SEDIMENT REMOVAL IN THREE EXAMPLE STORMWATER TREATMENT DEVICES

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INTRODUCTION

Stormwater management is an issue that has been steadily increasing in importance for years. It is now very common that an engineer will be required to design a system to remove sediment from stormwater before it is discharged to a receiving body. In many cases a manufactured device is the most compact and cost effective option for achieving this goal.

A manufactured device will not be as effective as a pond. A pond will be many times larger and it is well known that a larger area will allow more time for settling and thus more removal. However, a manufactured device can be more efficient than a pond. By controlling the flow path and velocity it is possible to get more removal per unit of surface area than a pond. So, where space is a consideration the pond versus manufactured device decision can be relatively easy.

If the decision is to use a manufactured device, the choice of which one to use is complicated by the fact that many devices have different modes of action and different claims but there is very little data available to compare these claims. The New Jersey Department of Environmental Protection (NJDEP) took an important step towards providing data for comparing devices by outlining a testing protocol as part of its Technology Assessment Reciprocity Program (TARP) Tier I requirements. Unfortunately, the first round of data from the TARP Tier I testing was not consistent. In particular, not all devices used the same particle size distribution so a head to head comparison is not really possible.

In the absence of lab data it is still possible to compare categories of devices based on first principles. This paper looks at ponds and two types of device, ones that rely on simple settling and ones that rely on a vortex effect. In particular it will focus on the forces that act on a particle while it is in a manufactured device. These forces are gravity, drag and, depending on flow pattern, centripetal forces.

Some scale model results are presented to help corroborate the theory. These include some results for a simple pond. Although ponds and manufactured devices do not compete directly, their relative performance is of general interest.

DISCUSSION

Although stormwater treatment devices have been around for decades and many of them rely on sedimentation, which is a well understood process, some confusion still exists as to how these devices work. The performance of these devices is certainly complicated by difficulty of calculating the flow rate into the unit, the difficulty of calculating the actual flow path in the unit and the fact that the particles to be settled out are not usually well defined. These complicating factors mean that sizing should be done using a computer model.

However, because the underlying principles are relatively simple a computer model is not needed when considering how a device works. Fundamentally, there are up to three primary forces acting on a particle in a settling device. These forces are discussed in more detail below. A comparison of these forces and analysis of which forces are active in a given device allow for devices to be compared at a general level.

Gravitational force

This force will be present in all settling devices, acting vertically downward. The equation for the force of gravity is well known:

$F = mg$

Where F = force (N)
m = mass of particle (kg)
g = gravitational constant = 9.81 m/s^2

So, the gravitational force acting on the particle is 9.81m. A model particle that is a sphere with a diameter of 100 microns and a density of 2,650 kg/m^3 will have a mass of 1.39×10^{-9} kg. This gives a gravitational force of

$(9.81)(1.39\times10^{-9}) = 1.36\times10^{-8}$ N.

Centripetal forces

The principle behind vortex separators is the same as that behind hydrocyclones. The water is directed tangentially so that a vortex is created. In this flow pattern, inertia moves the solid material out towards the wall. Particles that end up out at the wall then move downward and discharge from the bottom of the unit.

In order to maintain continuity in the fluid, an upward vortex rotating in the opposite direction is created in the centre of the device. Particles that do not move far enough out to the edge of the unit will be caught in the upward vortex and will escape the unit. So, the tangential force on the particles must be enough to carry the particles out to the wall relatively quickly.

The force involved acts radially inward and is referred to as a centripetal force. Sometimes the term centrifugal force is used to describe these rotating systems but centrifugal force it not a real force. It exists only in the reference frame that is spinning around with the water, standing in a reference frame outside the cyclone looking into the unit there is no centrifugal force [1]. The force acting on a particle in a circular flow field is [2]:

$$F = m\omega^2 r$$

with $\omega = v/r$ so that

$$F = \frac{mv^2}{r}$$

Where F = centripetal force acting radially inward (N)
m = mass of particle (kg)
ω = angular velocity (m/s^2)
r = radius (m)
v = linear velocity, which equals fluid velocity in a vortex separator (m/s)

From this it can be seen that the force pulling the particle inward increases as the particle moves toward the centre of the chamber. So, a particle has the greatest chance to escape when it is at the outside edge of the chamber. Several of the vortex separators tested as part of the TARP program had a chamber diameter of 1.22 m and were tested at ~30 L/s. The individual results can be found at reference [3], a summary at reference [4]. A typical inlet pipe diameter for one of these units would be 0.45 m. Assuming the pipe is full (submerged inlet) the inlet velocity will be on the order of

$$0.03\ \text{m}^3/\text{s} \div \pi^*(0.45/2\ \text{m})^2 = 0.19\ \text{m/s}$$

Taking this velocity and the chamber radius of 0.61 m gives a force on the particle of 0.059m. Using the same particle as in the section above, the force can be calculated as:

$$(0.059)(1.39\text{x}10^{-9}) = 8.23\text{x}10^{-11}\ \text{N}.$$

This is 165 times less than the force of gravity so it cannot be considered a significant contributor to sediment removal under these conditions.

In order for the vortex to be effective the fluid velocity must be as high as possible and the diameter of the inner vortex must be as small as possible. Typical velocities are on the order of

2-3 m/s and typical dimensions are on the order of centimeters. The resulting forces are >9.81*m*. Finally, hydrocylcones are conical and not cylindrical so that a downward vortex is created. These conditions lead to significant headloss so pumped flow is required. Thus, while a vortex separator operates on the same principle as a hydrocyclone, the application is very different.

Drag force

The other force acting on a particle, in all types of systems, is a drag force. This force acts in the direction of flow, for the sake of simplicity it can be assumed to act in the horizontal direction. The net drag force on a body is caused by pressure and viscous shear acting on the body. The action of the forces is a function of the boundary layer around the particle and this is a function of the fluid velocity. The equation for the drag force is [5]:

$$F_D = C\frac{\rho v^2}{2}A$$

Where: F_D = drag force (N)
C = drag coefficient (dimensionless)
ρ = density of water (~999 kg/m^3)
v = velocity (m/s)
A = projected area of particle (m^2)

In all but the simplest cases the forces cannot be accurately calculated so they are accounted for by the drag coefficient. For turbulent flows the drag coefficient cannot be calculated either so it is determined empirically.

A typical treatment condition for a non-vortex settling device, again based on the testing done for TARP [3,4], might be 18 L/s through a 0.38 m chamber inlet. The inlet is usually the point of flow restriction so the maximum velocity occurs there. In this case the maximum velocity is

$0.018\ \text{m}^3/\text{s} \div \pi*(.38/2\ \text{m})^2 = 0.16\ \text{m/s}$.

It can be shown that the Reynolds number under these conditions will be >10,000 so the particle will be surrounded by a turbulent wake. The drag coefficient for a spherical particle has been determined empirically for these conditions. It is nearly constant and equal to ~0.4 [5].

Again considering the model spherical particle, the resulting force is

$F_D = (0.4)(999.1)(0.16)^2[\pi*(.0001/2)^2]/2 = 3.95\text{x}10^{-8}$ N

The drag force is >480 times the centripetal force. So drag is the only significant horizontal force. There is negligible separation due to the circular motion. The drag force is even nearly triple the gravitational force so it is the dominant force in the system. What is important about inducing a swirl flow pattern is to increase the path length the particle sees. This provides more time for separation due to the only vertical force, gravity.

Based on the analysis of forces it is clear that the only two important forces are drag and gravity, with drag being dominant. This means particles will be pulled along horizontally faster than they will settle. So for a system to work it has to provide an adequate path length, or residence time, for a particle to become trapped. Thus ponds, settling devices and "vortex" devices can all be compared based on residence time.

EXPERIMENTAL

In order to corroborate the assumptions made in the above calculations, experiments were conducted using scale models. In order to get reasonable numbers for comparison the experimental conditions were scaled using Froudian similitude. It should be noted that the results are not intended to accurately model commercial scale systems, they are only intended to provide numbers for comparison.

The tank used to simulate the manufactured devices was 0.45 m in diameter and 0.65 m high. The pond was simulated by a tub 0.50 m wide, 0.30 m deep and 1.0 m long. In all cases the inlet diameter was 0.075 m. The flow rate used was 0.25 L/s and the particles tested were US Silica Sil-co-sil 250. The inlet concentration was 150 mg/L.

Outlet concentrations were measured after three detention times (device volume divided by volumetric flow rate). The results are shown in Figure 1. The high point in the curve for the pond is likely an artifact of the experimental procedure or analysis.

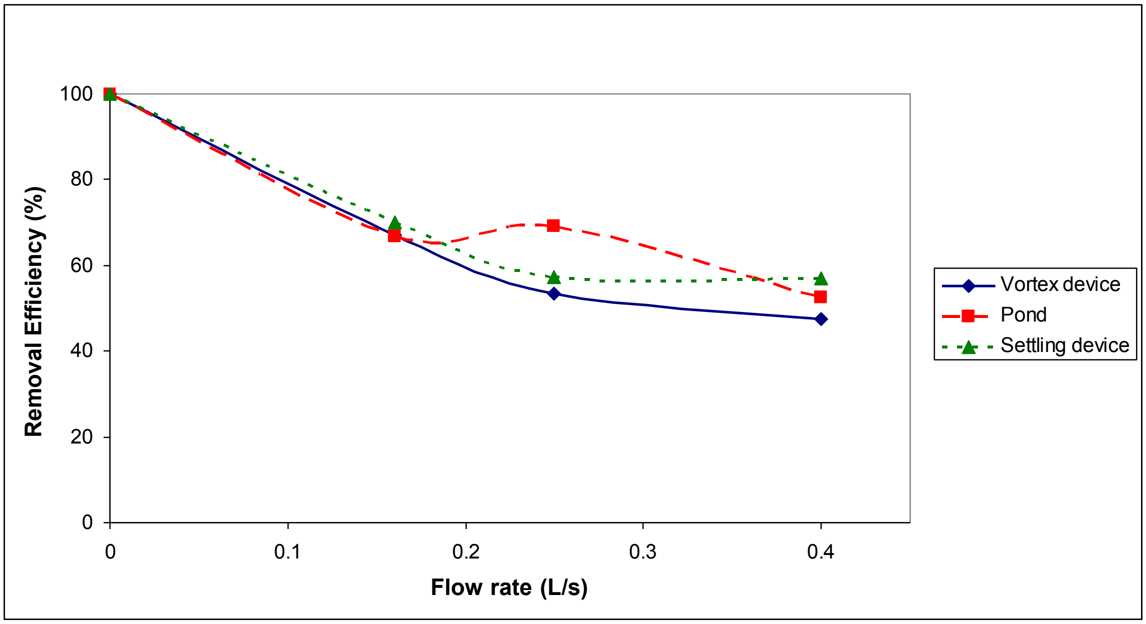

Figure 1 – Removal efficiency in three model sedimentation devices.

The results show that performance is quite similar for all the devices. This supports the discussion that the most important factor is residence time so that different geometries only improve efficiency if they improve residence time. Overall these results reinforce the importance of residence time as a figure of merit for stormwater settling devices.

Given the importance of this parameter a simple volume divided by flow rate is not an accurate enough measure. To get a really accurate comparison and sizing of devices, the residence time distribution should be determined. This can be done by tracer studies or approximated by computational fluid dynamics modeling. Unfortunately this type of information is difficult to obtain and not currently readily available

CONCLUSIONS

This analysis of the basic forces at work in gravity separators clearly shows that the drag force is the dominant force, followed by gravity. Centripetal force, sometimes referred to incorrectly as centrifugal force, is a distant third in terms of magnitude. Devices that employ a circular motion may achieve better settling through increased path length but the radial forces involved are negligible.

The analysis was confirmed in principle by experimental results obtained in scale models. A vortex device, a settling device and a pond, all of similar dimensions, gave similar separation results. This supports the conventional wisdom that the best indicator of a device's effectiveness is the residence time in the unit.

Thus an engineer faced with choosing a system for stormwater treatment can focus on the residence time in the unit. On this basis, different types of units can reasonably be compared. Once a unit is chosen it can be sized using additional input such as rainfall data, particle size distribution, impervious area to be treated, etc.

References

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