Proposed scaling relations for manufactured stormwater BMPs

John S. Gulliver, Qizhong Guo, John J. Sansalone, Gregory Williams, and J.S. Wu
for the Scaling Sub-Committee,
Guidelines for Certification of Manufactured Stormwater BMPs Task Committee

Manufactured stormwater best management practices (BMPs) generally apply one or both of two unit operations to remove particles from stormwater runoff: hydrodynamic separation and filtration. Hydrodynamic separation is best used to remove sand particles, while filtration is used to remove organic particles as well as silt and clay. Many manufactured stormwater BMPs also have a chamber designed to remove floatables, or particles that are lighter than water. The numerous designs and multiple sizes of these manufactured stormwater BMPs suggest the need for scaling criteria to size and apply designs in the field. This paper reviews the scaling criteria research that has been completed, the research that may be adopted from other areas, and the needs for developing scaling criteria in manufactured stormwater BMPs.

KEYWORDS

Best Management Practices, Unit Operations, Unit Processes, Stormwater, Particulate Matter, Particle Size Distributions, Dimensionless Numbers, Scaling

Introduction

Most manufactured stormwater BMPs (M-BMPs) function as either hydrodynamic separators or filters. Hydrodynamic separators utilize the difference in density to settle suspended solids into the bottom of the device and to retain floatables, such as hydrocarbons and trash at the surface of the device, while the effluent flows through an intermediate elevation. Filters use a media to retain particles of a given size while the effluent flows through the filter. These devices are generally placed below ground, and therefore are suited for high density locations and retrofits to existing infrastructure. There is a great need for these underground devices, and manufacturers have responded to this need. M-BMP units supplied by each vendor are manufactured with specific capacity/size categories. Scaling criteria help in developing performance specifications for various sizes of M-BMP and in utilizing model-scale tests to develop performance specifications. However, an industry-wide, uniform methodology to scale and size these devices does not currently exist. This paper will review the need for scaling criteria in M-BMPs, and propose scaling criteria for head loss and flow, particle separation, scour and filtration.

Need for Scaling Relations

Because of interaction with a complex flow field, the need for scaling criteria is probably greatest in hydrodynamic separators. The vertical velocity relative to water causes separation while the turbulence of the flow field tends to mix the media that is being separated back into the water. There are three issues that need to be addressed: 1) settling of heavier-than-water particles out of the flow, 2) rise of lighter-than-water compounds such as oils and trash out of the flow field, and 3) the tendency to entrain both after separation has been accomplished in high flow. Experimental tests are possible on model-scale or full-scale devices, but these tests will need to be scaled to another size of device in order to meet demand. In addition, if an accurate scaling procedure can be developed and verified, it will be possible to perform smaller-scale model studies on each device which can be scaled to full device size with a known accuracy.

A filter media can be tested through column studies. However, the parameters that need to be controlled (e.g., grain size versus column diameter) and scale-up to full scale filters needs to be documented. In addition, many filters are partially self-cleaning, utilizing turbulence in the flow field to remove caked material from the filter. The scaling relations developed in item 3) above may be sufficiently general to apply to this case as well. Tests would still be required on the devices to demonstrate and measure the self-cleaning properties. To apply the results of such tests to a multiple of device sizes would require scaling criteria.

Dimensionless Numbers and Scale Effects

One goal of scaling is to have one dimensionless number that represents the important processes of the device. This is not generally possible at all scales, so criteria are developed on the appropriate model scale. These criteria include a critical Reynolds number value that must be exceeded to assure that turbulent flow occurs:

$$\mathbf{Re} = \frac{Q}{\nu d} \geq \mathbf{Re_C} \tag{1}$$

and a critical Weber number that must be exceeded to assure that surface tension does not alter the flow field:

$$\mathbf{We} = \frac{\rho Q^2}{\sigma d^3} \geq We_C \tag{2}$$

where Q is discharge through the device, ν is kinematic viscosity, ρ is density of the liquid, σ is liquid surface tension, g is the acceleration of gravity, and d is the smaller of the important length scales in the flow field, such as the diameter of the device or depth of water. It is also common practice to enhance the wall roughness in a physically-scaled model to result in a similar relationship of wall shear stress to flow velocity (similar friction factor or drag coefficient) as in the full scale.

Fenner and Tyack (1997) reviewed the scaling criteria for removal efficiency and head loss of hydrodynamic separators and, in addition to geometric similarity, came up with the following dimensionless similarity criteria:

Removal Efficiency: Hazen number = $\mathbf{Ha} = \frac{AV_s}{Q}$ (3)

Froude number = **Fr =** $\sqrt{}$

scaling was more successful at higher removal efficiencies. They proposed a hybrid scaling formula which incorporates the impact of each dimensionless number:

$$\frac{Q_{prototype}}{Q_{model}} = \eta_m L_r^2 + (1-\eta_m) L_r^{2.5}\left(1+\frac{d_p}{3mm}\right) \tag{8}$$

Where η_m is the fraction of removal in the model, d_p is the mean particle diameter in mm and L_r is the length ratio (prototype/model). To be used in practice, Eq. (8) should be adjusted for the specific gravity of the particles, which typically will differ from those used in Fenner and Tyack's experiments, or arranged to use the settling velocity of the particles. The latter was performed on Fenner and Tyack's data to result in:

$$\frac{Q_{prototype}}{Q_{model}} = \eta_m L_r^2 + (1-\eta_m) L_r^{2.5}\left(1+\frac{V_S}{25mm/s}\right) \tag{9}$$

where V_S is settling velocity of the particles in mm/s.

A relationship for settling velocity has been developed by Ferguson and Church (2004)

$$V_s = \frac{gRd_p^2}{18\nu + \left(0.75CgRd_p^3\right)^{1/2}} \tag{10}$$

where ν is kinematic viscosity of the fluid, d_p is particle diameter, g is the gravitational acceleration, R is the specific gravity in water (1.65 for silica sand) and C is a constant equal to 0.4 for spheres and 1 for typical sand grains. Equation (10) becomes Stokes law at small particle diameters and results in a constant drag coefficient for large particle diameters.

A criticism of Eq. 8 is that it mixes flow scaling with particle settling into one equation. The result is that Eq. (8) and (9) will be applicable only to the particles that Fenner and Tyack tested. This is not necessary, and it is possible to separately scale settling velocity and flow. One proposal for scaling is outlined in the following sections.

Flow and Head Loss in Hydrodynamic Separators

Flow in most hydrodynamic separators is controlled by gravitational forces. The field of physical hydraulic models has been performing this type of scaling for many years. The criteria are as follows:

1. The model should be sufficiently large that surface tension (Weber number effects) does not alter performance and scaling of the model.
2. Reynolds numbers in the model should be sufficiently large such that the flow is not close to laminar. For open channels this is Re = 2,000 and for closed conduits, Re = 8,000 is recommended.
3. The friction factor in the model should be close to the prototype value. This often means adding some roughness to the model. This will make the ratio of turbulence to flow velocity similar in the model and prototype.

4. Froude number scaling is now possible:

$$Fr_p = Fr_m \tag{11}$$

where subscripts *p* and *m* indicate prototype and model scales, respectively. Then,

$$\frac{Q_p}{Q_m} = \left(\frac{L_p}{L_m}\right)^{5/2} \tag{12}$$

Settling and Rise in Hydrodynamic Separators

Scaling for settling with both retention (Hazen number) and turbulent mixing (Peclet number) result in a similar scaling parameter for settling of solids in hydrodynamic separators. Froude number scaling, Eq. (12), should also be followed. The final result is:

$$\frac{Q_p}{Q_m} = \frac{V_{Sp}}{V_{Sm}}\left(\frac{L_p}{L_m}\right)^2 \tag{13}$$

It is possible to satisfy both Eqs. (12) and (13) because of the addition of settling velocity to equation (12). Although model-prototype tests are needed to verify this scaling technique, the fact that both mixing and retention result in the same scaling parameters is encouraging. In addition, rise velocity for floatables should follow the same scaling parameters as settling.

Scour in Hydrodynamic Separators

Collected solids in hydrodynamic separators, if not cleaned, will eventually reach the height where scour of the collected solids will occur. In addition, some hydrodynamic separators are exposed to higher flows, beyond the design flow, and are therefore subject to potential scour of collected solids. Scour is physically modeled by equating (dimensionless) Shields stress, the presumed bottom stress where sediment begins to move off of the bottom, divided by parameters of the sediment. Shields stress is given by:

$$\tau^* = \frac{u_*^2}{gRd_P} \tag{14}$$

where $u_* = \sqrt{f/8}V$ is shear velocity.

Equating Shields stress for model and prototype results in

$$\frac{Q_p}{Q_m} = \sqrt{\frac{f_m d_{pp} R_p}{f_p d_{pm} R_m}}\left(\frac{L_p}{L_m}\right)^2 \tag{15}$$

As with settling, Froude number scaling, Eq (12) should also be followed. The process of scour in a Hydrodynamic separator is a combination of lifting sediment off of the bed and settling of that sediment back to the bed. Thus, scour similarity needs to simultaneously satisfy Eqs. (13) and (15). To get similarity relations (13) and (15) to both be satisfied, relatively large sediment is necessary, such that Eq. (10) becomes

$$V_s = \sqrt{\frac{gRd_p}{0.75C}} \tag{16}$$

This is often difficult to achieve.

Removal Efficiency for Filters

The particle trapping of a filter is a local phenomenon, dependent upon the characteristics of the media and the particle size distribution of the suspended solids. This can be relatively well simulated with a bench-top column test, where the media filtration efficiency is tested with the particle size distribution of interest. The scaling parameters of most interest are the media Reynolds number,

$$\boldsymbol{Re} = \frac{Q}{\varepsilon^{1/3} A^{1/2} \nu} \tag{17}$$

and the suspended solid-media size ratio:

$$L_s = \frac{d_p}{d_{med}} \tag{18}$$

where ε is the porosity of the filter media and d_{med} is the equivalent spherical diameter of the media. Then, scaling of discharge and media would follow the relations:

$$\frac{Q_p}{Q_m} = \left(\frac{\varepsilon_p}{\varepsilon_m}\right)^{1/3} \frac{L_p}{L_m} \frac{\nu_p}{\nu_m} \tag{19}$$

and

$$\frac{d_{med,p}}{d_{med,m}} = \frac{d_{p,p}}{d_{p,m}} \tag{20}$$

The scaling of one particle size distribution to another, and scaling with filter flow rate is of interest because it would reduce the required filtration tests. In addition, filters are often placed in the turbulent flow field of the device, resulting in differential pressure drop across the filter that varies spatially.

In the application of filters, one needs to also consider the fouling that will occur at the filter surface. Fouling will increase the frequency of cleaning and could reduce the filter life. The cleaning of particle cake which has accumulated on the surface of the filter, however, cannot be simulated with column tests because cleaning is often provided by turbulence generated in the chamber of the filter device. This would require a scaling analysis similar to high flow scour, since both are based upon the resuspension of collected material.

Conclusions

1. Scaling laws have been proposed for head loss, settling, scour and filtration. These laws need to be tested with combined model and prototype studies of manufactured BMPs.
2. The scaling relation of Fenner and Tyack is not recommended, because it combines settling and head loss similarity and is applicable only to the type of spheres used in their experiments.
3. Froude number scaling, with approximately equal friction factors, should be used in all model studies.
4. Settling can be modeled with Peclet number or Hazen number scaling. They are equivalent, and encompass the important processes of settling.
5. Scaling for scour should follow Shields stress and Hazen (Pecltet) number scaling. This will be difficult, but is possible if the sediment is sufficiently large, such as with plastic beads.
6. The scaling of filtration units is dependent upon the size of the particles relative to the size of the media and the pressure distribution in the filtration chamber. Froude scaling with equal friction factors should be sufficient for pressure distribution. In addition, cleaning of a filter unit is similar to scour, such that the scour scaling parameters should also be followed to simulate cleaning of the filter fouling. While bench tests are acceptable to test the filter media, the operation of the filter as a whole deserves a full scale prototype test, because of the complexities of pressure distribution and fouling. Model scaling relations would help in determining the performance of manufactured filtration units.

The ability to scale the performance of manufactured stormwater BMPs through similitude relationships will help size and design these products for municipalities. In addition, it will focus the research and experiments on items that are truly essential to performance. The result will be more focused research, improved quality of tests, and better manufactured stormwater BMPs. Although there is much work to be completed in improving scaling relations for these devices the committee believes that the benefits will outweigh the costs.

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