Hjulström Diagram and Stoke's Law as Indicators of Performance of a Hydrodynamic Separator at Various Particle Size Distribution, Density and the Surface Loading

Hans de Bruijn
Gene LaManna
Terre Hill Stormwater Systems
A Division of Terre Hill Concrete Products
Terre Hill, Pennsylvania

Purpose

a) Use of the Hjulström Diagram to illustrate the performance of a stacked inclined plate hydrodynamic separator Water Quality Treatment device for various Particle Distribution Samples, density variations and surface loading.

b) Stating treatment performance as a percentage reduction of Total Suspended Solid (TSS) concentrations in the effluent at specific Particle Size Distribution (PSD) and concentrations in influent.

Other factors such as water temperature, particle density, hydraulic radius of the device, and dissolved solids which affect the sedimentation of particles will be assumed constant for purposes of this paper.

Background

Differences in density causes particle separation from water. Chemical bonding (i.e. agglutination) changes the density of a particle by creating a floc with higher weight to surface area ratio. The particle separation discussed in this paper is that caused by gravity. Gravity's effect on particle separation is directly proportional to the particle's density.. In flowing water there is a fundamental difference between transportation of fine particles (silt and clay) and larger particles (sand grit, and gross pollutants). Low flow turbulence holds fine particles in suspension. The size and specific gravity of a particle determines whether the particle ①floats ②sinks or ③remains suspended at a given flow rate.

Topic

The Hjulström Diagram graphically illustrates particle behavior relative to flow rate. By using this diagram and considering its validity boundaries, it can be predicted whether a particle settles, stays in suspension, or erodes. Estimating the Total Suspended Solids (TSS) and Particle Size Distribution (PSD) for the influent is required to size the grit-chamber sedimentation area to obtain the desired TSS removal performance. Thus, the horizontally projected grit-chamber-sedimentation area, of a Water Quality Treatment device can be sized based on a desired removal rate of the estimated non-colloidal fraction of TSS based on PSD and average influent concentration levels. Further practical concerns are the removal of gross-pollutants, hydrocarbons and prevention of scouring sediment and loss of captured gross pollutants by future events.

Discussion

Stormwater carrying pollutants has turbulent flow in a pipe conveying the runoff. Properly designed stormwater systems are necessary to collect and convey the water. However, particle pollutant removal is directly related to their density and rate of water flow. Thus, at some point in the conveyance process the rate of flow and turbulence must be reduced to facilitate sedimentation. The engineering design must allow for high flow rates at the collection points to remove high volumes of stormwater from the surface and, at the water quality treatment device reduce the flow rate in an effort to maximize the performance of the device. This "hurry-up" scenario is necessary for safe roads and dry homes. The "wait" is necessary to reduce the pollution load to the environment (i.e. slow the water to allow sedimentation). The ultimate "wait" phase can be seen when infiltrated water follows a laminar flow pattern as ground water where the Reynolds number is less than 400. The NPDES Phase II regulations require pollutant removal "to the maximum extent practicable". Treatment with a hydrodynamic separator is an economically viable option, if designed properly. Since sedimentation efficiency is a factor of: 1) rate of flow, 2) particle size and density, 3) particle size distribution and influent concentration, the economic goal "to remove pollutants to the maximum extent practicable" requires finding the most efficient hydrodynamic separator.

The Hydrodynamic Separator

Hydrodynamic separators provide treatment to improve water quality before stormwater is discharged to surface waters or infiltrated to recharge ground waters. Baffles and screens can trap floating particles or relatively large particles, (Gross Pollutants), which are found in the water along with the sediment load. Scouring of collected sediment, as well as wash out of collected scum, oil and gross pollutants must be prevented if a device is to be effective between cleanings. A well-designed sedimentation chamber, or grit chamber, offers great benefit to a system by removing particles that otherwise would stay suspended in the flow and be discharged from the device.

Particle behavior has been graphed as size vs. flow rate and this can be used to effectively document the performance of a hydrodynamic separator. The New Jersey Department of Environmental Protection (NJDEP) soil sample in the Draft proposal of October 3, 2003 for the Total Suspended Solids Laboratory Testing Procedure matches very closely with the river deposits in the Netherlands. “Keileem” (translated is “Rock-loam”) is a product of the deposits from the rivers in western Europe. The Hjulström Diagram, (Figure 1), shows the global relationship between flow intensity and particle size if the particle density is 165 $\#/ft^3$ and the hydraulic radius of the flow channel is 3.28 ft. Further, the diagram presumes relatively clean water and no strong turbulence. Using this diagram, it can be determined whether a particle settles, stays in suspension, or erodes depending on the flow rate. As metals Phosphorous, etc. bond to the surface of large particles, they are also removed.

Stokes’ Law predicts the settling rate of a smooth rigid spherical particle in a liquid of a given viscosity. For example, a particle size of 75 Microns will settle at about $^{3}/_{16}$ inch/second in water with a normal viscosity. By comparison, the Hjulström Diagram shows the same settling rate of $^{3}/_{16}$ inch/second for the same particle size of 75 Microns. For the purpose of this paper, we reference the Hjulström Diagram because it is more conservative towards the larger particle fraction of a sample. That is, it predicts a lower settling velocity than Stokes’ Law for particles larger than 75 Microns. A lower settling velocity equates to a lower surface loading rate for the design of a treatment device, which makes the device larger in horizontally projected settling area, hence a conservative design. For particles smaller than 75 Microns, the Hjulström Diagram shows higher velocities than those calculated with Stokes’ Law. Here too we reference the Hjulström Diagram because in this range the resultant effect of gravity on the settling velocity diminishes. Additions such as filters and floc forming agents should be introduced to help remove particles smaller than 20 Microns.

It must be understood that there is a fundamental difference between transportation of fine particles (silt and clay) and coarse particles (fine sand) in flowing water. During transportation, fine particles are largely held in suspension. This means the concentration of the particles in the water is independent of the water depth. In fact, there is a nearly uniform distribution of particles in the vertical cross-section. It is an en-masse type of transportation. The fine particles move at the same speed as the water. The coarse particles are predominantly transported near the bottom of the flow channel. It is a type of bottom transportation where the particles more or less jump across the bottom. The coarse particle speed is much less than the speed of the water. The flow conditions that exist in a hydrodynamic separator will create a practical limit to the smallest sized particles that can be removed without chemical addition and/or filtration. As a secondary effect, a hydrodynamic separator can remove nutrients, dissolved solids, or bacteria as such items adhere to a particle that is itself removed.

In a sedimentation device, a particle separates from the water if the rise rate of the water is less than the sinking rate of the particle. In other words, water velocity up must be smaller than particle velocity down. ($V_{water}<V_{Particle}$). For any device, it is important to realize that the water enters and departs at the same elevation of the considered chamber[Note 1]. Thus, the quotient of the flow and the horizontally projected area of the chamber is the rise rate in Ft/s or Gpm/Ft^2. The greater the horizontally projected sedimentation area in the hydrodynamic separator’s GRIT CHAMBER, the greater the flow rate, for a given settling particle property can be allowed for removal of that particle because rise rate is directly proportional with the flow rate and the grit chamber area. To obtain the greatest removal rate in order to

---

[Note 1] The placement of chambers in series is not improving capacity, for they do not reduce the effective rise rate. Chambers placed in parallel will reduce the rise rate and be beneficial to solids removal.

achieve the “maximum extent practicable” it stands to reason that a stacked inclined plate sedimentation system housed within a structure having a small footprint will provide the lowest square foot cost of sedimentation area, thus making the goal of removal to the “maximum extent practicable” more readily attainable.

The Terre Kleen,™ patented by Terre Hill Concrete Products, provides the following:

		Terre Kleen Unit				
		Single cell Column A	Stacked parallel cells Column **B**	Column C		
Item	Terre Kleen Model	Primary Chamber Ft^2	Grit Chamber Ft^2	Device footprint Area Ft^2	Ratio (A+B)/C	Functional Price per square foot Device Cost/**B**
1	TK-09	9	57	27	2.44	\$228/Ft^2
2	TK-18	13	115	39	3.28	\$191/Ft^2
3	TK-27	17	172	51	3.7	\$181/Ft^2
4	TK-36	21	230	74	3.39	\$179/Ft^2
5	TK-45	25	288	88	3.55	\$167/Ft^2

The relatively low cost for the square foot sedimentation area is achieved by stacking the inclined plate cells, resulting in a projected sedimentation area that is 2.34 to 3.7 times greater than the square foot of the structure housing the Terre Kleen hydrodynamic separator. This increased size of the sedimentation area treats higher flow rates with various PSD and influent concentrations more efficiently than any other hydrodynamic separator.

The placement of the cells like floors in a high-rise building would require mechanical scrapers to remove the sediment. When the cells are inclined at 55 degrees to the horizontal the sediments slides to a hopper below and scour by future events is avoided and mechanical scrapers not required. Because the primary chamber precedes the grit chamber and flow goes below a vertical baffle, floatation of gross-pollutants and hydrocarbons occurs in the primary chamber and remains captured. Because the inclined cells are self-cleaning and the hopper below protected from future event flows, the scouring of collected sediment is avoided and internal by-pass of high flow events possible. This future High flow event treats Gross Pollutants and other floatable matter such as oil & grease and continues to partially treat the water by allowing flow through the inclined plate cells and a internal by-pass duct that is between the grit chamber and the baffle that separates the grit chamber from the primary chamber. This design avoids internal and traditional external by-pass methods to by-pass high flows around the device that do not trap gross pollutants.

Hjulström Diagram

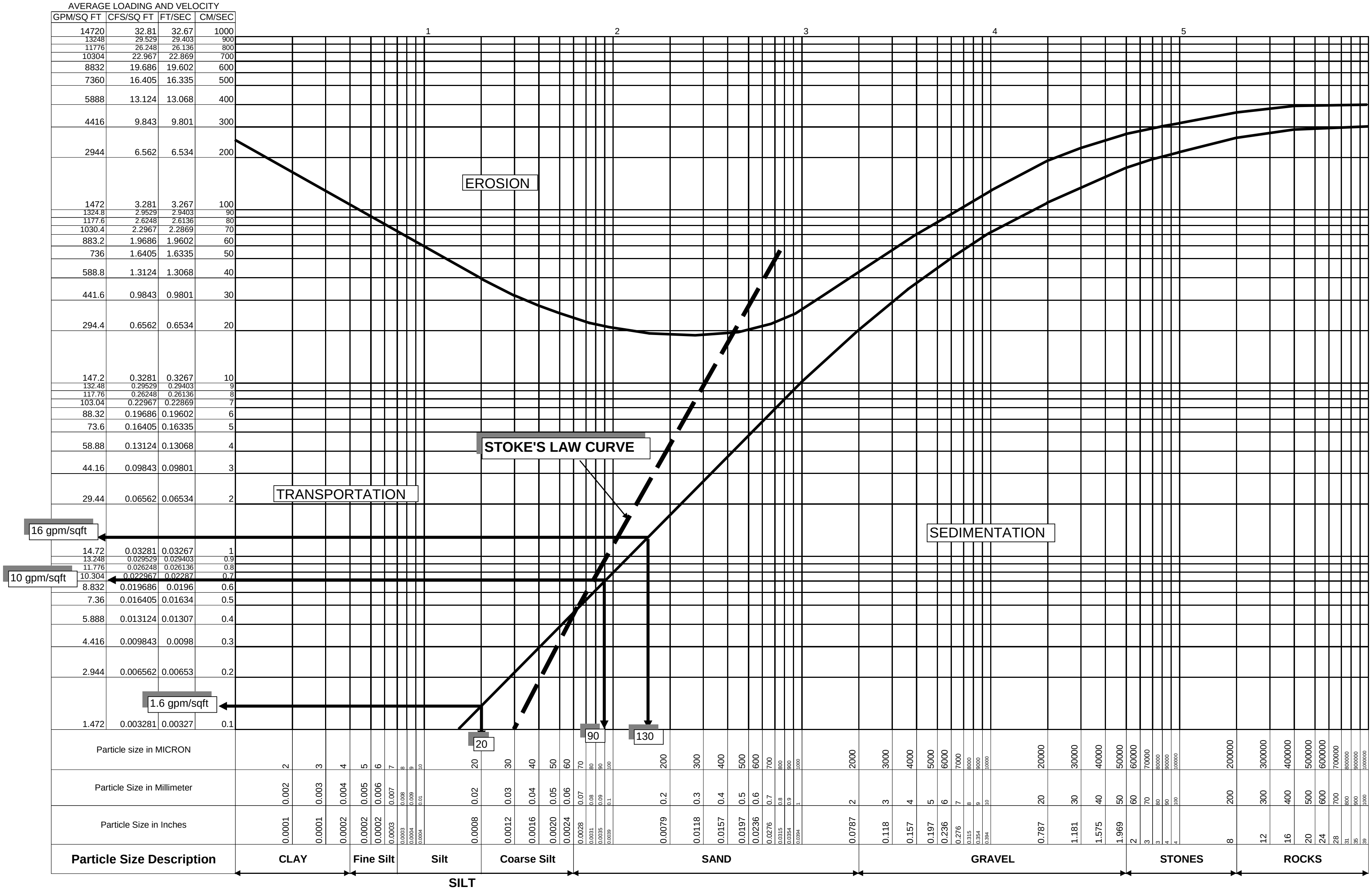

FIGURE 1

Design Scenario
Figures 2a, 2b, and 2c show the particle distribution of four soil samples and the NJCAT/ NJDEP TARP Tier II Protocol sample. In the case of the dune sand, Fig. 2a, it is clear that all particles larger than 130 Microns must be removed to obtain a 50% removal rate and all particles larger than 90 Microns to obtain an 80% removal rate. Using these particle sizes in the Hjulström Diagram, Fig. 1, this means the projected surface area in a hydrodynamic separator must be sized for a surface loading of 16 gpm/ft^2 to remove 50% of the suspended solids or a surface loading of 10 gpm/ft^2 to remove 80%. From Fig. 2b, the best results with clay are about 25% removal because 75% of the particles will be smaller than 20 Microns. The surface loading to remove particles of this size, 1.6 gpm/ft^2, is very low for a hydrodynamic separator. Figure 2c shows the removal rate for the NJDEP Laboratory sample will be about 65% for the size limit of 20 Microns. A filter is required to increase the removal percentage because the particles are too fine with low density to settle in these devices.

Flow conditions that exceed design flows will settle fewer solids in the grit chamber, because the surface loading rate is also proportionally increased. Gross pollutants and hydrocarbons should be screened and trapped prior to the grit chamber and remain trapped even above design flow conditions.

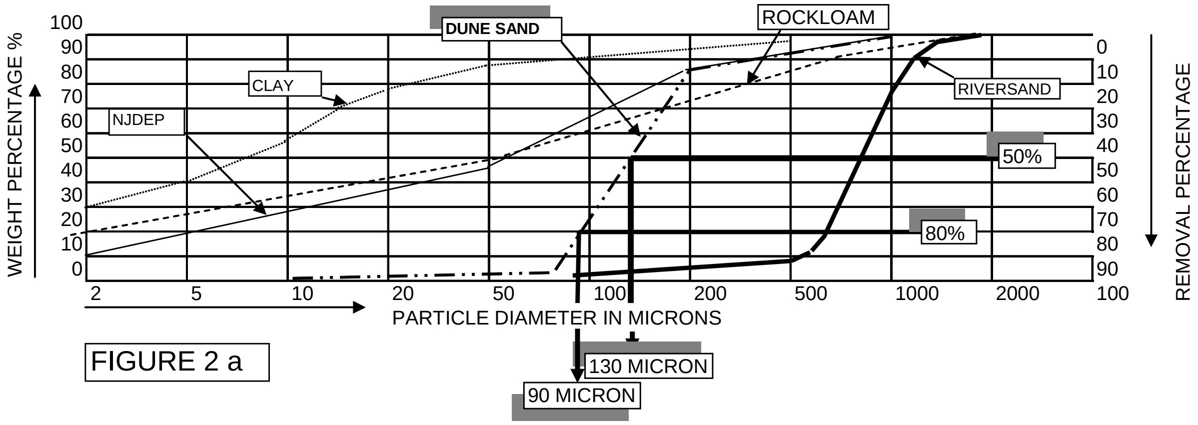

FIGURE 2 a

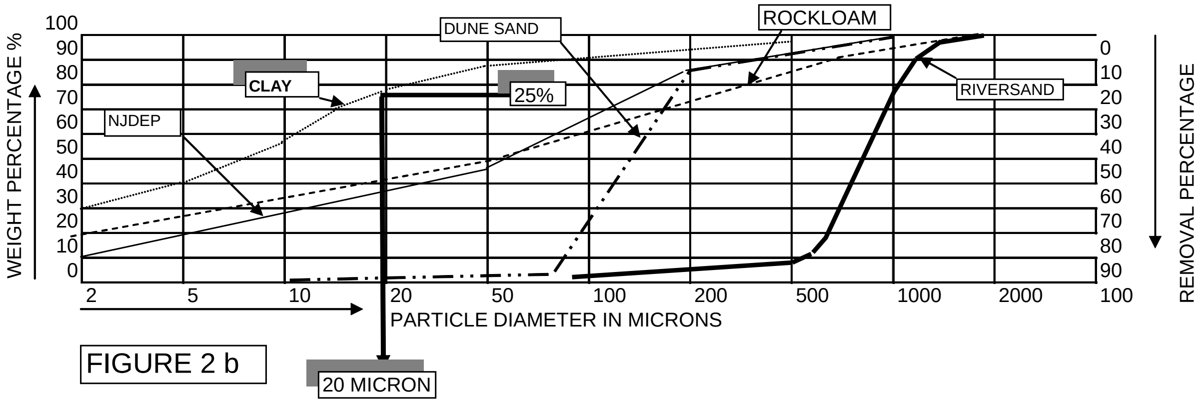

FIGURE 2 b

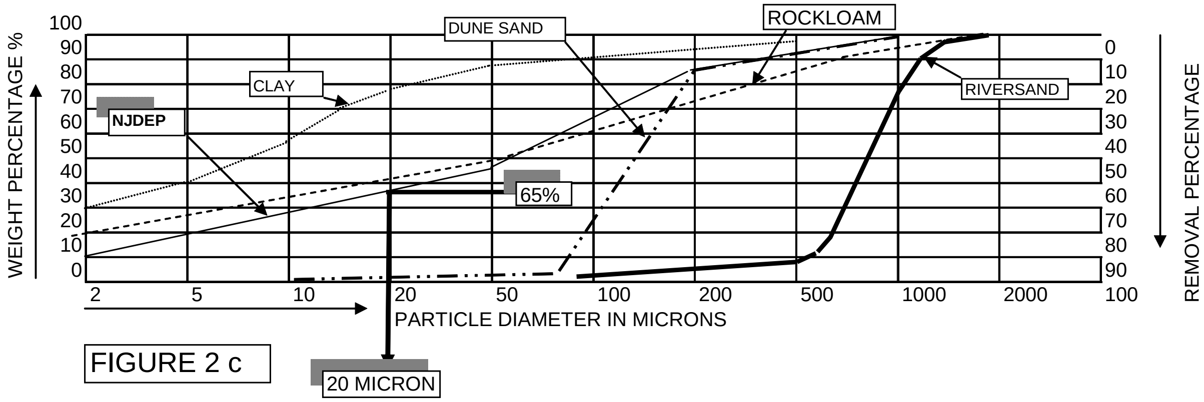

FIGURE 2 c

Conclusion

Pollutant removal design criteria must be more specifically defined and must reference Particle Size Distribution, Particle Size Density, and Influent Concentration Levels. With these design criteria, the Hjulström Diagram can be used to determine the size of the sedimentation area necessary to produce the desired level of pollutant removal at designed flow rates.

The authors propose the creation of **Solids Runoff Maps**, similar to soil maps, with associated particle distribution charts that list expected particle distributions in run-off of geographical areas. State and local authorities can then establish the removal requirements that apply a specific site in order to attain pollutant **removal "to the maximum extent practicable".**

Until specific pollution reduction goals are established, design engineers can write project specific requirements with an assumed sample distribution. This will guide the selection of a hydrodynamic separator with enough projected surface area to meet the removal requirements. The performance of the device is predictable because horizontally projected surface area or rise rate versus particle sinking rate and not depth is the controlling factor in sedimentation efficiency.