TECHNICAL PAPER CST-07-002

UNDERSTANDING RE-SUSPENSION RATES

Abstract

Re-suspension is a concern for structural BMPs. This includes ponds, manufactured vaults, underground storage pipes, and any other vessel. The velocity of water moving over sediments is the primary factor affecting re-suspension. Peak flows do not represent typical conditions and should not be emphasized in re-suspension studies. The size of a flow in cubic feet per second does not directly relate to the velocities in a vessel which are in feet per second. The periods between storm flows represent the normal conditions in a vessel, with periods of flow being the exception rather than the rule, therefore, the effects of settling, sorting, adhesion, other physical and chemical processes have an influence on re-suspension. Even when the conditions are right for re-suspension, only particles on the surface of a sediment bed will be subject to re-suspension. Any re-suspended particles immediately become candidates for re-deposition. These factors vary by the type of vessel and the material under scrutiny, but simple studies of scouring rates based on flow velocity and particle size can provide a high confidence level for controlling re-suspension.

Factors Affecting Re-Suspension

1. Velocity

When a certain flow volume carrying sediments enters a vessel, it usually has been confined to some conveyance structure, such as a pipe or a swale. The rate of flow can be measured in cubic feet per second, but the entry velocity is dependent on the size and slope of the conveyance. Five cubic feet per second (cfs) might have a velocity of five feet per second (fps) if it enters a vessel through a relatively small pipe, or it might have a velocity of 1/4 fps if it enters through a relatively large pipe. These are vastly different conditions at the front of a vessel (or pond) and demonstrate that the same peak flow measured in cfs is not the primary indicator of re-suspension conditions which depend directly on velocity and turbulence. Figure 1 below shows the scouring velocities for various sized particles as determined in a study done by T. R. Camp in 1946. This table is based on typical conditions, but variables such as the density and angularity of the particles can affect scouring speeds as well as the particle size itself. Under normal conditions, 2.36 fps will scour 2000 micron particles which most people would recognize as very large grains of sand. This means that a five fps entry velocity will cause enormous re-suspension problems when water enters something like a wet pond at that velocity. A velocity that high would scour particles over 8,000 microns which is fine gravel. On the opposite end of the velocity scale, a ¼ fps entry velocity would not be fast enough to scour 31 micron particles which are mid-range silt. This is a tremendous variation for two situations with the exact same rate of flow in cfs. It points out that the velocity of flow in fps, not the rate of rate in cfs is the dominant factor in re-suspension.

The following table is taken from, "Wastewater Engineering: Treatment Disposal and Reuse", Metcalf and Eddy, Third Edition, McGraw-Hill, New York (1991), where they cite a famous study by Camp, Camp, T.R. 1946, "Sedimentation and the design of settling tanks". ASCE Trans. 1946, page 895.

Scouring Velocities

Particle Size	Velocity (m/s)	Velocity (ft./s)
2000	0.72	2.36
1000	0.51	1.67
500	0.36	1.18
250	0.25	0.84
125	0.18	0.59
62	0.13	0.42
31	0.09	0.29
16	0.06	0.21
8	0.05	0.15
4	0.03	0.11

Figure 1

2. Physical Properties of the Sediments

The table of scouring velocities was developed from a rather complex formula that takes into account the porosity of the sediments being scoured, the internal friction characteristics of the sediments, the viscous friction of the water, the density of both the water and the sediments, the pull of gravity, and the size of the sediments. Obviously, different particles of the same size will have different friction (roughness and adhesion) characteristics, different densities, and may be in a matrix with different porosity, which will change the scour speed. The formula can be expressed as follows:

$$s_s = \sqrt{\frac{8 \cdot (1-n) \cdot \mu \cdot (\rho_q - \rho_w) \cdot g \cdot d_s}{\lambda \cdot \rho_w}}$$

(from Camp as above) where,

S_s = scour speed (m/s),
n = porosity coefficient
μ = friction coefficient
ρ_q = density of the particle (tons / m^3)

ρ_w = density of water (tons / m^3)
g = gravitational constant (9.81)
d_s = diameter of the particle (m or microns / 10^6)
λ = viscous friction coefficient

Each parameter has an effect on scouring. Note that the scour speed varies as the square root of the result from the division of two numbers. The numerator, or top number is a constant value of 8 times several other factors. The denominator is the viscous friction coefficient (lambda) times the density of water in tons per cubic meter. As the numerator (top number) becomes larger, the speed to scour a particle becomes larger which makes scouring more difficult, and as the denominator (bottom number) becomes larger, the speed to scour a particle becomes smaller, and makes scouring more likely.

From a simple common-sense approach, as the density of the water increases and the viscosity friction increases, the "thicker" water would naturally seem more likely to scour particles, and this is exactly what the formula indicates. The density of water at any temperature is readily available from charts. At zero degrees Celsius, it is almost exactly 1000 kg/m^3, or 2,204.62 pounds, which is 1.1023 tons/m^3. As water warms to 20 degrees Celsius, the density goes down to 998.2 kg/m^3. The density of the water has a small, but measurable effect on scouring speed.

The value of lambda, the viscous friction coefficient, is not as easy to calculate, but it ranges from 0.01 to 0.03. For almost all water vault calculations this value will be 0.03 or very close to that value. If we assume 0.03, it is a conservative assumption, as the larger value will give a larger denominator, which would act to lower the scour speed and make re-suspension more likely. The product of the density of the water and the viscous friction coefficient gives us the value of the denominator. Under normal circumstances, the value of this part of the equation will be very close to (1.1023 * 0.03) or 0.033069. For rough calculations on a spread sheet, this value could be expressed as a constant.

In evaluating the numerator or top part of the expression in this equation, we find that this value is the product of six terms. The first term is a constant value of eight. The next term is (1–n) or one minus the porosity coefficient. In Camp's table above, he calculated the scour speeds for silica sand. He used a porosity coefficient of 0.6 which is the highest value in the range. Porosity is essentially the amount of space between particles. Less porous sediments can be thought of as more tightly packed, and more difficult to re-suspend. More porous can be thought of as arranged more loosely, and easier to re-suspend. The co-efficient ranges from about 0.4 (more tightly packed) to 0.6 (more loosely packed) for bed sediments. This is a relatively narrow range, but it can be important if sediments have a chance to become sorted and packed down. Note that using 0.6 as Camp did will make the value of (1–n) smaller, which will act to lower the scour speed. Once again, this is a conservative value. If you have sediments that are tightly packed, you can safely move the coefficient to a lower value. This will make (1–n) larger, and because it is in the numerator, it will raise the scour speed.

The internal friction of the sediments (μ) can be much more variable. The range is from 0.1 to 0.6 for sand grains. Friction depends on the shape and roughness of the particles, and obviously can have a very large effect on scouring speeds. A low number indicates low internal friction, which and make a particle very easy to scour. From the range given, it can be seen that the value can be up to 6 times greater than the lower part of the range for some sand particles. Camp used a value of 0.15 for his charts, which is well to the lower end of the range. This will tend to make the scour speed lower. If you have valid reasons to raise this value it will raise the scour speed and make re-suspension less likely, but higher values are not usually valid for vaults or ponds where deposition of the material is recent and has resulted from wash-off.

The next term is simply the difference in density between the sediments and the water ($\rho_q - \rho_w$) given in tons/m^3. The Camp chart uses the density of quartz, which has a theoretical density of 2.65 gm/cc or 2.65 times that of water. If we used 1.1023 for water, we can then use 2.9208 for quartz. In nature the density of quartz varies from 2.60 to 2.65, but this variation is minor. The variation in density for the equation that can occur from particles washing off of a parking lot or other developed portions of a site is not minor at all. If the density of a particle washing off of a site is less dense than quartz, the value of this term will go down. If the density of the particle is close to that of water, the value will be very small, and will make the scour velocity very small. This will mean very high re-suspension rates for that type of particle. For more dense particles, like a small particle of copper, which has a relative density of 8.94 to that of water, the value of the term would go up, so that the scour speed would increase dramatically. This would mean that re-suspension of this type of particle would be very unlikely. Field data has shown us that the average relative density of sediments removed from vaults in the field is approximately 1.70. This is a mixture of particles such as sand, very low density trash and vegetative debris, and heavier particles with more metallic content. When we determine a re-suspension curve for any vessel, the density of the particles must be considered as a prime factor.

The next two terms are very straightforward. The gravitational constant that is appropriate to use for this formula with the units of the values stated as they are in metricsis 9.81. This will not change unless the gravity of earth changes. The final term in the numerator is the size of the particle in meters. This number can be found by dividing the size in microns by 1,000,000 (1 meter = 1,000 millimeters, 1 millimeter = 1,000 microns). It is important to remember this conversion because other terms in the equation are in meters and cubic meters. Entering the particle size in microns would yield a very high scour speed indeed and eliminate re-suspension altogether.

3. The Relative Influence of Physical Properties

Any study of how these parameters affect re-suspension should keep in mind that the re-suspension speed is the square root of the result of dividing the numerator by the denominator. This means the result of any change in a value is mitigated by the fact that the square root of that value is the actual effect. For example, a change density from 2.6 to 1.7 for the particles would make that term change from a value of (2.6 – 1.0) or 1.6 to a value of (1.7 – 1.0) or 0.7. The square roots of those numbers are 1.26 and 0.84 respectively. The difference between 1.6 and 0.7 is 0.9 and seems large compared to the difference between 1.26 and 0.84 which is 0.42. This fact is the major reason why some of the parameters introduced by Camp and others do not have a very large effect on re-suspension, while others need to be considered carefully.

4. How to Simplify the Equation for Typical Usage

In the lab, most tests utilize silica. The temperature of the water, the physical characteristics of the sand, and the velocity of the water are well known and closely controlled. A very simple formula can be applied if we take all of Camp's assumptions (which are very well within reason for silica sand in a vault) and boil them down to one constant. In this simplification, we set the porosity at 0.6, viscous friction at 0.15, the density difference at 1.819, the gravity at 9.81, viscous friction at 0.3 and the density of water at 1.102, all in the appropriate units, of course. Using these values, and expressing the diameter of the particles in microns, we can state the equation in much more understandable terms, and state it for both metric and English units. In summary, for the standardized conditions:

$S_s = \sqrt{d}/62.11$ (d is diameter in microns, S_s is in meters per second

And

$S_s = \sqrt{d}/18.931$ (d is diameter in microns, S_s is in feet per second

Using these values will duplicate Camp's table exactly. These formulas can be modified to accommodate other densities if it is remembered that a density adjustment factor should be a ratio of 1.65 / ($\rho_{other} - \rho_w$), where ρ_{other} is the density of the other particles to be considered. The chart (Figure 2) below plots the scour velocity in fps versus particle size in microns.

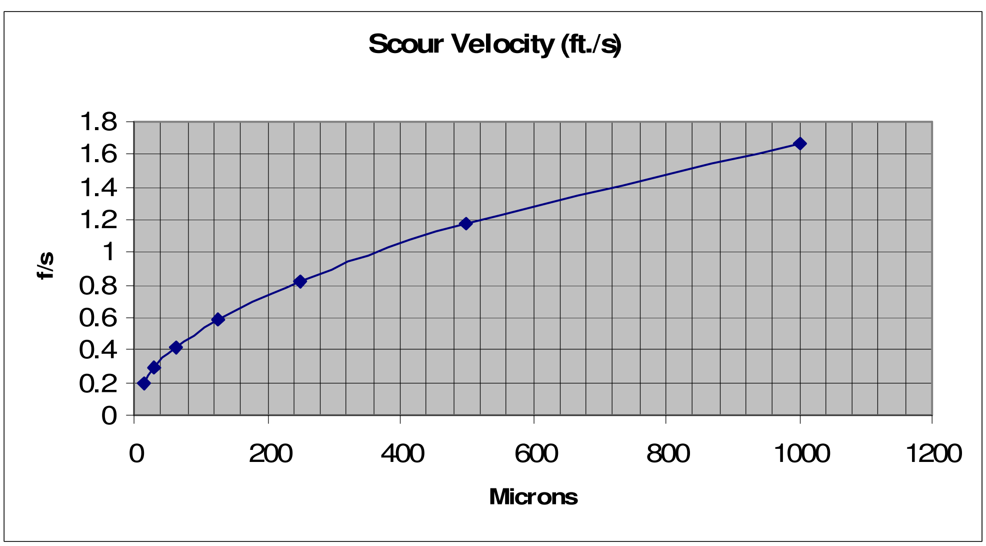

Figure 2

The curve is parabolic with a steep slope in the small particle range. This means that a small increase in absolute velocity from 0.21 fps to 0.42 fps results in scouring particles 4 times as large. This is because of the relative increase in velocity, where the higher velocity is double the lower velocity. The lower velocity scours 16 micron particles, where the higher velocity scours 64 micron particles. This ratio holds for the entire curve, so that doubling the scour velocity will result in scouring particles four times as large. This has a profound effect on designing a vessel to avoid re-suspension. The simplistic approach would be to pick a particle size, and then avoid any velocity above the scour speed for that particle. This practice is evident in most vessels that incorporate some form of bypass to avoid high flows and high velocities. A vessel designed to trap particles and not re-suspend them has to balance the need to keep velocities low in the vessel with the need to be in service when particles are delivered to the vessel by the stormwater run-off. As shown by Camp's table, more particles and larger particles will be scoured off of the surfaces upstream of the vessel in higher flows. When the vessel is bypassing to avoid re-suspension, it traps no particles at all and has a removal rate of zero. The very particles that it is designed to trap will never be collected and exposed to possible re-suspension – they will be allowed to proceed downstream unimpaired. Using a by-pass is the equivalent of accepting a 100% re-suspension rate.

5. Developing a Strategy That Properly Addresses Re-suspension

It should be obvious that avoiding re-suspension at all times is the wrong strategy. A more practical approach is to assess the duration of higher velocities in a vessel where small particles exist. In a vessel where 16 micron particles are deposited, the scour chart indicates that a velocity of 0.21 fps will re-suspend those particles. Avoiding that velocity at all costs creates a far greater problem than the threat of re-suspension. Total avoidance makes the assumption that each particle large enough to suspend at a given velocity is available at the top of the sediment bed and will immediately re-suspend. This is simply not true. The "availability factor" dominates re-suspension potential. The duration of a given velocity can be used as an indicator of the amount of re-suspension from a sediment bed, but it is important to consider the particle size distribution in the top layer as re-suspension occurs. As smaller particles are picked up from the top layer, the larger particles are left behind and tend to shield the particles below, so that the rate of re-suspension will steadily decline as the availability of smaller particles declines.

The re-suspension factors are complicated by the fact that different sites will have different particle size distributions, and the same site will have different delivery patterns based on various flows. The geometry of the site surface and the delivery system will also differ from site to tie, adding another layer of complexity. Field research that has looked at the bed of sediments in vessels has shown that they are layered with zones of larger and smaller particles, each representing a historical surface. Identical velocities from the same site reaching the bed of the same vessel will yield different re-suspension rates based on the surface characteristics and antecedent events.

All of the information above relating to the variability of re-suspension rates points up the need for an overall assessment of strategies to control or avoid re-suspension.

Summary

Re-suspension is a minor factor in well designed vessels, but it must be studied. The size and density of the particles in question are the major factors in determining the re-suspension velocity. Given a specific particle size and density, the major factors for re-suspension are the availability of the particle at the surface, and the velocity of the flow moving across the sediment bed. Vessels that control velocity, limit turbulence, and avoid constrictions and small orifices will have lower re-suspension rates than vessels that have uncontrolled velocities at the entry point, around treatment elements, or at the exit structures. These high velocity regions in a vessel contribute the most to re-suspension. In general, accepting a by-pass strategy to control re-suspension, instead of controlling velocity, is a poor practice because it accepts an effective 100% res-suspension rate for the by-passed flows.

References for further study:

[1] Camp, T.R. 1936, "Study of rational design of settling tanks". Sen. Works Journal, Sept. 1936, page 742.

[2] Camp, T.R. 1946, "Sedimentation and the design of settling tanks". ASCE Trans. 1946, page 895.

[3] Camp, T.R. 1953, "Studies of sedimentation design". Sen. Ind. Wastes, jan. 1953.