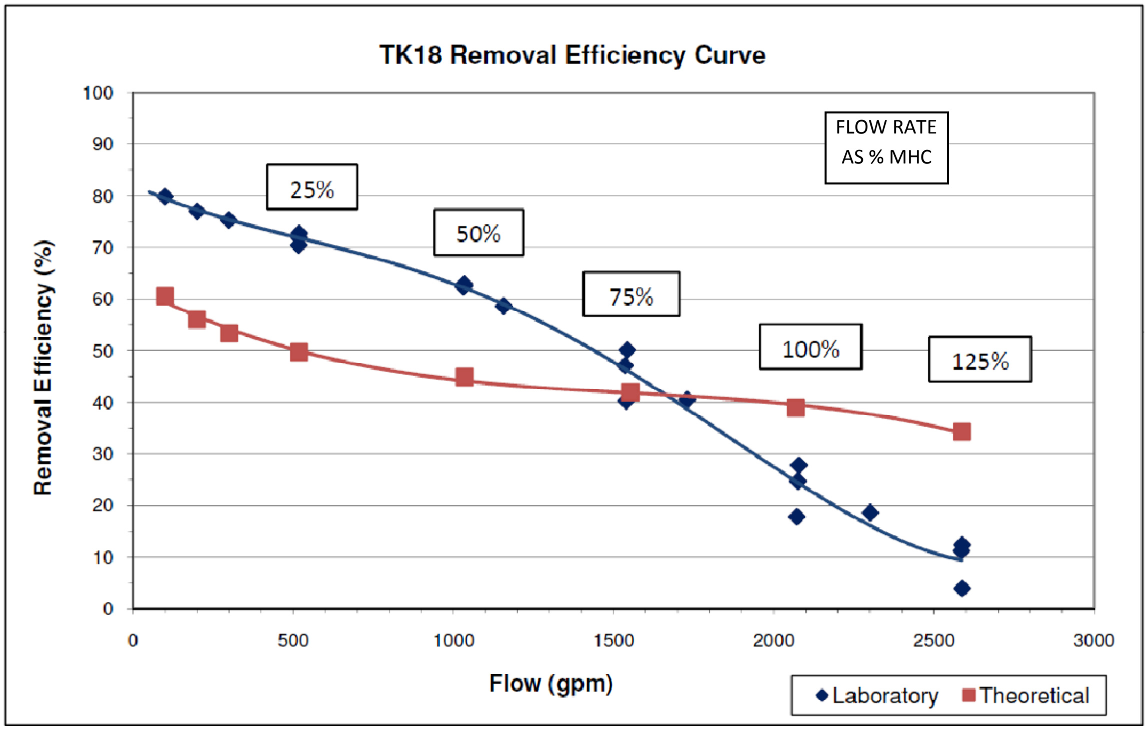


FIGURE 8 COMPARISON OF LABORATORY AND THEORETICAL EFFICIENCIES FOR THE TK18

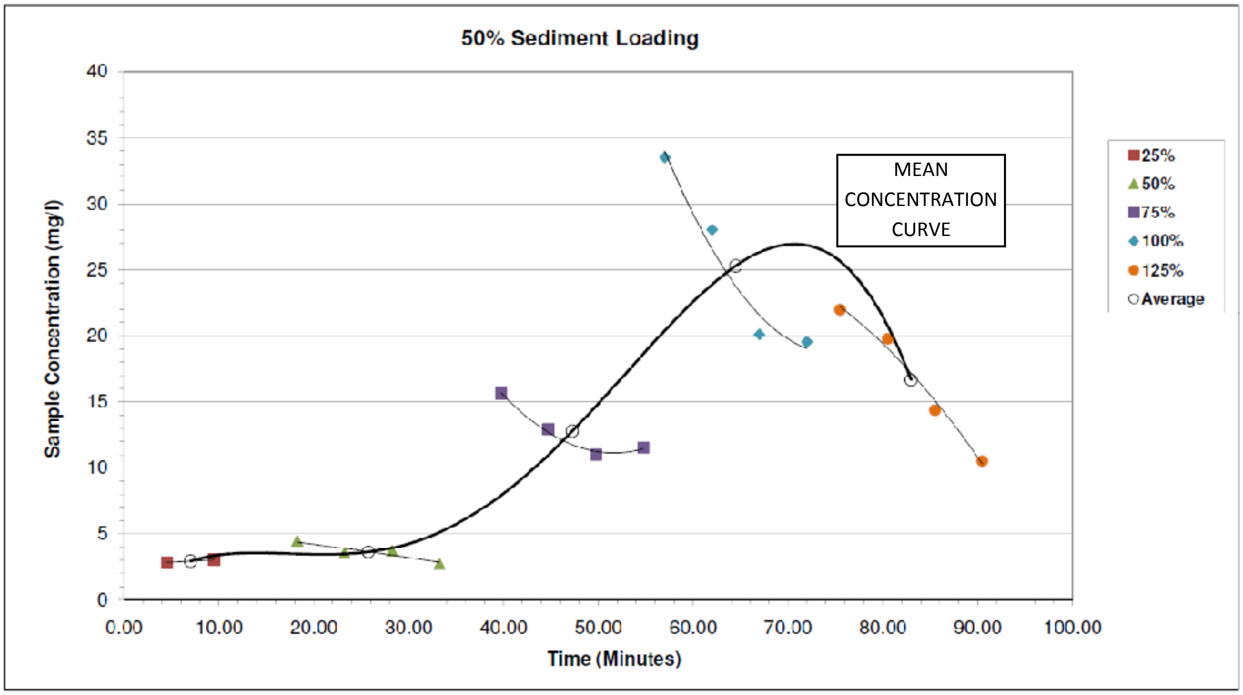


FIGURE 9 LABORATORY 50% REENTRAINMENT TEST RESULTS FOR THE TK18

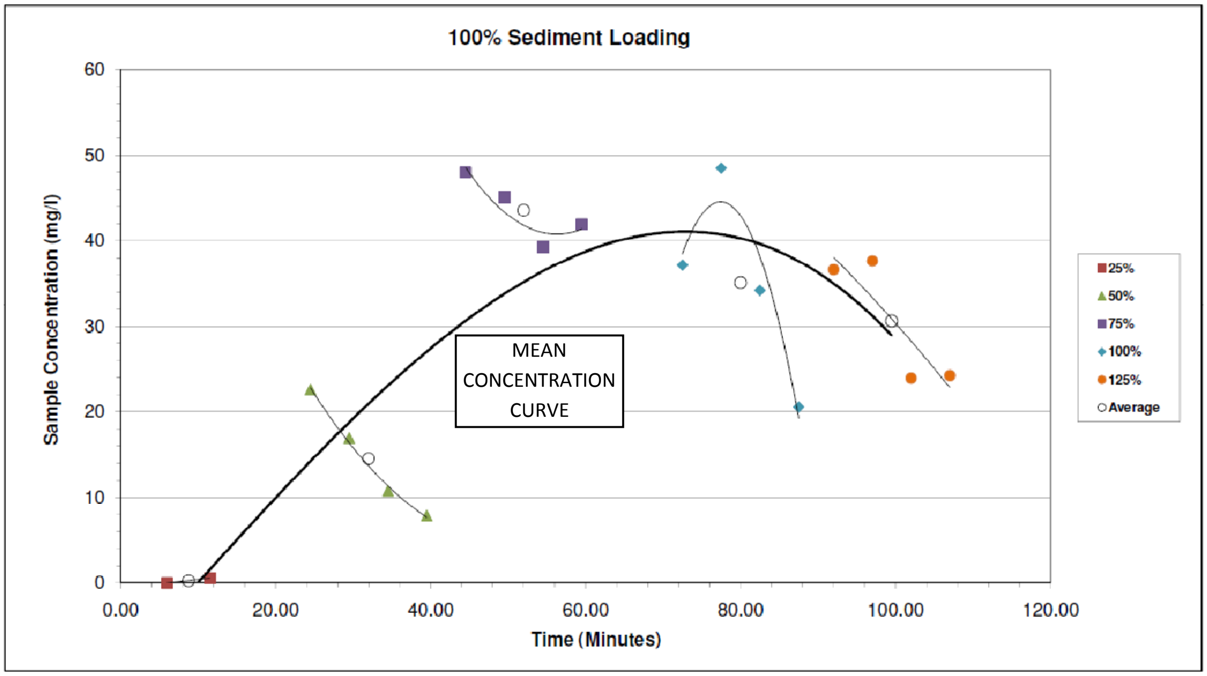


FIGURE 10 LABORATORY 100% REENTRAINMENT TEST RESULTS FOR THE TK18

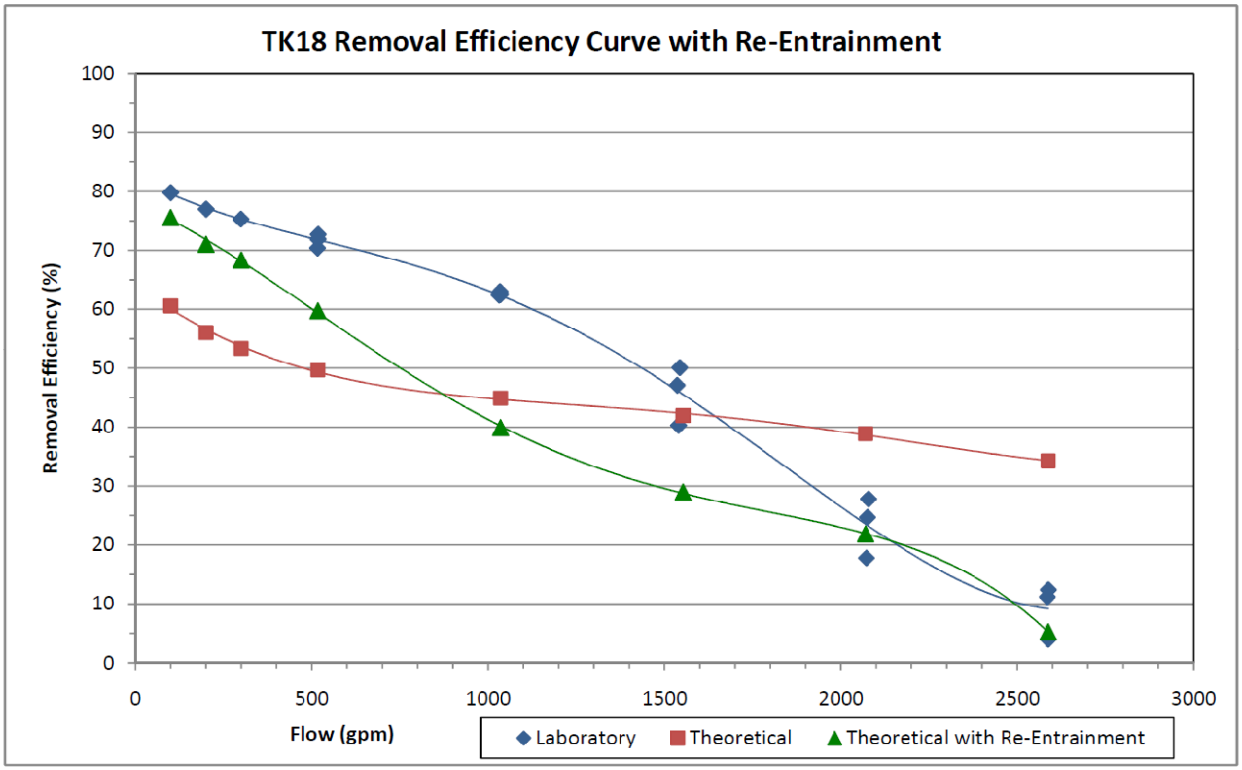


FIGURE 11 FINAL COMPARISON OF LABORATORY AND THEORETICAL EFFICIENCIES FOR THE TK18

APPENDIX 1: REFERENCES

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