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Geotechnical Sampling in a Confidential River
(Photo courtesy of Anchor QEA, LLC)

IN THIS ISSUE

AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects, and case studies.

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THE DELFT HEAD LOSS & LIMIT DEPOSIT VELOCITY FRAMEWORK (DHLLDV)

S. A. Miedema[1], R. C. Ramsdell[2]

ABSTRACT

Models for modeling slurry flow present difficulties on long lines with large pipe diameters and with broad graded sands or gravels.

In order to get more insight in the slurry flow process, a framework has been developed, the DHLLDV Framework, integrating 5 main flow regimes of slurry transport: fixed or stationary bed transport; sliding bed transport; heterogeneous transport; homogeneous transport and sliding flow transport. Additional models—for the limit deposit velocity, the holdup function, the bed height, the concentration distribution and graded sands and gravels—complete the framework.

The framework is based on constant spatial volumetric concentration curves for uniform sands and gravels. The models for the flow regimes and the limit deposit velocity are based on energy considerations. By means of a holdup function, the constant spatial volumetric concentration curves can be transformed into constant delivered volumetric concentration curves. Curves for graded sands and gravels can be constructed by splitting the particle size distribution (PSD) into fractions and use the superposition principle on the resulting curves of each fraction.

The framework makes use of two important graphs. The mixture hydraulic gradient (ordinate) as a function of the line speed (abscissa) and the relative excess hydraulic gradient (ordinate, solids effect) as a function of the liquid hydraulic gradient (abscissa). The latter has the advantage of being almost dimensionless for constant spatial volumetric concentration curves.

The framework can be used with user models, but here newly developed models are described. The framework is validated with many experiments from literature.

Keywords: Slurry Transport, Hydraulic Gradient, Limit Deposit Velocity

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INTRODUCTION

Although sophisticated 2 and 3 layer models exist for slurry flow (here the flow of sand/gravel water mixtures), the main Dutch and Belgian dredging companies still use modified Durand & Condolios (1952) and Fuhrboter (1961) models for heterogeneous transport, while the main companies in the USA use a modified Wilson et al. (1992) model, and the coal industry uses the Wasp model or the Saskatchewan Research Council (SRC) model. The empirical models use one term for the excess head losses resulting from the solids (the solids effect). Most models are based on experiments in small diameter pipes. The use of these models does not give a satisfying result on projects with large diameter pipelines (D_p>0.75 m), very long pipelines (up to 36 km) or broad PSD's (particle size distributions). This is the reason to study all existing models and develop a framework that agrees with most existing models, but also solves the shortcomings. The result is the DHLLDV Framework.

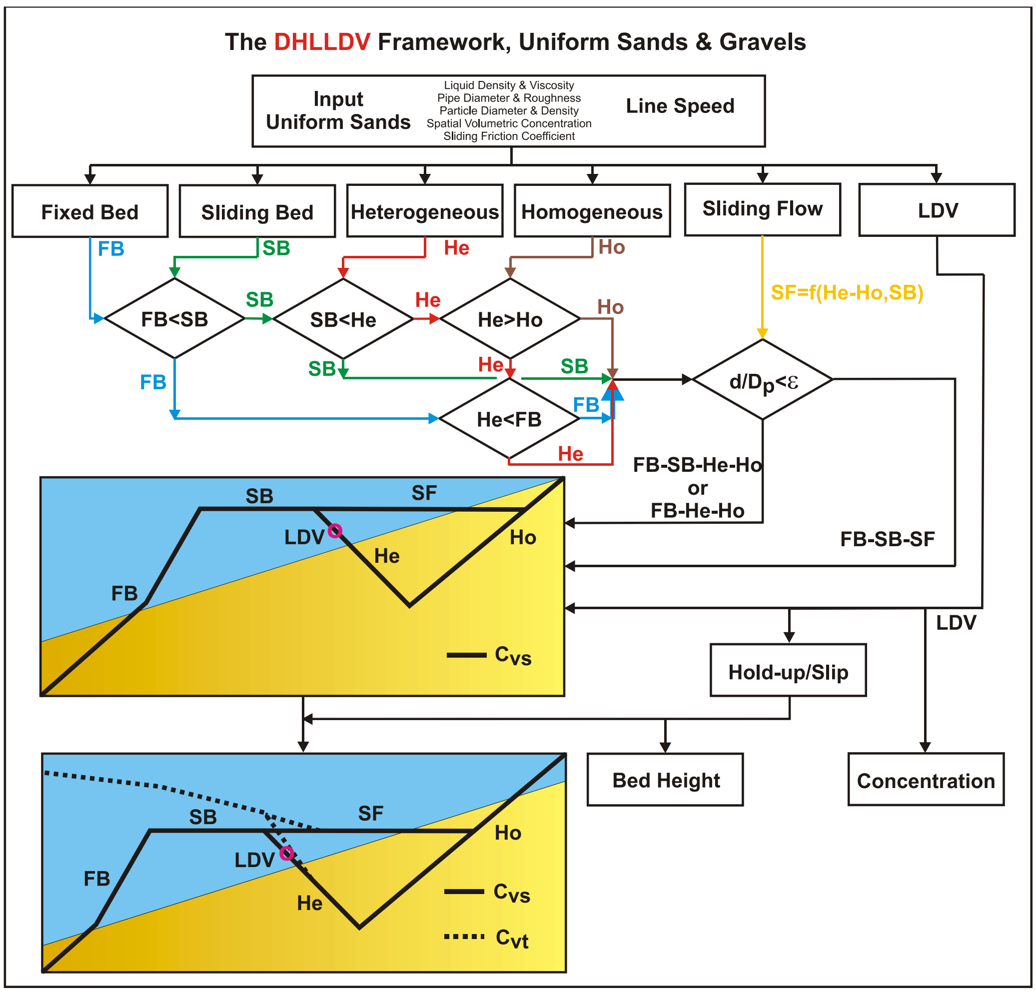

Figure 1: The algorithm to determine the constant C_{vs} and C_{vt} curves for uniform sands and gravels.

The DHLLDV Framework determines the resulting hydraulic gradient curve for spatial volumetric concentrations and uniform sands, consisting of parts of all flow regimes occurring for the pipe and particle diameter in question.

Since the slurry flow process in dredging is a non-stationary process, the PSD and concentration may be time and space dependent, resulting in time varying line speeds, density waves, moving dunes and so on, the modelling should be based on time averaged properties and parameters. In the DHLLDV Framework the main models are based on energy considerations. Each flow regime has its own physical and mathematical model. Once the resulting hydraulic gradient curve and the limit deposit velocity (LDV) are determined, a holdup function enables the user to construct the delivered volumetric concentration curve and the bed height. The latest addition to DHLLDV is a method to determine the concentration distribution based on the LDV and the Wasp model. The LDV is defined here as the line speed above which there is no stationary or sliding bed.
For graded sands and gravels the curves are determined for each uniform grain fraction individually, and the resulting curves are then combined by superposition to form the overall hydraulic gradient curve, holdup function and bed height curve.

THE DHLLDV FRAMEWORK

The DHLLDV Framework (Miedema & Ramsdell, 2014) is based on the philosophy that hydraulic gradients and limit deposit velocities can only be determined based on the spatial volumetric concentration for uniform PSD's, in contrast with most empirical models from literature, which are based on transport volumetric concentrations. Most physical models have the spatial concentration as an input and the transport concentration as an output. To find constant transport concentration curves, iterative methods are used. For heterogeneous and homogeneous transport the spatial and transport volumetric concentrations are close, but for the fixed, the sliding bed and the sliding flow regimes the differences are substantial.

To use the DHLLDV framework for uniform sands and gravels, the following steps have to be carried out:

1. The hydraulic gradient curves and the relative excess hydraulic gradient curves for the fixed or stationary bed regime (FB), for the sliding bed regime (SB), for the heterogeneous flow regime (He), for sliding flow regime (SF) and for the homogeneous flow regime (Ho) have to be determined separately.
2. The resulting curve, based on the algorithm according to Figure 1 has to be constructed.
3. The limit deposit velocity has to be determined. There are 5 possible LDV regions and 1 limiting condition; very small particles, small particles, medium particles or transition region, large particles and very large particles where $d/D_p>0.015$.
4. The transport or delivered concentration curves are determined based on a holdup or slip factor function, where the LDV plays a very important role.
5. The bed height and bed fraction are determined based on the LDV and the slip factor.
6. The concentration profile is also determined based on the LDV.

THE FIXED OR STATIONARY BED

The model for the force equilibrium on a stationary or sliding bed has been described by Wilson et al. (1992) and lately by Miedema (2014) and Miedema & Ramsdell (2014). Only modifications will be discussed here. In the following equations, the index 1 points to the liquid-pipe wall interface or liquid velocity, the index 2 to the bed-pipe wall interface or bed velocity and the index 12 to the liquid-bed interface. For the flow in the restricted area above the bed, the shear stress between the liquid and the bed for small values of v_{12}, when sheet flow is not occurring, is:

$$\tau_{12} = \frac{\lambda_{12}}{4} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{12}^2 \quad \text{with:} \quad \lambda_{12} = \frac{1.325}{\left(\ln\left(\frac{0.27 \cdot d}{D_H} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \quad \text{and} \quad Re = \frac{v_{12} \cdot D_H}{\nu_l} \tag{1}$$

In this equation the particle diameter is used as the bed roughness. Others use the particle diameter multiplied with a factor ranging from 0.6 to a multiple. For larger values of values of v_{12}, when sheet flow does occur, the following equation has to be applied:

$$\tau_{12} = \frac{\lambda_{12}}{4} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{12}^2 \quad \text{with:}$$

$$\lambda_{12} = 0.83 \cdot \lambda_1 + 0.37 \cdot \left(\frac{v_{12}}{\sqrt{2 \cdot g \cdot D_H \cdot R_{sd}}}\right)^{2.73} \cdot \left(\frac{\rho_s \cdot \frac{\pi}{6} \cdot d^3}{\rho_l \cdot 1^3}\right)^{0.094} = 0.83 \cdot \lambda_1 + 0.37 \cdot Fr_{DC}^{2.73} \cdot \left(\frac{m_p}{\rho_l}\right)^{0.094} \tag{2}$$

Miedema & Matousek (2014) derived the above equation, except for the particle mass term. This last term increases the correlation coefficient of the curve fit of experimental data from 0.86 (without this term) to 0.91 (including this term). Reason for adding this last term is, that in sheet flow energy losses are not only determined by the submerged weight of the particles, but also by the mass of the particles. The use of equations (1) and (2) is simple, if equation (2)>equation (1), equation (2) is used and sheet flow is assumed, otherwise equation (1) is used and a flat bed with maybe individual particles moving is assumed. Wilson et al. (1992) assume that the sliding friction is the result of a hydrostatic normal force between the bed and the pipe wall multiplied by the sliding friction factor. It is however also possible that the sliding friction force results from the weight of the bed multiplied by the sliding friction factor. For low volumetric concentrations, there is not much difference between the two methods, but at higher volumetric concentrations there is. The average shear stress as a result of the sliding friction between the bed and the pipe wall, according to the weight normal stress approach, as is used here, is:

$$\tau_{2,sf} = \frac{\mu_{sf} \cdot \rho_l \cdot g \cdot R_{sd} \cdot C_{vb} \cdot A_p}{\beta \cdot D_p} \cdot \frac{\left(\beta - \sin(\beta) \cdot \cos(\beta)\right)}{\pi} \tag{3}$$

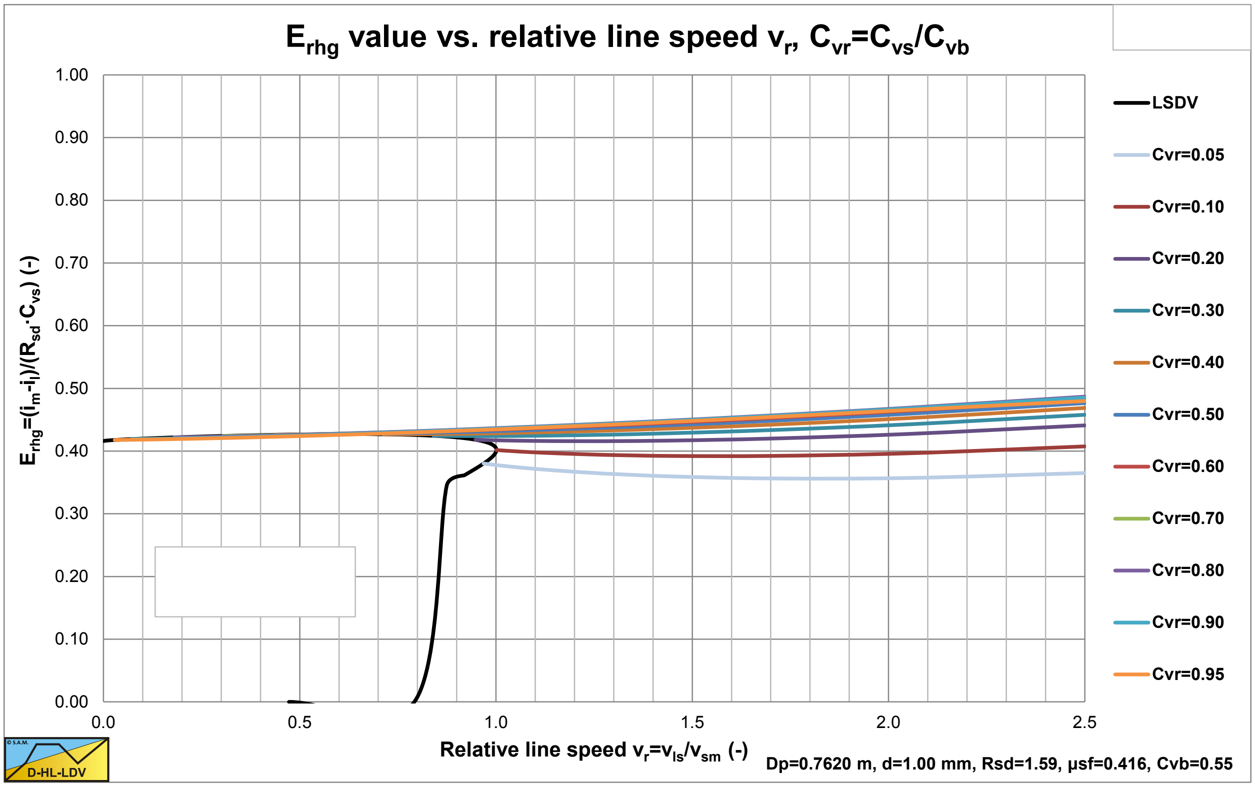

Figure 2: The relative excess hydraulic gradient E_{rhg} versus the relative line speed for a sliding bed, including the stationary bed region.

THE SLIDING BED

For the sliding bed the same set of equations is used as for the stationary bed. The only difference is that for a stationary bed the bed velocity v_2 equals 0, while of course for a sliding bed the bed has a positive velocity v_2, smaller than v_1. A convenient parameter to show the results of the calculations is the Relative Excess Hydraulic Gradient, E_{rhg}. This parameter gives an almost dimensionless graph of the head losses.

$$\mathbf{E_{rhg}} = \frac{\mathbf{i_m - i_l}}{\mathbf{R_{sd} \cdot C_{vs}}} \tag{4}$$

Figure 2 shows the E_{rhg} parameter as a function of the relative volumetric concentration ($C_{vr}=C_{vs}/C_b$) and the relative line speed ($v_{ls}/v_{ls,ldv,max}$) for the weight approach sliding bed friction (Miedema & Ramsdell (2014)) and a sliding bed friction factor μ_{sf}=0.416, including sheet flow. The E_{rhg} parameter is very close to the sliding friction coefficient μ_{sf}, especially for relative line speeds up to 1.5, the region where most probably the sliding bed will occur. This parameter does not seem to depend much on the spatial volumetric concentration and the line speed, so the conclusion is, that in the sliding bed regime this parameter approximates the sliding friction coefficient.

So for the sliding bed regime, the E_{rhg} will be set equal to the sliding friction coefficient μ_{sf} for the constant spatial volumetric concentration case. The coefficient for sand and gravel is derived below, or can be measured experimentally.

$$\mathbf{E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=\mu_{sf}} \tag{5}$$

The sliding friction coefficient μ_{sf} is the tangent of the external friction angle δ between the sand or gravel and the steel pipe wall. From soil mechanics it is known that the external friction angle δ is about 2/3 of the internal friction angle φ. This internal friction angle has a minimum of about 30° for loose packed sand, giving 20° for the external friction angle. The tangent of 20° is 0.364. Miedema & Ramsdell (2014) also analyzed the hydrostatic approach of Wilson et al. (1992) and the normal stress carrying the weight approach. These two approaches are similar up to a relative concentration of 0.5, giving an increase of the E_{rhg} parameter with a factor 1.3 compared to the weight approach as used here. In practice the relative concentration will be between 0 and 0.5 giving a multiplication factor between 1 and 1.3 depending on the relative concentration. Taking an average, gives a sliding friction factor of about 0.416. Resuming it can be stated that the E_{rhg} parameter should have a value of about 0.364 if the weight approach is applied, or a value of about 0.416 if the hydrostatic or normal stress carrying the weight approach are applied. In the current model a constant value of 0.416 is used to be on the safe side, resulting in linear hydraulic gradient versus line speed curves parallel to the liquid curve as already observed by Newitt et al. (1955) and others.

HETEROGENEOUS TRANSPORT

Miedema & Ramsdell (2013) derived an equation for the Relative Excess Hydraulic Gradient for heterogeneous transport based on energy considerations. This equation consists of two parts. A first part for the contribution due to potential energy losses and a second part for the kinetic energy losses. The equation is based on uniform sands or gravels, but Miedema (2014) also derived a modified equation for graded sands and gravels. In its basic form the equation looks like:

$$\mathbf{E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=\frac{v_t\cdot\left(1-\frac{C_{vs}}{\kappa_C}\right)^{\beta}}{v_{ls}}+\left(\frac{v_{sl}}{v_t}\right)^2=S_{hr}+S_{rs}} \tag{6}$$

The Settling Velocity Hindered Relative, S_{hr}, is the Hindered Settling Velocity of a particle $v_t\cdot(1-C_{vs}/\kappa_C)^{\beta}$ divided by the line speed v_{ls}. The S_{hr} value gives the contribution of the potential energy losses to the Relative Excess Hydraulic Gradient. The S_{hr} is derived for and can be applied to the heterogeneous regime. The Slip Relative Squared S_{rs} is the Slip Velocity of a particle v_{sl} divided by the Terminal Settling Velocity of a particle v_t squared and this S_{rs} value is a good indication of the Relative Excess Hydraulic Gradient due to the solids, since its contribution to the total is 90%-100%. The S_{rs} value gives the contribution of the kinetic energy losses to the Relative Excess Hydraulic Gradient. The S_{rs} is derived for and can be applied to the heterogeneous regime. The potential energy term is explicit and all the variables involved are known, so this term can be solved. The kinetic energy term however contains the slip velocity, which is not known. The kinetic energy term has been derived by Miedema & Ramsdell (2013) based on kinetic energy losses due to collisions or interactions with the pipe wall or the viscous sub layer. This means that the slip velocity used in the above equation is not necessarily the average slip velocity, but it is the slip velocity necessary to explain the kinetic energy losses. The average slip velocity of the particles will probably be larger, but of the same magnitude. The derivation of the slip velocity equation for uniform sands or gravels will be subject of Miedema (2015), but the resulting equation for the E_{rhg} parameter is given here. Giving for the relative excess hydraulic gradient, the E_{rhg} parameter:

$$\mathbf{E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=S_{hr}+S_{rs}=\frac{v_t\cdot\left(1-\frac{C_{vs}}{\kappa_C}\right)^{\beta}}{v_{ls}}+8.5^2\cdot\left(\frac{1}{\lambda_l}\right)\cdot\left(\frac{v_t}{\sqrt{g\cdot d}}\right)^3\cdot\left(\frac{\left(\nu_l\cdot g\right)^{1/3}}{v_{ls}}\right)^2} \tag{7}$$

The equation has been modified slightly since the original article of Miedema & Ramsdell (2013). The potential energy term now contains a factor κ_C taking the vertical concentration distribution in the pipe into account. The value of κ_C is estimated at $0.175\cdot(1+\beta)$. The kinetic energy term now contains the Darcy-Weisbach friction coefficient λ_l for the wall friction of the carrier liquid.

HOMOGENEOUS TRANSPORT

The basis of the homogeneous transport regime model is the equivalent liquid model (ELM). In terms of the relative excess hydraulic gradient, E_{rhg}, this can be written as:

$$\mathbf{E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=\frac{\lambda_l\cdot v_{ls}^2}{2\cdot g\cdot D_p}=i_l} \tag{8}$$

Now it is known that the so called fines influence the effective density and viscosity of the carrier liquid. The definition of fines is not always clear. Sometimes the fraction $d<0.063$ mm is used, but this is disputable. Here the fraction $d<0.1$ mm is used. A criterion based on the d/D_p ratio, the line speed v_{ls} and the spatial concentration C_{vs} is subject to further research. Once this fraction f is known, the density of the carrier liquid can be determined by:

$$\mathbf{\rho_{l,m}=\rho_l\cdot\left(1+R_{sd}\cdot f\cdot C_{vs}\right)} \tag{9}$$

Based on this Thomas (1965) derived an equation to determine the modified liquid dynamic viscosity as a function of the concentration $f\cdot C_{vs}$ of the fine particles in the mixture.

$$\mathbf{\mu_{l,m}=\mu_l\cdot\left(1+2.5\cdot f\cdot C_{vs}+10.05\cdot\left(f\cdot C_{vs}\right)^2+0.00273\cdot e^{16.6\cdot f\cdot C_{vs}}\right)} \tag{10}$$

Talmon (2013) derived an equation to correct the homogeneous equation (the ELM model) for the slurry density, based on the hypothesis that the viscous sub-layer hardly contains solids at very high line speeds in the homogeneous regime. This theory results in a reduction of the resistance compared with the ELM, but the resistance is still higher than the resistance of clear water. Talmon (2013) used the Prandl approach for the mixing length, which is a 2D approach for open channel flow with a free surface. The Prandl approach was extended with damping near the wall to take into account the viscous effects near the wall, according to von Driest (Schlichting, 1968). Miedema (2015) improved the equation for pipe flow and a concentration distribution giving for the relative excess hydraulic gradient E_{rhg}:

$$\mathbf{E_{rhg}} = \frac{\mathbf{i_m - i_l}}{\mathbf{R_{sd} \cdot C_{vs}}} = \mathbf{i_l} \cdot \frac{\mathbf{1 + R_{sd} \cdot C_{vs} - \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1\right)^2}}{\mathbf{R_{sd} \cdot C_{vs} \cdot \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1\right)^2}} \tag{11}$$

The concept of Talmon (2013) is applicable for determining the pressure losses in the homogeneous regime, however this concept has to be modified with respect to the shear stress distribution, the concentration distribution and a check on conservation of volume flow and concentration. The resulting equation (11) with A_{Cv}=1.3 gives a good average behavior based on the data of Talmon (2011) and Thomas (1976). The original factor A_{Cv}=3.4 of Talmon (2013) seems to overestimate the reduction of the solids effect. It should be mentioned that the experiments as reported by Talmon (2011) were carried out in a vertical pipe ensuring symmetrical flow. For horizontal pipes the results may differ, since the velocity and concentration profiles are not symmetrical at the line speeds common in dredging. Since the model is based on a particle free viscous sub-layer and the viscosity of the carrier liquid, it may not give good predictions for very small or large particles. Very small particles may influence the viscosity, while very large particles are not influenced by the viscous sub-layer.

The error of using A_{Cv}=1.3 is difficult to define. With respect to the relative excess hydraulic gradient E_{rhg} the accuracy is about +/- 10%. With respect to the hydraulic gradient i_m, which is of interest for the dredging companies, the accuracy is better to much better, since this hydraulic gradient equals $i_m=i_l+E_{rhg}\cdot R_{sd}\cdot C_v$.

SLIDING FLOW VERSUS HETEROGENEOUS FLOW

For fine and medium sized particles there is a transition from a sliding bed to heterogeneous transport at a certain line speed. Figure 9 shows this transition clearly. However for large particles the turbulence is not capable of lifting the particles enough resulting in a sort of sliding bed behavior above this transition point. One reason for this is that the largest eddies are not large enough with respect to the size of the particles. Sellgren & Wilson (2007) use the criterion d/D_p>0.015 for this to occur. The density of the bed decreases with the line speed. Gillies (1993) gave an equation for the reduction of this bed density:

$$\mathbf{C_{vb} = C_{vb,max} - 0.074 \cdot \left(\frac{v_{ls}}{v_t}\right)^{0.44} \cdot \left(1 - C_{vs}\right)^{0.189} \cdot \left(C_{vb,max} - C_{vs}\right)} \tag{12}$$

A pragmatic approach to determine the relative excess hydraulic gradient in the sliding flow regime is to use a weighted average between the heterogeneous regime and the sliding bed regime. First the factor between particle size and pipe diameter is determined:

$$\mathbf{f = \frac{d}{0.015 \cdot D_p}} \tag{13}$$

Secondly the weighted average relative excess hydraulic gradient is determined:

$$\mathbf{E_{rhg,SF} = \frac{E_{rhg,HeHo} + (f-1) \cdot \mu_{sf}}{f}} \tag{14}$$

The resulting curves match very well with the SRC model in the range of operational line speeds. This method also explains the reduction of the power of the line speed in the Sellgren & Wilson (2007) 4 component model for very large particles.

THE LIMIT DEPOSIT VELOCITY

It should be noted that the limit deposit velocity, LDV, as used here is the velocity above which there is no stationary or sliding bed. In the Wilson et al. (1992) approach the limit deposit velocity is the velocity where the bed starts to slide, the limit of stationary deposit velocity, LSDV. Miedema & Ramsdell (2015) derived a new model for the LDV based on energy considerations. Figure 3 shows the algorithm to determine the LDV. Basically the model distinguished 5 particle size ranges, with borders based on solid, liquid and geometrical properties. These ranges are:

1. Very fine (very small) particles.
2. Fine (small) particles.
3. Medium sized particles or transition region.
4. Coarse (large) particles.
5. Very coarse (large) particles, $d/D_p>0.015$.

Beside the 5 regions, there is a limit to the LDV, which is the transition line speed between the sliding bed regime and the heterogeneous regime as described by Miedema & Ramsdell (2015).

For very fine particles the Thomas (1979) approach is adopted, but slightly modified. For very large particles, transported in the sliding flow regime, it is the question whether one can still speak of an LDV, since there is a gradual transition of the sliding bed regime to the sliding flow regime. This will not be discussed here since it is still subject to further research.

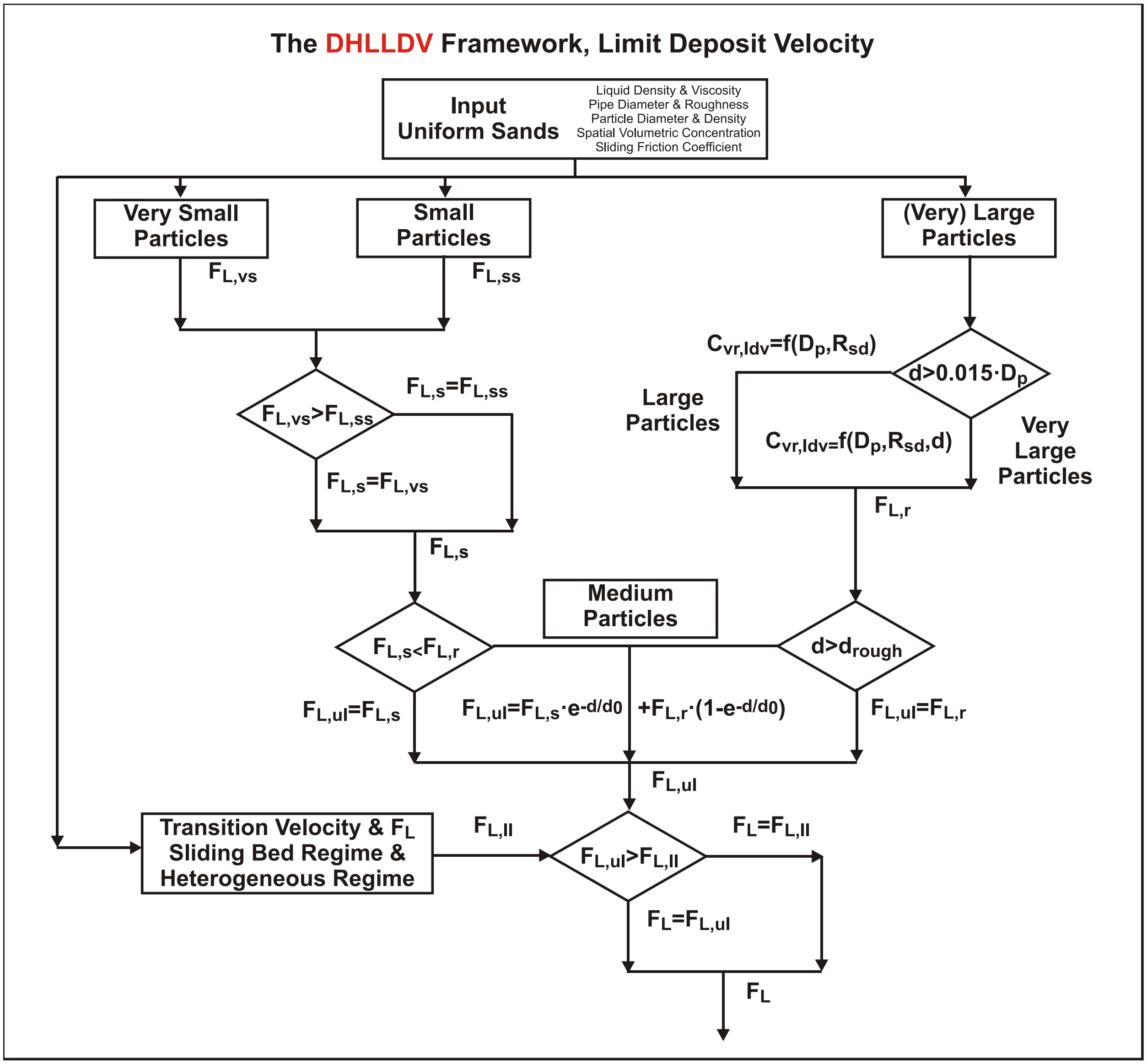

Figure 3: The Limit Deposit Velocity Algorithm.

For fine (small) particles it is assumed that when the required potential energy of the solids to keep them in suspension is larger than a certain fraction of the energy in the liquid flow, there will be a bed. If it is smaller, all particles will be suspended. In terms of the Durand & Condolios LDV Froude number F_L this can be written as:

$$F_{L,s} = \frac{v_{ls,ldv}}{\left(2 \cdot g \cdot R_{sd} \cdot D_p\right)^{1/2}} = \alpha_p \cdot \left(\frac{v_t \cdot \left(1 - \frac{C_{vs}}{\kappa_C}\right)^{\beta} \cdot C_{vs}}{\lambda_l \cdot \left(2 \cdot g \cdot R_{sd} \cdot D_p\right)^{1/2}} \right)^{1/3} \quad \text{with:} \quad \begin{array}{l} \alpha_p = 3.5 \cdot \left(\frac{1.65}{R_{sd}}\right)^{1/9} \\ \kappa_C = 0.175 \cdot (1+\beta) \end{array} \tag{15}$$

The values found for α_p=3.5 and κ_C=0.175·(1+β) are based on many experiments from literature. The value of α_p of 3.5 found shows that the LDV occurs when the potential energy losses of the particles are about 2.33% of the energy losses of the liquid flow for small particles. The value of κ_C means that the average particle is at 0.175·(1+β) of the radius of the pipe, measured from the bottom of the pipe and not at the radius. This is in fact the concentration eccentricity factor. It also appears that the Limit Deposit Velocity found for small particles is close to the transition between the heterogeneous regime and the homogeneous regime, which makes sense, because in the homogeneous regime all particles are supposed to be in suspension. The value of α_p=3.5 is based on the maximum LDV values found in literature and not on a best fit. In fact α_p may vary from 3.0 as a lower limit to 3.5 as an upper limit. So the value of 3.5 is conservative. A best fit would probably give a value of about 3.25. However in dredging the LDV should be a safe LDV, since the particle size, the concentration and the line speed may vary in time. For coarse particles an approach based on bed shear stress and a limiting relative volumetric concentration $C_{vr,ldv}$, resulting in a limited bed, is used. If the bed shear stress exceeds the sliding friction, the limited bed vanishes. In terms of the Durand & Condolios LDV Froude number this gives:

$$\mathbf{F_{L,r} = \frac{v_{ls,ldv}}{\left(2 \cdot g \cdot R_{sd} \cdot D_p\right)^{1/2}} = \alpha_p \cdot \left(\frac{\left(1 - \frac{C_{vs}}{\kappa_C}\right)^{\beta} \cdot C_{vs} \cdot \left(\mu_{sf} \cdot C_{vb} \cdot \frac{\pi}{8}\right)^{1/2} \cdot C_{vr,ldv}^{1/2}}{\lambda_l} \right)^{1/3}} \tag{16}$$

The limiting relative volumetric concentration $C_{vr,ldv}$ appears to depend on the pipe diameter D_p and the relative submerged density R_{sd}. With a constant thickness of a thin layer h, the amount of solids in this thin layer is proportional to the pipe diameter D_p. The cross section of the pipe however is proportional to the pipe diameter D_p squared. So the limiting relative volumetric concentration $C_{vr,ldv}$ will be reversely proportional to the pipe diameter. The limiting relative volumetric concentration $C_{vr,ldv}$ is decreasing with increasing relative submerged density R_{sd}. This can be explained by assuming that a certain critical bed shear stress τ_{12} requires a decreasing relative volumetric concentration $C_{vr,ldv}$ with an increasing relative submerged density R_{sd}.

$$\mathbf{C_{vr,ldv} = 0.00012 \cdot D_p^{-1} \cdot \left(\frac{R_{sd}}{1.65}\right)^{-1} = \frac{0.0039}{2 \cdot g \cdot R_{sd} \cdot D_p}} \tag{17}$$

The final F_L value, including the transition region, can now be determined according to:

$$\mathbf{F_L = F_{L,s} \cdot e^{-d/d_0} + F_{L,r} \cdot \left(1 - e^{-d/d_0}\right) \quad with: \quad d_0 = 0.0005 \cdot \left(\frac{1.65}{R_{sd}}\right)^{1/2}} \tag{18}$$

Figure 4 shows the resulting LDV curves compared with the Durand & Condolios (1952) experiments**.** The resemblance is very good, including the limiting LDV based on the transition of the sliding bed regime and the heterogeneous regime.

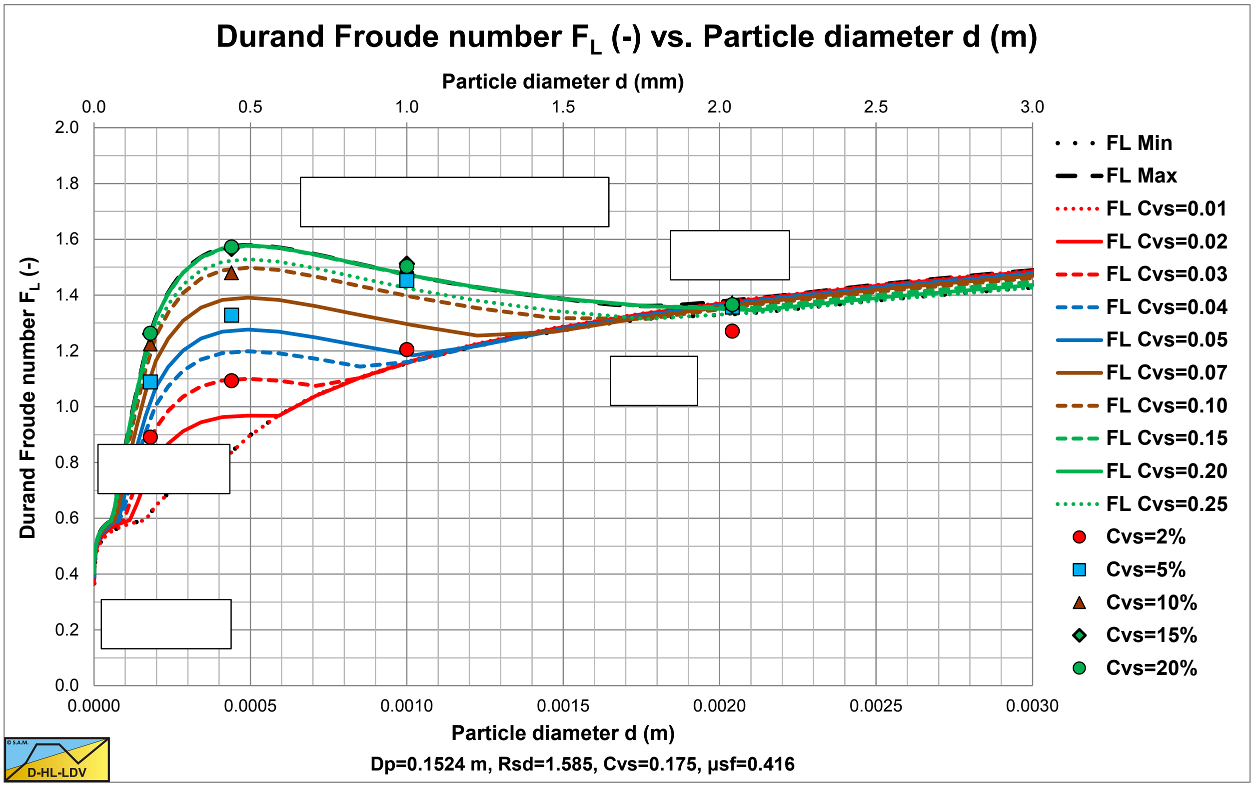

Figure 4: The resulting LDV curves compared with the Durand & Condolios (1952) experiments.

CONSTRUCTING THE TRANSPORT CONCENTRATION CURVES

In order to construct the transport or delivered concentration curves, the ratio between the spatial and the delivered volumetric concentration has to be known. This ratio is defined as:

$$\frac{C_{vt}}{C_{vs}} = \left(1 - \frac{v_{sl}}{v_{ls}}\right) = (1 - \xi) \tag{19}$$

The asymptotic value of this slip ratio for a line speed approaching 0 is not equal to 1, but equal to:

$$\xi_0 = \frac{v_{sl}}{v_{ls}} = 1 - \frac{C_{vt}}{C_{vb}} \tag{20}$$

The slip ratio around the LDV can be estimated as:

$$\xi = \frac{v_{sl}}{v_{ls}} = \frac{1}{2 \cdot C_D} \cdot \left(1 - \frac{C_{vt}}{0.175 \cdot (1 + \beta)}\right)^{\beta} \cdot \left(\frac{v_{ls,ldv}}{v_{ls}}\right)^4 \tag{21}$$

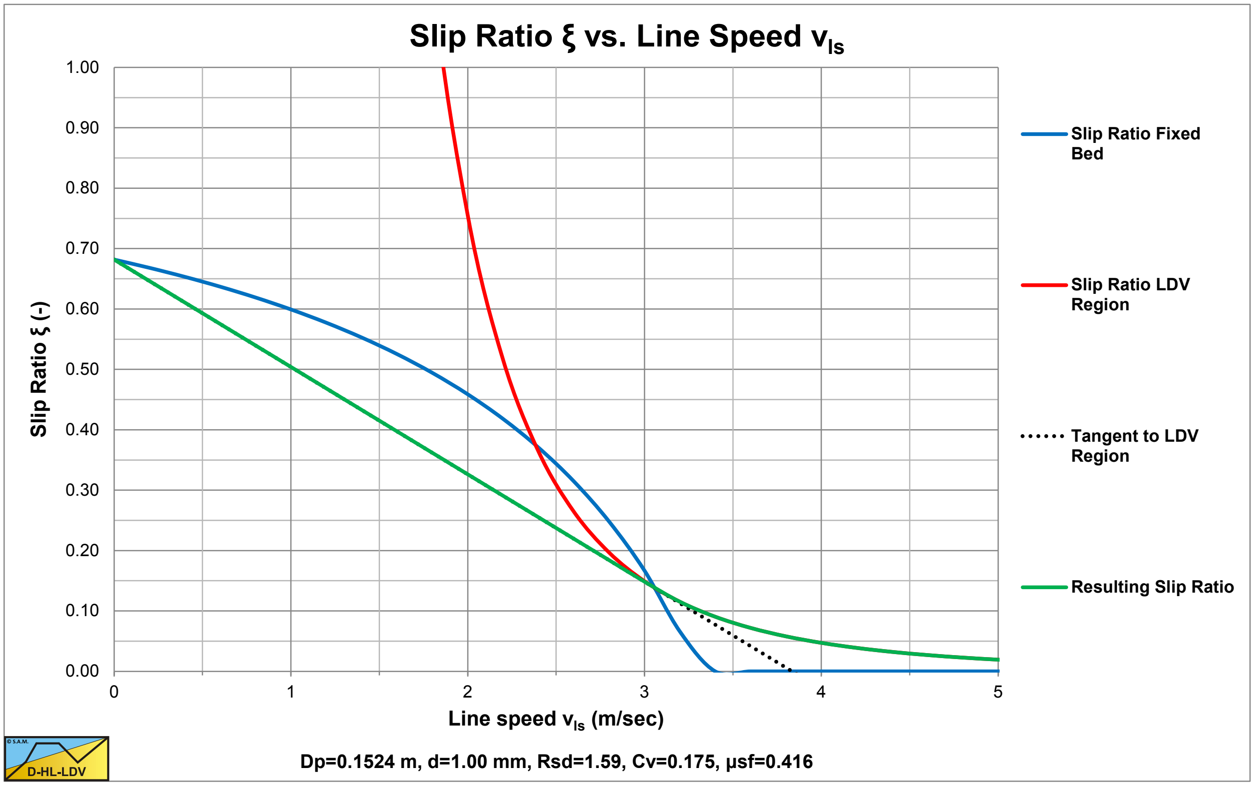

Figure 5: Construction of the slip ratio.

For line speeds from 0 to the LDV, the slip ratio is estimated by taking the tangent line from the line speed of 0 and the slip ratio of equation (20) to the curve of equation (21) as is shown in Figure 5. For line speeds above the LDV, the slip ratio determined for the heterogeneous regime is used. Figure 6 shows the resulting slip ratio curves compared with experiments of Yagi et al. (1972). Now 3 regions can be distinguished, the region of low line speeds giving a sliding bed, the region around the LDV and the region far above the LDV.

Once the slip ratio ξ is known, the bed fraction ζ can be determined by dividing the original relative spatial concentration C_{vr} by the slip factor. The bed fraction is the fraction of the pipe occupied by the bed as is shown in Figure 7 for a number of particle diameters.

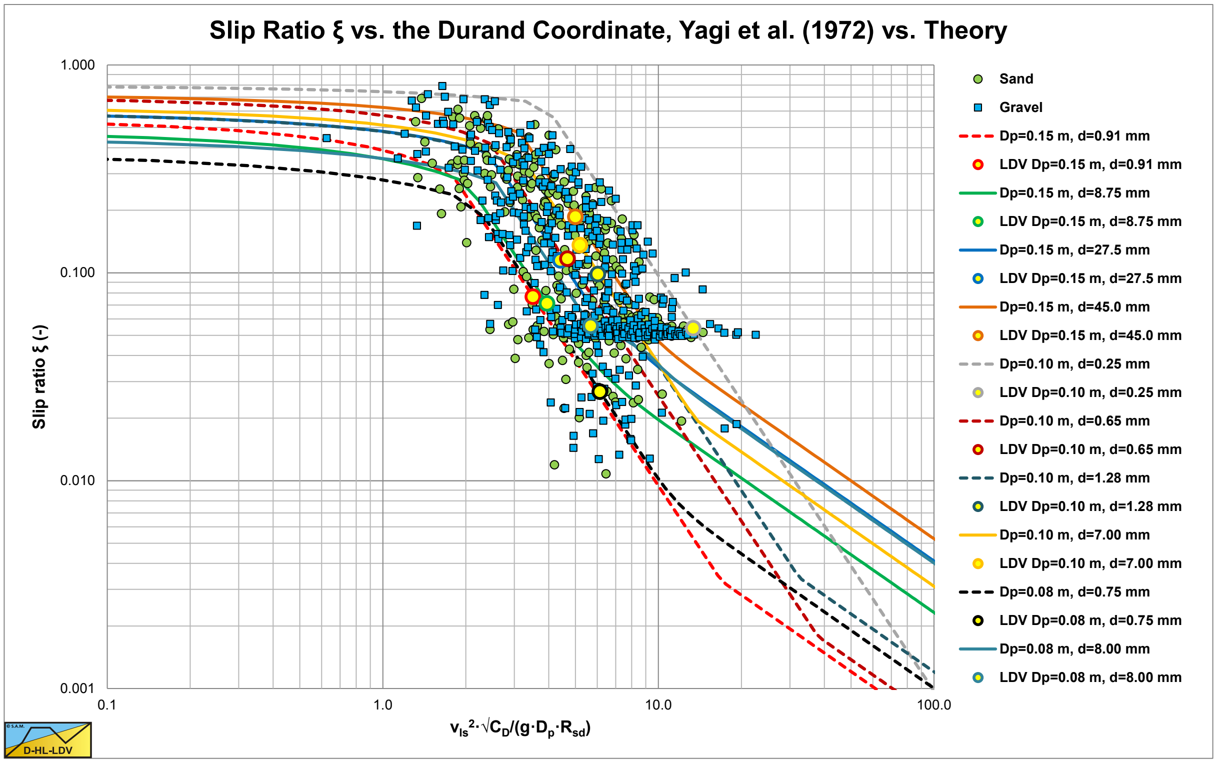

Figure 6: Slip ratio curves matching the Yagi et al. (1972) experiments.

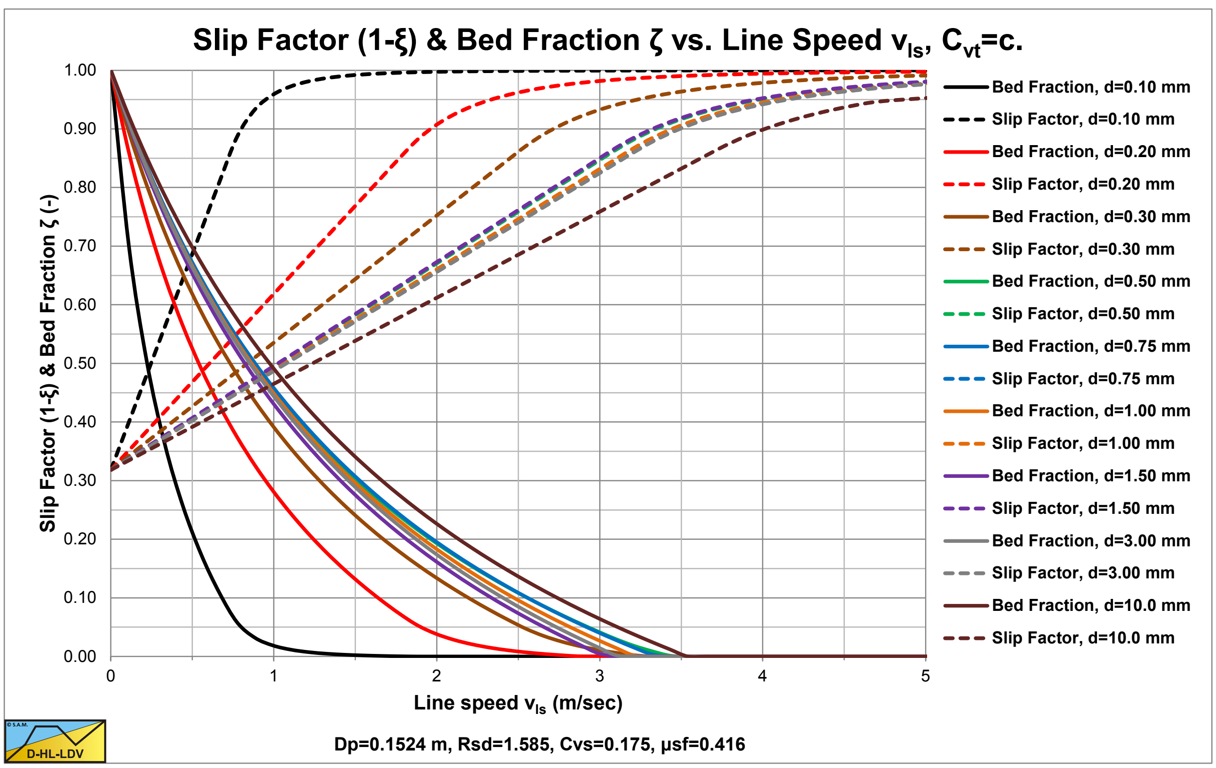

Figure 7: The resulting bed fraction curves.

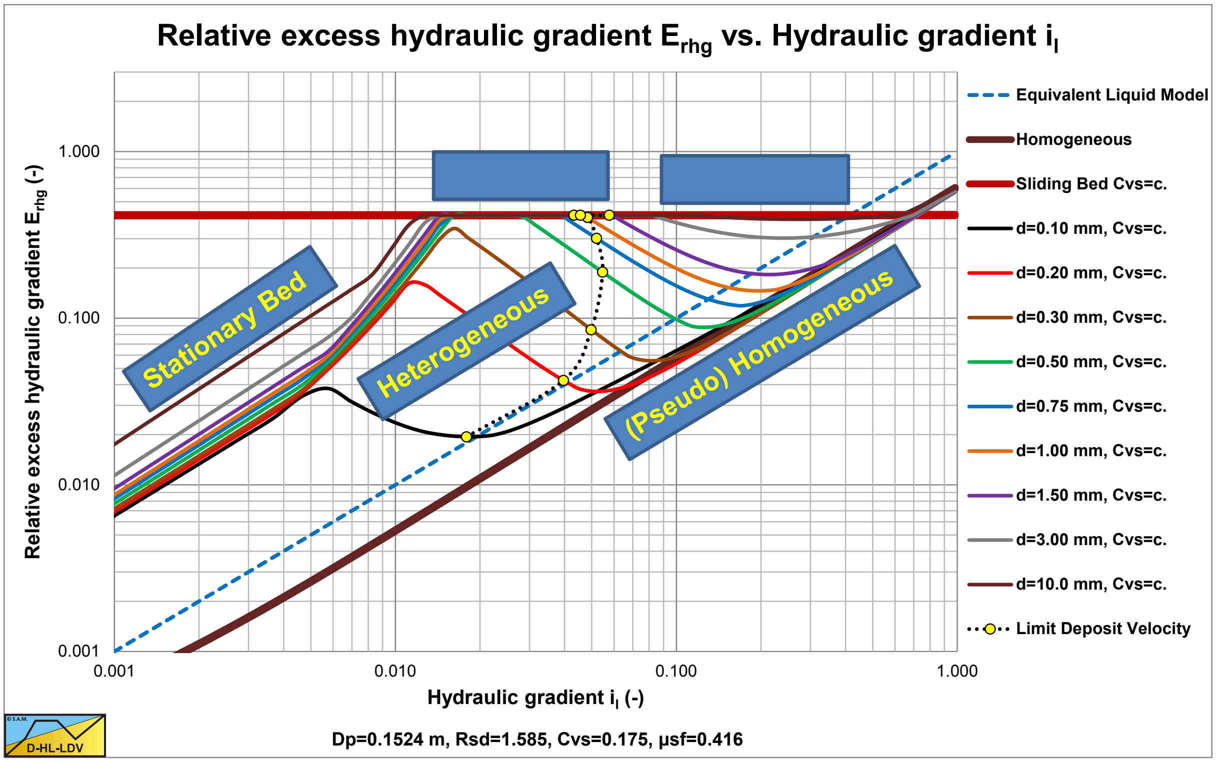

Figure 8: The main flow regimes for constant spatial concentration.

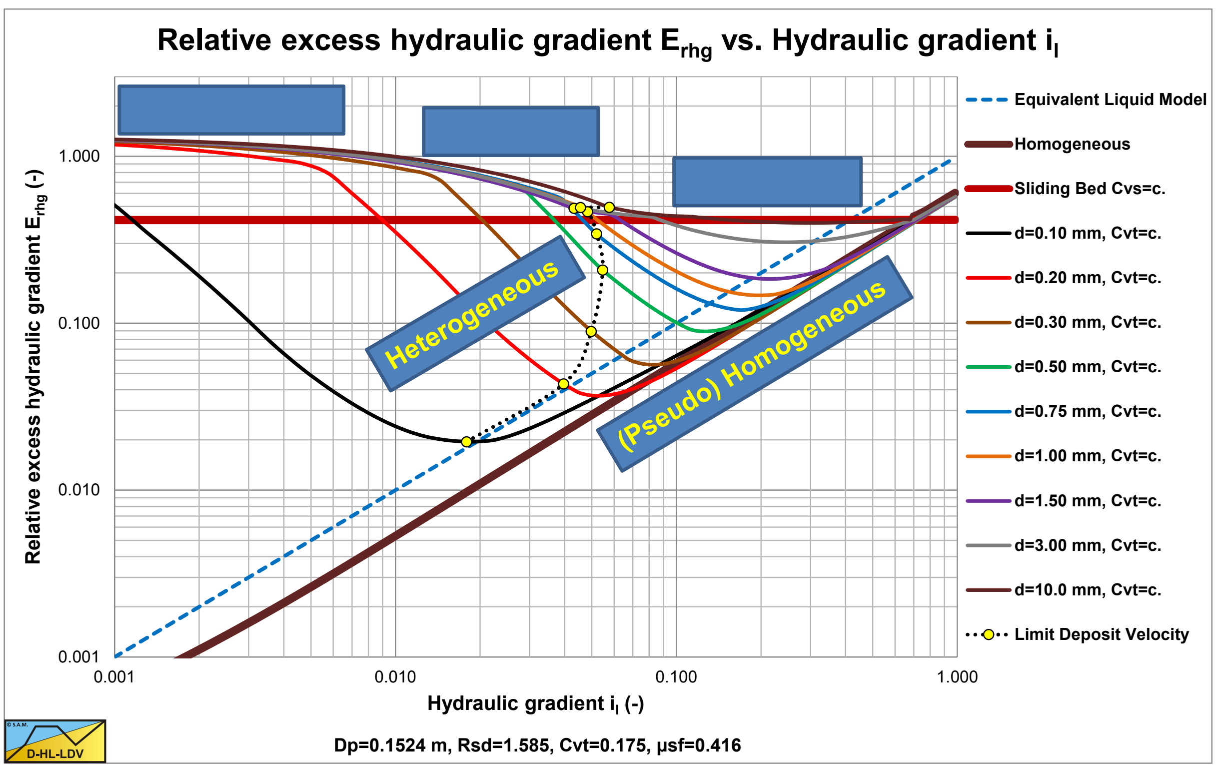

Figure 9: The main flow regimes for constant delivered/transport concentration.

RESULTING RELATIVE EXCESS HYDRAULIC GRADIENT CURVES

Figure 8 gives an example of the resulting relative excess hydraulic gradient curves for a 0.1524 m diameter pipe and particles ranging from 0.1 mm to 10 mm, showing the different flow regimes for the spatial concentration case. Figure 9 shows the resulting relative excess hydraulic gradient curves for the delivered (transport) concentration case. These graphs also match the regime diagram of Newitt et al. (1955) showing that not all flow regimes occur for each particle diameter to pipe diameter ratio.

THE CONCENTRATION DISTRIBUTION WITHIN THE PIPE

The advection diffusion equation when in equilibrium shows the balance between the upwards flow of particles due to diffusion and the downwards flow of particles due to gravity (the terminal settling velocity). Wasp et al. (1977) and Doron et al. (1987) use the solution of the advection diffusion equation for low concentrations, while Karabelas (1977) and Kaushal & Tomita (2002B) use the Hunt (1954) approach with upwards liquid flow. Hindered settling is not yet included in the basic solutions, but added by replacing the terminal settling velocity by the hindered terminal settling velocity. For the diffusivity and the relation between the sediment diffusivity and the turbulent eddy momentum diffusivity different approaches are possible. Using the Lane & Kalinske (1941) approach, the following equation can be derived for pipe flow:

$$\mathbf{C_{vs}(r) = C_{vB} \cdot e^{-12 \cdot \frac{v_{th}}{\beta_{sm} \cdot \kappa \cdot u_*} \cdot \frac{r}{D_p}}} \tag{22}$$

Now based on the assumption that the diffusivity has to have a value such that at the LDV the concentration at the bottom of the pipe equals the bed concentration (the definition of the LDV), the following equation can be derived:

$$\mathbf{C_{vs}(r) = C_{vB} \cdot e^{-\frac{\alpha_{sm}}{C_{vr}} \cdot \frac{u_{*,ldv}}{u_*} \cdot \frac{v_{tv}}{v_{tv,ldv}} \cdot \frac{r}{D_p}}} \quad \textbf{with:} \quad \mathbf{\alpha_{sm} = 1.0046 + 0.1727 \cdot C_{vr} - 1.1905 \cdot C_{vr}^2} \tag{23}$$

The settling velocity v_{tv} is the settling velocity of the particle, based on the properties of the liquid, adjusted for the homogeneous fraction, resulting in the vehicle liquid according to Wasp et al. (1977). The correction factor α_{sm} appears to depend only on the relative concentration C_{vr}.

The bottom concentration C_{vB} is now for line speeds above the LDV:

$$\mathbf{C_{vB} = C_{vb} \cdot \frac{u_{*,ldv}}{u_*} \cdot \frac{v_{tv}}{v_{tv,ldv}}} \tag{24}$$

The friction velocities used in these equations can be determined by, because the hydraulic gradients are known:

$$u_* = \sqrt{\frac{i_m \cdot g \cdot D_p}{4}} \quad \text{and} \quad u_{*,ldv} = \sqrt{\frac{i_{m,ldv} \cdot g \cdot D_p}{4}} \tag{25}$$

Figure 10 shows the concentration profiles for different relative concentrations, adjusted for the circular shape of the pipe at the LDV, compared with data from Kaushal et al. (2005) giving a reasonable match.

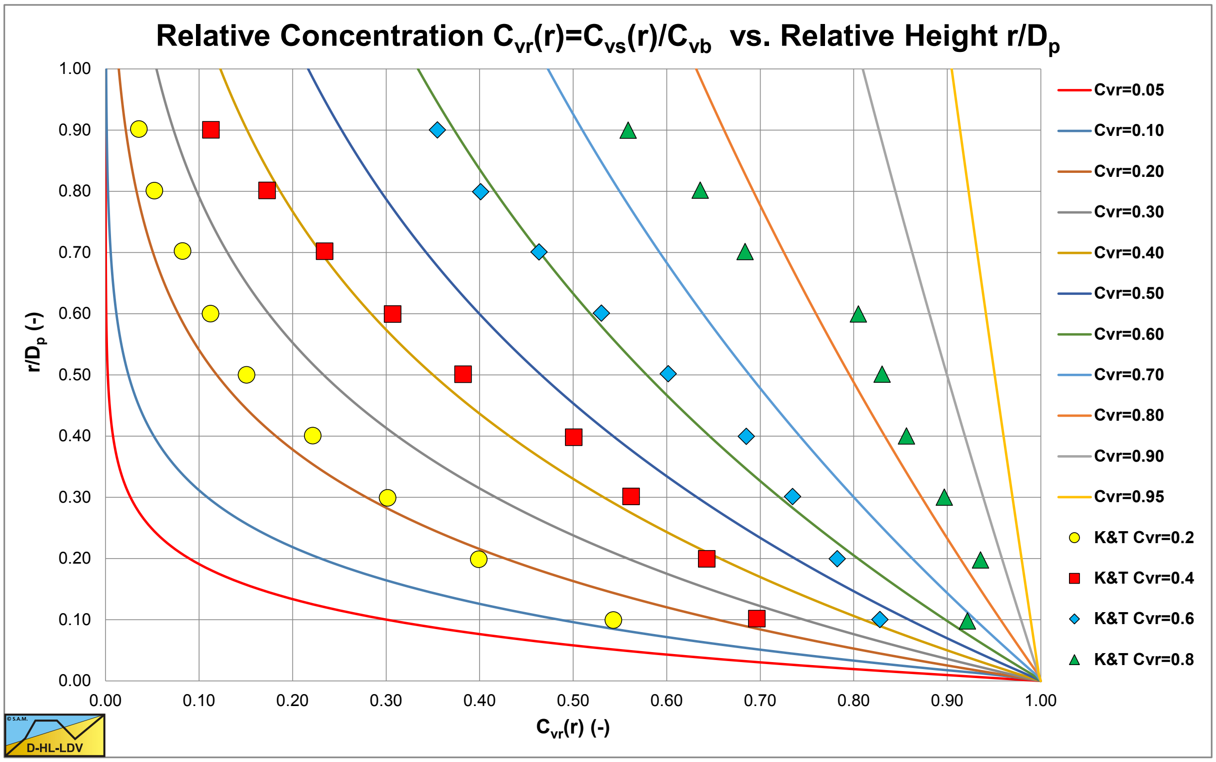

Figure 10: The concentration distribution at the LDV as a function of the relative concentration.

GRADED SANDS AND GRAVELS

For graded sands and gravels the following steps have to be taken according to Figure 11:

1. The PSD has to be divided into a number of fractions.
2. The homogeneous fraction has to be determined based on a limiting particle diameter.
3. The liquid density and viscosity have to be adjusted based on the homogeneous fraction.
4. The sliding flow fraction has to be determined based on the $d/D_p>0.015$ Sellgren & Wilson (2007) criterion and the Zandi & Govatos (1967) criterion.

5. Now head loss curves and bed height hydraulic gradient curves are determined for each fraction independently, both for C_{vs} and for C_{vt}, using the liquid density and viscosity from step 3.
6. Summation of the head loss curves and bed height curves proportional to their fraction, both for C_{vs} and for C_{vt}.

Figure 11 shows the algorithm in order to determine the hydraulic gradient and the relative excess hydraulic gradient curves for graded soils. The method is straightforward. For each fraction of the PSD the hydraulic gradient is determined and the hydraulic gradients determined are added up to a resulting hydraulic gradient, both for constant spatial and constant delivered concentration curves.

$$\mathbf{i_m = \sum_{i=1}^{n} f_i \cdot i_{m,i}} \tag{26}$$

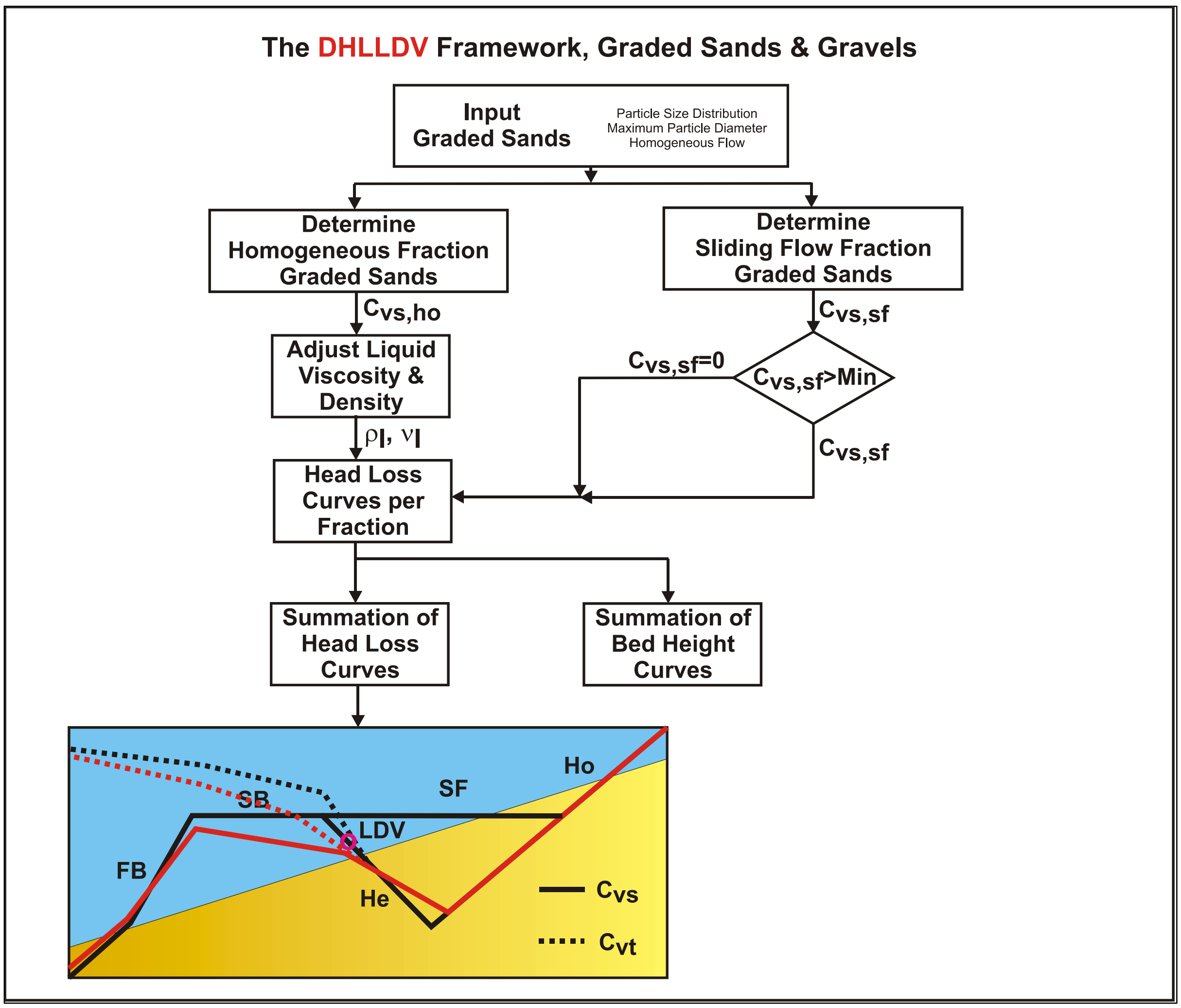

Figure 11: The algorithm to determine the constant C_{vs} and C_{vt} curve for graded sands and gravels.

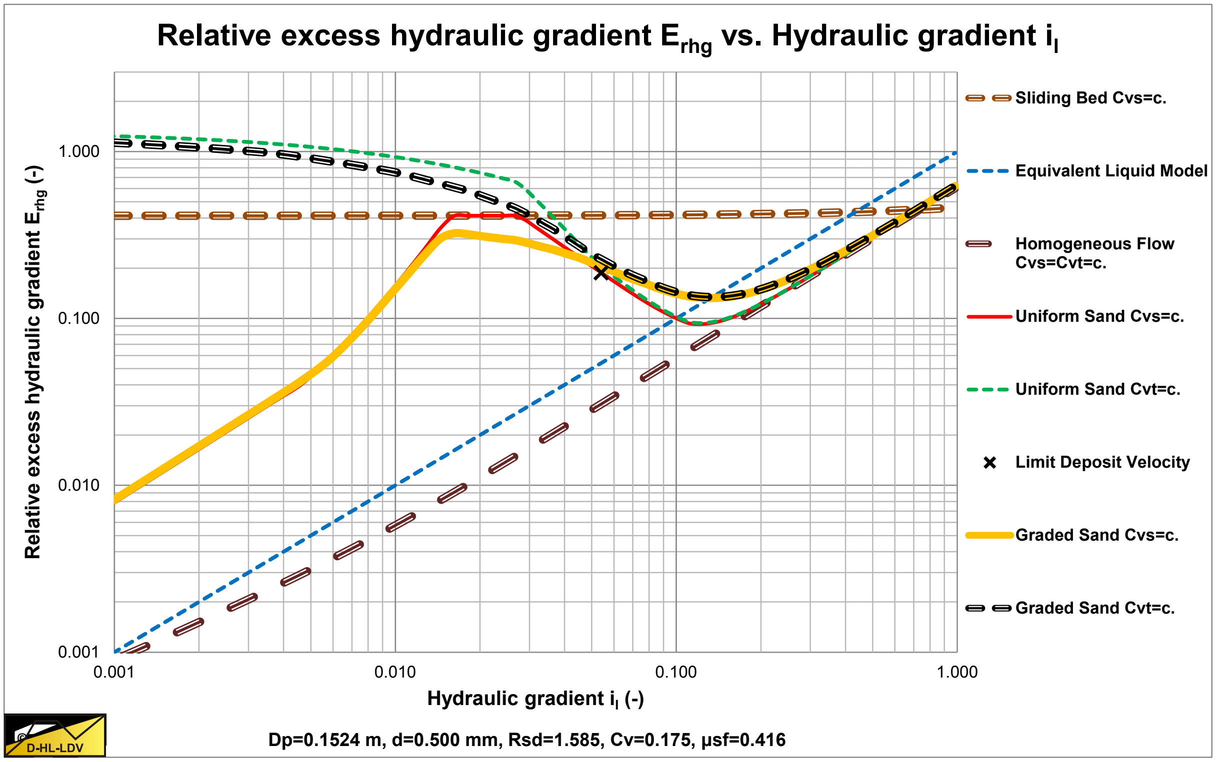

Figure 12: Graded sand $d_{85}/d_{50}=d_{50}/d_{15}=e$, $d_{50}=0.5$ mm.

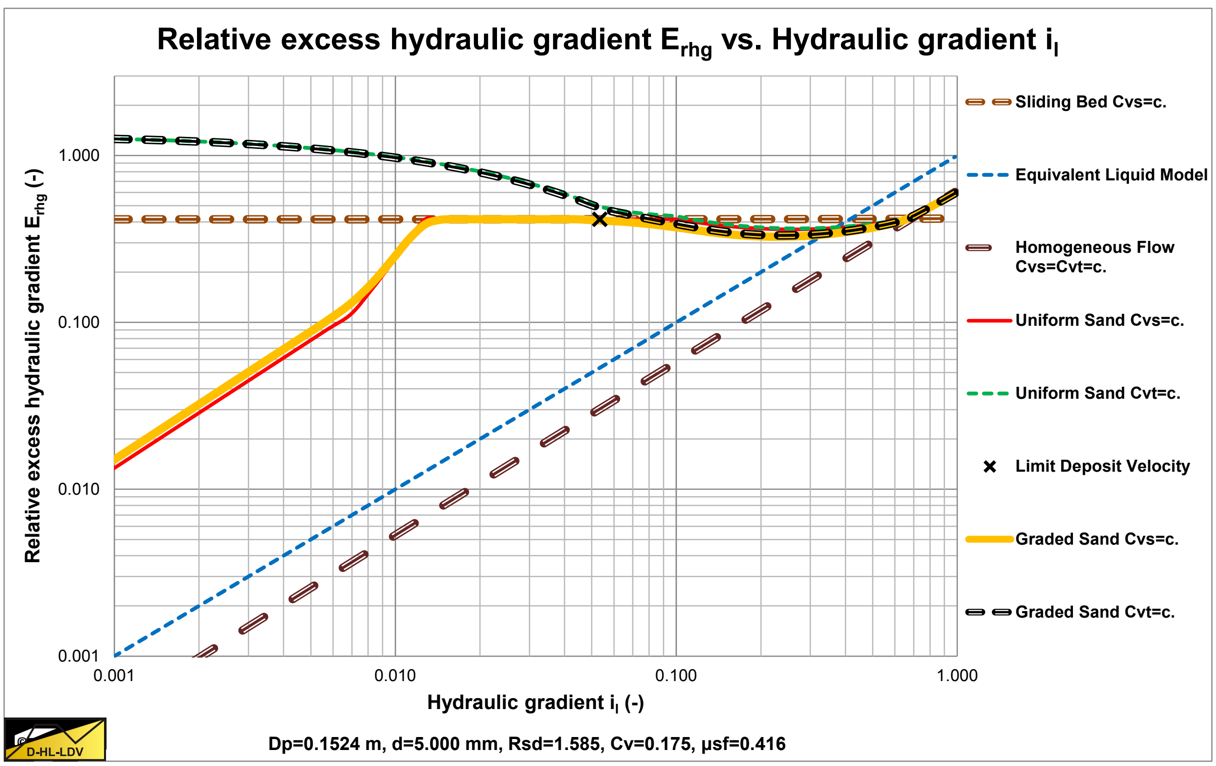

Figure 13: Graded sand $d_{85}/d_{50}=d_{50}/d_{15}=e$, $d_{50}=5$ mm.

In the case the sand contains fines, first the fraction of fines is determined based on a particle diameter. The fraction of fines is used to adjust the liquid density and viscosity with equations (9) and (10). With the adjusted liquid density and viscosity, the hydraulic gradients for each fraction of the PSD are determined and added up according to equation (26). In the case the sand contains a coarse fraction matching the criterion of Sellgren & Wilson (2007), first this fraction is determined. If the fraction times the volumetric concentration matches the criterion of Zandi & Govatos (1967) the hydraulic gradients of the corresponding PSD fractions are determined with the sliding flow model. All fractions with smaller particle diameters are determined with the heterogeneous model.

Figure 12 and Figure 13 shows the resulting E_{rhg} curves for a medium sand with d_{50}=0.5 mm and a coarse sand/gravel with d_{50}=5 mm. Figure 12 shows a reduction of the power of the line speed for the graded sand as already predicted by Wilson et al. (1992). The effect of the very coarse particles according to the Sellgren & Wilson (2007) criterion is clear in Figure 13.

APPLICATION OF THE DHLLDV FRAMEWORK

The absolute hydrostatic pressure at the inlet of the suction mouth of the cutter head or in the drag head is:

$$\mathbf{p_s = \rho_l \cdot g \cdot H_{0,in} + 100} \tag{27}$$

The pressure losses from the suction mouth to the end of the pipeline are:

$$\begin{aligned}\mathbf{p_m} &= \mathbf{\tfrac{1}{2}\cdot\rho_m\cdot v_{ls}^2 + \lambda_l\cdot\frac{L_{tot}}{D_p}\cdot\tfrac{1}{2}\cdot\rho_l\cdot v_{ls}^2 + \rho_l\cdot g\cdot L_{tot}\cdot R_{sd}\cdot C_{vt}\cdot E_{rhg} + \sum_1^n \xi_n\cdot\tfrac{1}{2}\cdot\rho_m\cdot v_{ls}^2} \\ &\quad \mathbf{+\rho_m\cdot g\cdot\left(H_{0,in}+H_{n+1,out}\right) - \rho_l\cdot g\cdot H_{0,in}}\end{aligned} \tag{28}$$

In this example it is assumed that the suction pipe and the discharge pipe have the same diameter. In reality this is often not the case. The suction pipe is usually a bit larger than the discharge pipe. However for this example it does not make a lot of difference.

1. The first term represents the acceleration losses. Outside the pipe the mixture is assumed not to have a velocity, but inside the pipe it has the line speed. So the mixture has to be accelerated, resulting in some pressure loss. For the total pressure loss this is not relevant, but for the calculation of possible cavitation at the inlet of the first pump it is.
2. The second term is the so called Darcy-Weisbach term for straight pipeline resistance of pure liquid (water in this case). The Darcy-Weisbach friction factor can be determined from the Moody diagram.
3. The third term is the solids effect based on the DHLLDV Framework. **Figure 15** shows the relative excess hydraulic gradient for different particle diameters in a 30 inch pipe as a function

of the line speed. The graph is constructed for a 17.5% constant delivered volumetric concentration. For other concentrations the graph can also be used for the heterogeneous and the homogeneous regimes (so if the slip can be neglected), but not for the sliding bed regime.

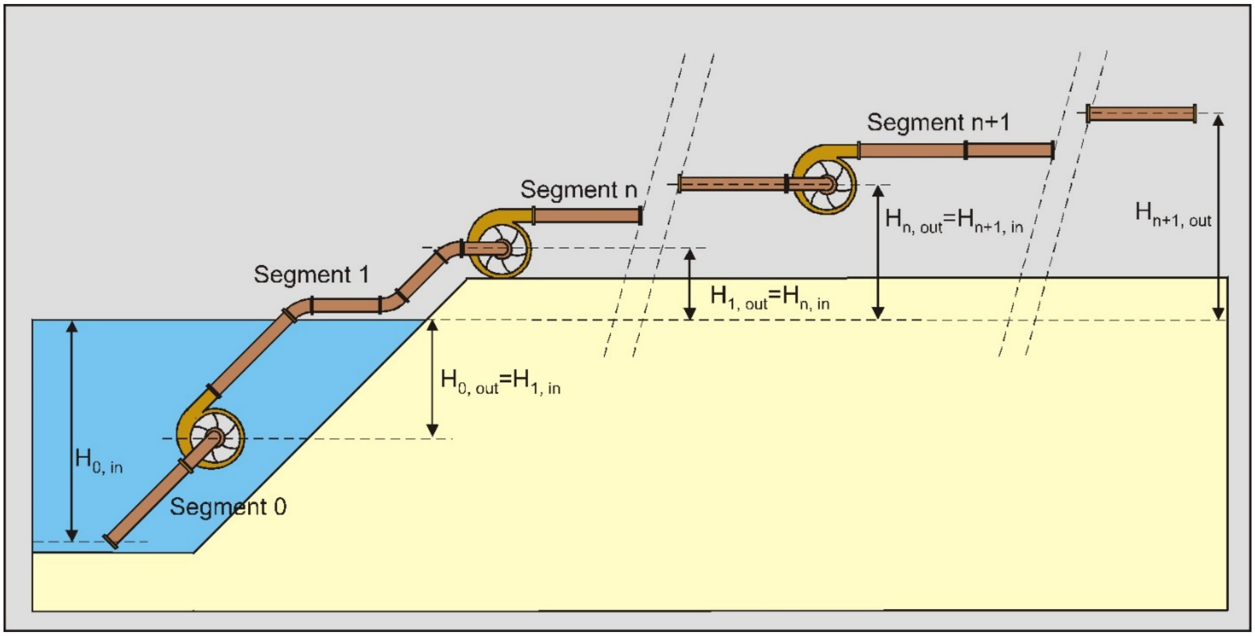

Figure 14: A pump pipeline system with boosters.

4. The fourth term represents the pressure losses due to fittings, telescopes and so on.
5. The fifth term represents the total elevation pressure loss, from suction mouth to discharge.
6. The sixth term represents the hydrostatic pressure at the location of the suction mouth.

The Limit Deposit Velocity can be determined with:

$$\mathbf{v_{ls,ldv} = F_L \cdot \left(2 \cdot g \cdot R_{sd} \cdot D_p\right)^{1/2}} \tag{29}$$

The value of the F_L Froude number can be found in Figure 16.

For a 0.762 m (30 inch) pipe, a particle diameter of 0.5 mm, a pipe length of 4000 m, a water depth of 20 m and an elevation of 10 m, the pressure losses are given in Figure 17. The graph shows the water curve (blue), the ELM curve (brown), the DHLLDV Framework curve (red) and a resulting pump curve for the mixture. The graph also shows the LDV and the concentration dependent LDV curve. The LDV is 6.35 m/s or 10417 m^3/hour. The working point (intersection of pump and resistance curves) is above 11000 m^3/hour. The pressure losses at this working point are about 1500 kPa or 15 bar.

It should be mentioned that in this example one should not stop pumping and later try to restart, since at low flow rates the pipe resistance is higher than the available pump pressure.

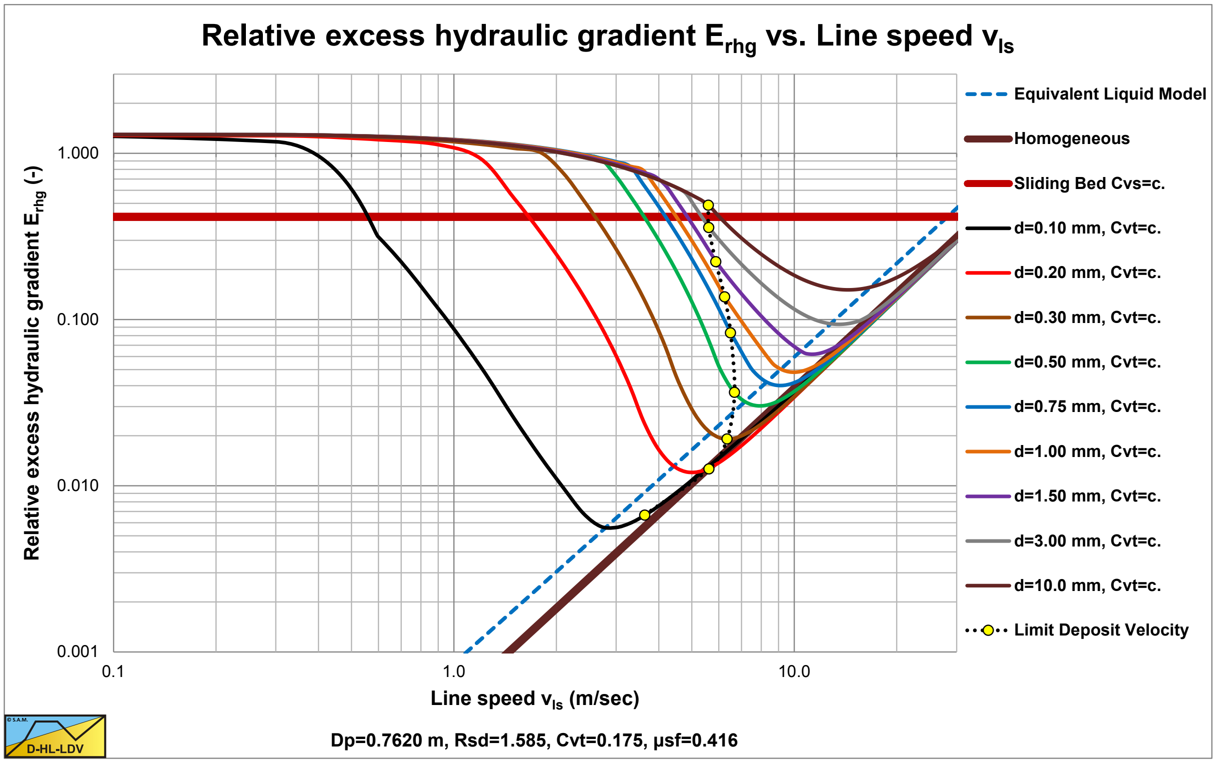

Figure 15: The relative excess hydraulic gradient for a 0.762 m (30 inch) pipe and 9 particle diameters for a constant delivered volumetric concentration of 17.5%.

CONCLUSIONS & DISCUSSION

The DHLLDV Framework is explained for determining head losses and the limit deposit velocity based on uniform sands and gravels and a spatial volumetric concentration. Using a holdup function, the delivered concentration head loss curve(s) can be determined and from there the bed height. By means of superposition, after some adjustments of the liquid properties, the head loss curve(s) for graded sands and gravels can also be determined. The full DHLLDV Framework is more complicated and detailed as described here and would require a multiple of pages. On the website www.dhlldv.com many additional graphs can be found and the latest developments will be shown after being published, including a list of papers about this subject. In 2016 a book will be published revealing all the details.

The choice of basing the model on spatial volumetric concentration and uniform sands or gravels enables an explicit formulation for the different sub-models.

The criteria determining heterogeneous flow or sliding flow still require more investigation, although they match the Doron & Barnea (1993) experiments and the SCR model. Concentrations of 4.2% and 5% of their experiments clearly show heterogeneous behavior, while all higher concentrations show sliding flow behavior.

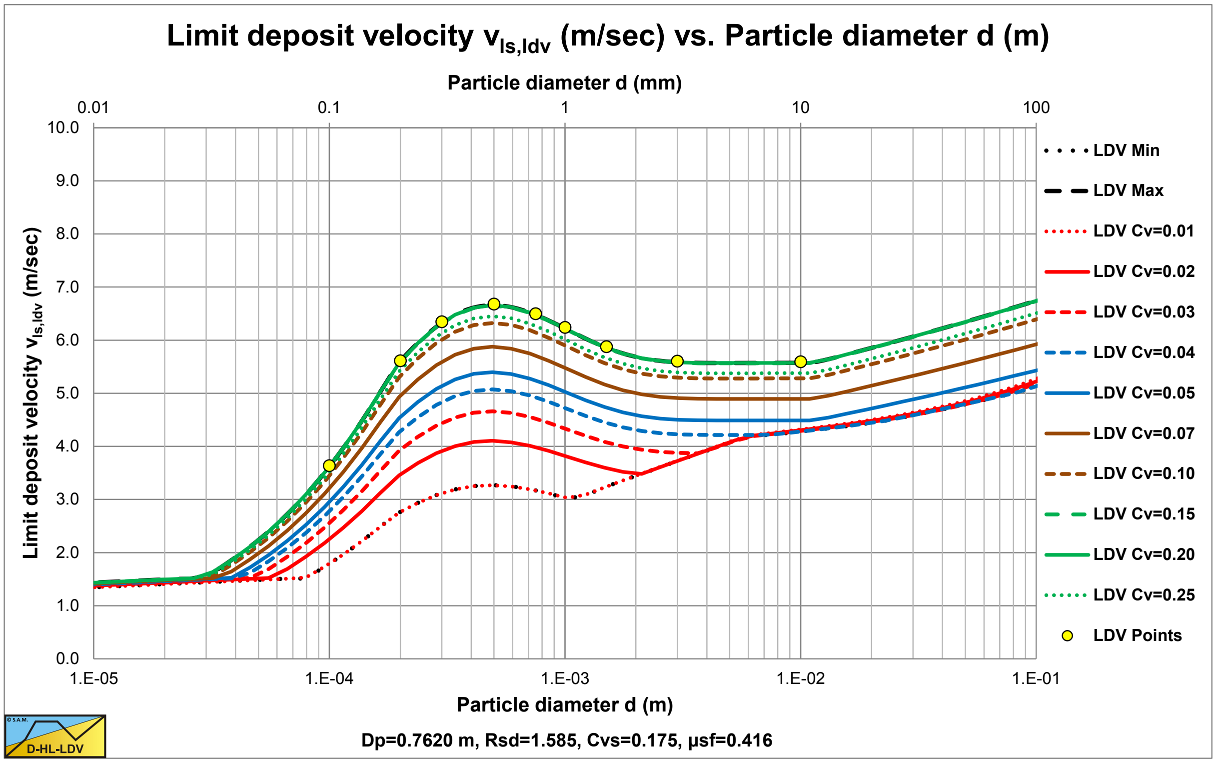

Figure 16: The limit deposit velocity for a 30 inch pipe.

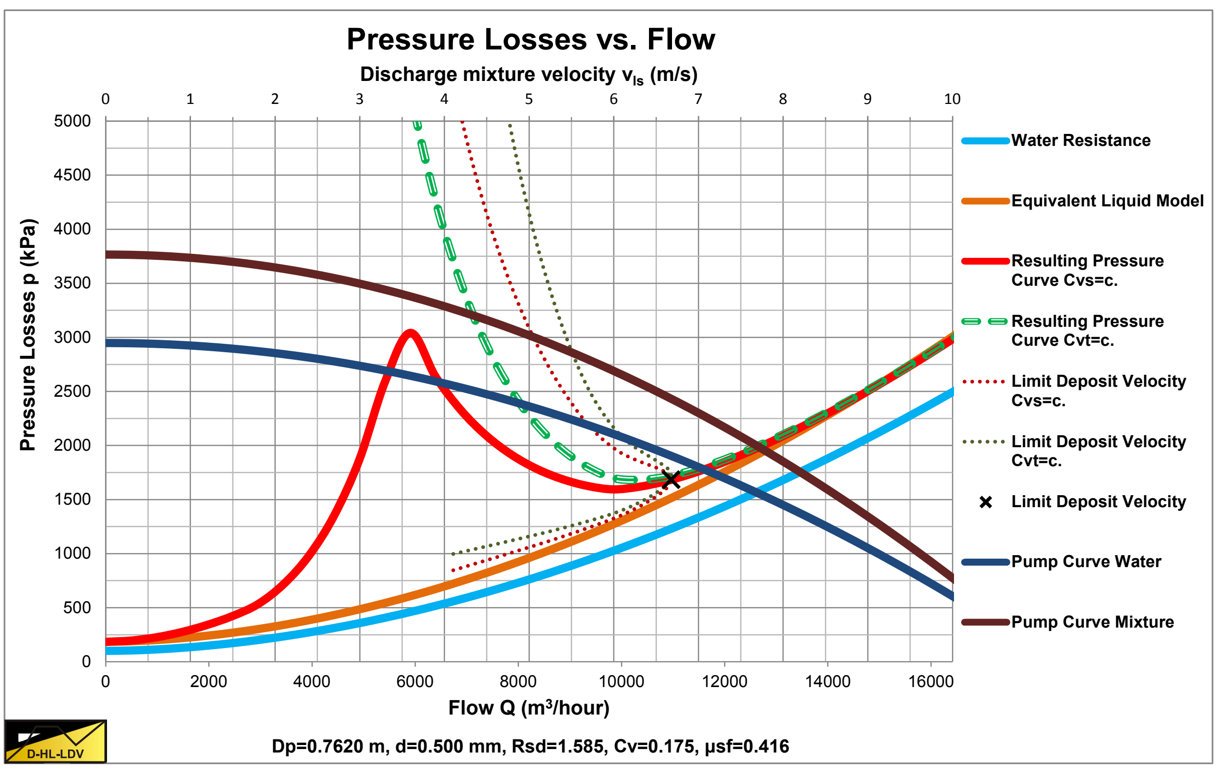

Figure 17: Pressure losses versus flow for d=0.5 mm particles.

The method for graded sands is promising, but may need some fine tuning. Unfortunately there is not much experimental data available, while only Wasp (1963), Kaushal & Tomita (2002C) and Sellgren & Wilson (2007) developed models for graded PSD's.

The DHLLDV Framework has been compared with the Wasp (1963), the Wilson et al. (1992), the Kaushal & Tomita (2002C) and the SCR model, as well as many more from literature, with good results. In addition the model compares well to a wide range of experimental data from literature. These comparisons are also available on the website. The DHLLDV Framework enables the user to implement user defined sub models for the different flow regimes, for the holdup function, for the bed height function and for the concentration distribution function.

The DHLLDV framework gives a reference framework for slurry flow in horizontal pipes. The DHLLDV Framework will be published as a book in 2016, with detailed information on how to use it. The book will be accompanied by an Excel workbook and Python software. The book, the Excel workbook and the Python software will be published free of charge in **Open Access** at the WODCON in Miami, June 2016.

NOMENCLATURE

A_{Cv}	Coefficient homogeneous regime (1.3 by default)	-
A_p	Cross section of the pipe	m^2
C_{vb}	Bed volumetric concentration	-
$C_{vb,max}$	Maximum bed volumetric concentration	-
C_{vB}	Concentration at the bottom of the pipe	-
C_D	Particle drag coefficient	-
C_{vs}	Spatial volumetric concentration	-
C_{vr}	Relative concentration C_{vs}/C_{vb}	-
$C_{vr,ldv}$	Relative concentration in bed at LDV	-
C_{vt}	Transport or delivered volumetric concentration	-
C_x	Durand & Condolios coefficient	-
d	Particle diameter	m
d_0	Particle diameter LDV transition region	m
D_H	Hydraulic diameter	m
D_p	Pipe diameter	m
E_{rhg}	Relative excess hydraulic gradient	-
$E_{rhg,SF}$	Relative excess hydraulic gradient in the sliding flow regime	-
$E_{rhg,HeHo}$	Relative excess hydraulic gradient in the heterogeneous/ homogeneous flow regimes	-
f	Fraction of fines	-
f	Factor determining sliding flow	-
F_L	Durand limit deposit velocity Froude number	-
$F_{L,s}$	Durand limit deposit velocity Froude number, smooth bed	-
$F_{L,ss}$	Durand limit deposit velocity Froude number, small particles smooth bed	-

$F_{L,vs}$	Durand limit deposit velocity Froude number, smooth bed, very small particles	-
$F_{L,r}$	Durand limit deposit velocity Froude number, rough bed, large particles	-
$F_{L,ul}$	Durand limit deposit velocity Froude number, upper limit	-
$F_{L,ll}$	Durand limit deposit velocity Froude number, lower limit	-
Fr_{DC}	Durand & Condolios Froude number	-
g	Gravitational constant (9.81)	m/s^2
h	Thickness of bed at LDV	m
i_l	Hydraulic gradient of liquid	-
i_m	Hydraulic gradient of mixture	-
$i_{m,i}$	Hydraulic gradient of i^{th} fraction of PSD	-
$i_{m,ldv}$	Hydraulic gradient mixture at LDV	-
K	Durand & Condolios constant (85)	-
m_p	Mass particle	kg
N	Zandi & Govatos deposit criterion	-
r	Position in pipe starting at the bottom	-
Re	Reynolds number based on velocity difference liquid flow - bed	-
R_{sd}	Relative submerged density	-
S_{hr}	Settling Velocity Hindered Relative	-
S_{rs}	Slip Velocity Relative Squared	-
u_*	Friction velocity	m/s
$u_{*,ldv}$	Friction velocity at the LDV	m/s
v_1	Average velocity above the bed	m/s
v_2	Velocity of the bed	m/s
v_{12}	Velocity difference bed interface (v_1-v_2)	m/s
v_{ls}	Cross-section averaged line speed	m/s
$v_{ls,ldv}$	Limit Deposit Velocity (LDV)	m/s
v_r	Relative line speed $v_{ls}/v_{ls,ldv,max}$ or v_{ls}/v_{sm}	m/s
v_{sl}	Slip velocity (velocity difference between particle and liquid)	m/s
v_{sm}	Maximum LSDV according to Wilson	m/s
v_t	Particle terminal settling velocity	m/s
v_{th}	Hindered settling velocity	m/s
v_{tv}	(Hindered) settling velocity in the vehicle (Wasp model)	m/s
$v_{tv,ldv}$	(Hindered) settling velocity in the vehicle (Wasp model) at LDV	m/s
α_h	Coefficient homogeneous equation	-
α_p	LDV factor	-
α_{sm}	Factor concentration distribution	-
β	Angle of bed with vertical	rad
β	Power of Richardson & Zaki hindered settling factor	-
β_{sm}	Relation sediment diffusivity eddy momentum diffusivity	-
φ	Internal friction angle	rad
δ	External friction angle	rad
λ_1, λ_l	Darcy Weisbach friction factor liquid to pipe wall	-
λ_{12}	Darcy Weisbach friction factor bed interface	-
κ	Von Karman constant (about 0.4)	-

κ_C	Concentration distribution constant	-
ρ_l	Density of liquid	ton/m^3
$\rho_{l,m}$	Density of liquid including fines	ton/m^3
ρ_m	Mixture density	ton/m^3
ρ_s	Density of solids	ton/m^3
ν_l	Kinematic viscosity liquid	m^2/s
μ_l	Dynamic viscosity liquid	Pa·s
$\mu_{l,m}$	Dynamic viscously liquid including fines	Pa·s
μ_{sf}	Sliding friction coefficient	-
$\tau_{2,sf}$	Shear stress bed – pipe wall due to sliding friction	kPa
τ_{12}	Bed shear stress	kPa
ξ	Slip ratio	-
ξ_0	Slip ratio asymptotically for line speed zero	-
ζ	Bed fraction	-

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REVIEW OF ENVIRONMENTAL DREDGING IN NORTH AMERICA: CURRENT PRACTICE AND LESSONS LEARNED

Ram Mohan[1], J. Paul Doody[2], Clay Patmont[3], Rebecca Gardner[4], and Amanda Shellenberger[5]

ABSTRACT

Environmental dredging has been used for more than 30 years to remove contaminated sediments from water bodies in an effort to restore them from historical chemical impacts. Contaminated sediment cleanup has been implemented under a number of regulatory frameworks, and one of the most commonly used tools, dredging, has been used to remove contaminated sediment deposits with an aim to reduce potential risks to human health and the environment. As would be expected, there are valuable lessons from these projects, including positive and negative aspects, which can help inform current and future projects around the world. This paper provides an overview of the history of environmental dredging in North America, highlighting important lessons learned, and how they have informed subsequent projects. The performance of these projects are evaluated to determine where progress has been made, and also to identify areas requiring further improvement. Finally, some general guidelines for claims avoidance are provided, based on the author's experience in related litigation support, over the years.

Keywords: contaminated sediments, remediation, superfund, adaptive management, case studies, costs

INTRODUCTION

Contaminated sediments exist around the world and pose unique challenges, both technically and administratively. In the United States and Canada, federal and state governments and responsible parties have been investigating, evaluating, and remediating contaminated sites since the early 1980s. To date, environmental dredging has been the most common technique

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employed for contaminated sediment cleanup. Over the past 30 years, much has been learned from environmental dredging experience. Many of the lessons learned have been considered and recognized in recent guidance documents developed by the U.S. Environmental Protection Agency (USEPA; 2005) and the U.S. Army Corps of Engineers (Bridges et al., 2008; USACE, 2008), as well as in the U.S. National Academy of Sciences (NAS) study on the effectiveness of environmental dredging (NAS, 2007). Some other studies offer additional insights as well (Mohan and Thomas, 1997; Doody and Cushing, 2002; Patmont and Palermo, 2007; Bridges et al., 2010). This paper builds further on those lessons learned, particularly from the more highly contaminated and regulated sites across the remediation spectrum, with an aim to improve planning and implementation of future environmental dredging projects.

Typical regulatory programs driving contaminated sediment cleanup in the United States and Canada include the following:

- USEPA Comprehensive Environmental Response, Compensation and Liability Act (also known as Superfund)
- USEPA Resource Conservation and Recovery Act
- USEPA Clean Water Act
- Fifty different state regulatory programs (some similar to USEPA programs)
- Federal Contaminated Sites Action Plan (Canada)

Although each of these programs has unique regulatory processes and other requirements, they all involve investigation of potential risks posed by contaminated sediment sites, evaluation of alternative site-specific cleanup remedies, implementation of the agency-selected remedy, and often (but not always) long-term monitoring to document the effectiveness of the remedy.

Compared with upland cleanup sites, contaminated sediments present unique challenges from a technical perspective. For example, there are often multiple sources of contamination (e.g., legacy and ongoing sources that may or may not have been fully controlled) and different chemical contaminants that may not behave similarly during dredging; these and other key variables need to be well understood in order to develop and implement an effective cleanup remedy. Contaminated sediment deposits from a given source may be spread over relatively large areas and may also be subject to a range of environmental forces and transport pathways. The types of aquatic environments can vary amongst and within sites, ranging from marine tidal environments and oceans to freshwater lakes, ponds, rivers, and streams—all of which present different technical challenges. The underwater environment can also provide unique and sensitive habitats for aquatic flora and fauna.

Experience in North America has shown that environmental dredging can be expensive, with a large portion of the total cost attributable to management and disposal of the sediment removed from the waterway. The combined cost to remediate three of the largest sites in the United States—the Hudson River, Onondaga Lake, and the Lower Fox River—is currently estimated at more than $3 billion, with other large sites on the horizon. Observations and data from smaller projects, and during implementation stages of the Hudson River, Onondaga Lake, and Lower Fox River projects, clearly demonstrate that there are limitations associated with environmental dredging that need to be recognized when embarking on future projects. Several of the important lessons learned include the following:

- Implications of technology advancements (bucket designs and hydraulic equipment)
- Improvements in survey and sampling equipment

- Inevitability of residuals, resuspension, release, and risk (the Four Rs; e.g., see Bridges et al., 2010)
- Limited effectiveness of resuspension control techniques (silt curtains, rigid containment systems)
- Recognition of the need for post-dredge residuals management
- Benefits associated with integrating adaptive management principles
- Understanding project costs associated with environmental dredging projects

SUMMARY OF REMEDY DECISIONS FOR CONTAMINATED SEDIMENT

To help provide some context of remedy decision making in the United States, Doody et al. (2011) and Patmont et al. (2013) presented results of research into USEPA decisions for contaminated sediment sites over the past three decades. The research included a review of USEPA Record of Decision (ROD) documents to evaluate trends resulting from the expanded dialogue, scientific review, and development of agency guidance on environmental dredging that has occurred since the late 1990s. Figure 1 illustrates the chemical contaminants for which cleanup levels were established in the ROD. As shown, polychlorinated biphenyls (PCBs) have been the primary contaminant targeted for sediment cleanup at sites in the United States, and there has been little change in this trend during the past decade.

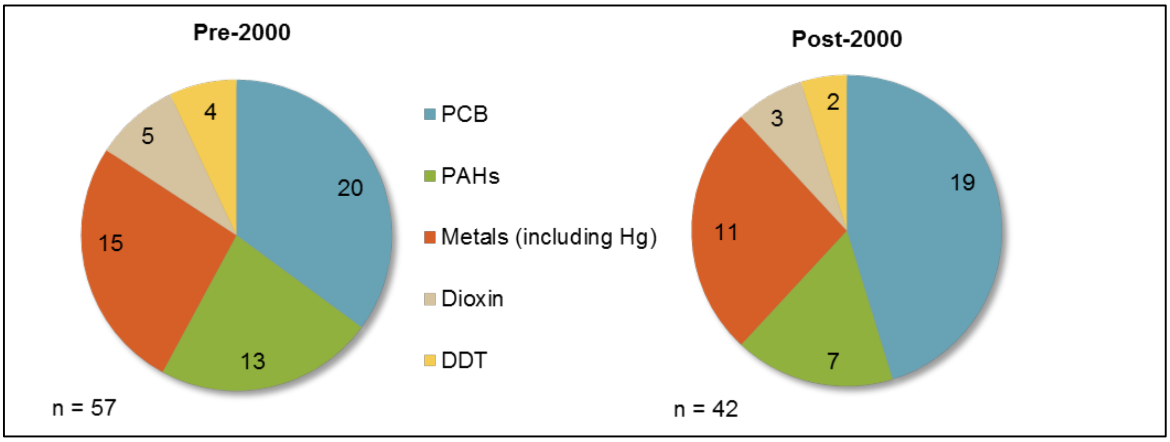

Figure 1. Primary Contaminants of Concern in USEPA Records of Decision.

Sediment removal continues to represent the largest proportion of USEPA's sediment cleanup decisions; however, since 2005, there has been an increase in remedies with multiple approaches, such as removal, capping, and monitored natural recovery (MNR; referred to as hybrid remedies). The year 2005 was used as it coincides with the year USEPA released its contaminated sediment remediation guidance (USEPA, 2005). All of the hybrid remedies implemented since 2005 have included removal, and environmental dredging continues to represent the most frequently selected sediment cleanup technology, even for projects with hybrid remedies. Figure 2 illustrates the shift in the decision making process by USEPA.

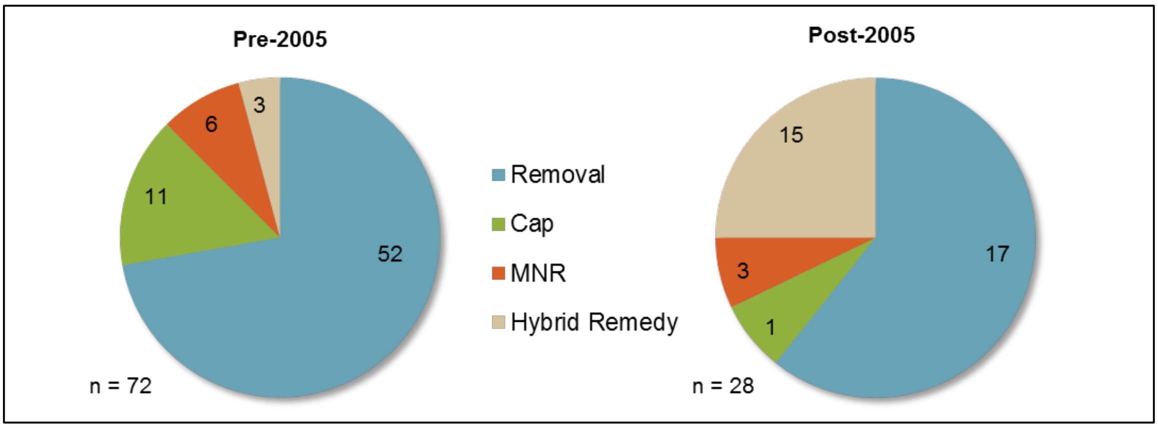

Figure 2. Selected Remedial Technologies included in USEPA Records of Decision.

Another important trend is that post-dredge residual management, such as placing a clean cover, backfill, or cap layer over dredged areas, is becoming more frequent with environmental dredging, particularly since 2005 (Figure 3). One of the important lessons learned is that environmental dredging will inevitably leave behind some contaminated sediment on the newly exposed surface (Bridges et al., 2008). This residual layer of contaminated sediment typically has contaminant concentrations equal to the average dredge prism concentration over the entire cut (USEPA, 2010). Because pre-dredge subsurface sediment dredge prism concentrations are often higher than surface sediments, dredging can increase risks at least temporarily. Management of dredging residuals has been an increasing focus of environmental dredging projects, particularly at sites with relatively low cleanup levels (e.g., for PCBs and other bio-accumulative compounds when based on USEPA's assumptions of relatively high consumption rates of fish and shellfish). As a result, it is becoming increasingly common that environmental projects include post-dredge residual management to try to mitigate such dredging-related risks.

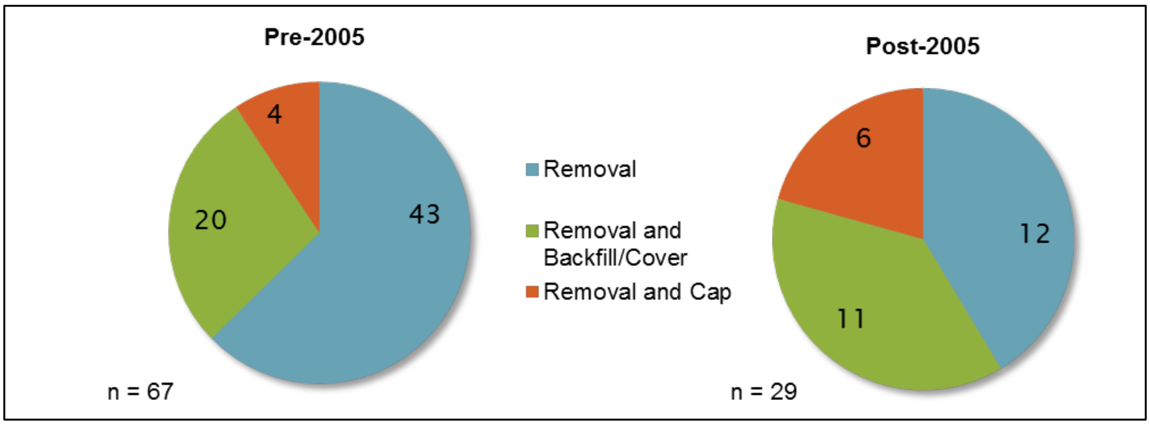

Figure 3. Selected Residual Management Approaches included in USEPA Records of Decision.

ENVIRONMENTAL DREDGING EXPERIENCE IN NORTH AMERICA

Doody and Cushing (2002) examined 59 completed projects, which included 32 environmental dredging projects (mechanical or hydraulic dredging) and 27 wet/dry excavation projects. The authors noted the prevalence of post-dredge residual, sediment resuspension, and dissolved contaminant release impacts associated with many of these projects; the need for residual management actions; and the relatively high cost of environmental dredging projects. Information from these completed projects is documented in the Major Contaminated Sediment Sites Database (SMWG, 2008).

In the mid-2000s, NAS undertook a study of the effectiveness of environmental dredging (NAS, 2007), and examined 26 sediment dredging projects for which detailed monitoring data were available. More recently, Mohan et al. (2010) prepared an updated summary of the costs of environmental dredging projects and associated management actions, compiling the cost basis of more than 100 completed environmental dredging projects throughout North America. Table 1 provides a summary of major remedial dredging projects in North America, while Table 2 provides a unit cost analysis, identifying that the major component of the environmental dredging cost is for disposal.

Table 1. Summary of Major U.S. Remedial Dredging Projects.

Project	Location	Contaminant(s) of Concern	Dredge Method	Volume Dredged (m^3)	Completion Date
Lavaca Bay	Texas	Mercury	Hydraulic cutter	53,200 (70,000 cy)	1999
Ashtabula River	Ohio	PCBs, PAHs, heavy metals	Hydraulic cutter	478,800 (630,000 cy)	
Bayou Bonfouca	Louisiana	PAHs (creosote), VOCs	Mechanical; custom backhoe	128,440 (169,000 cy)	1995
Black River	Ohio	PAHs	Hydraulic cutter; mechanical clamshell	45,600 (60,000 cy)	1990
Buffalo River	New York	PAHs, PCBs, lead, mercury	Mechanical	349,600 (460,000 cy)	2015
Commencement Bay, Sitcum Waterway	Washington	Metals, PCBs	Hydraulic cutter and mechanical clamshell	1,720,800 (2,258,000 cy)	1994
Elizabeth River, Money Point Site	Virginia	PAHs	Mechanical clamshell	38,000 (50,000 cy)	2017 (Planned)

Table 1. Summary of Major U.S. Remedial Dredging Projects (cont'd).

Project	Location	Contaminant(s) of Concern	Dredge Method	Volume Dredged (m^3)	Completion Date
Grand Calumet River (USX)	Indiana	PAHs, metals, PCBs	Hydraulic cutter	598,880 (788,000 cy)	
Grasse River	New York	PCBs	Mechanical dredge (anticipated)	82,840 (109,000 cy; estimate)	2018 (Planned)
Hudson River	New York	PCBs	Mechanical buckets	>1,520,000 (>2,000,000 cy)	2015
Lake Champlain	New York	PCBs	Hydraulic cutter	144,400 (190,000 cy)	2001
Lipari Landfill Site	New Jersey	VOC	Dry and wet excavation	124,260 (163,500 cy)	1996
Lower Fox River (Phase 2)	Michigan	PCBs	Horizontal auger; backhoe	38,240 (50,316 cy)	2000
Lower Fox River (OU's 2-5)	Wisconsin	PCBs	Hydraulic cutter	2,888,000 (3.8 million cy); Expected total 3,876,000 (5.1+ million cy)	2018 (Planned)
Lower Rouge River – Old Channel	Michigan	PAHs	Mechanical dredge (anticipated)	58,140 (76,500 cy; ROD estimate)	2017 (Planned)
Lower Saginaw River	Michigan	PCBs	Environmental clamshell bucket	262,200 (345,000 cy)	2000
LTV Steel Site	Indiana	PAHs and oil	Diver-assisted vacuum; hydraulic cutter	82,840 (109,000 cy)	1996
Manistique River and Harbor	Michigan	PCBs	Diver-assisted, hydraulic auger	89,338 (117,550 cy)	2001
Marathon Battery Company	New York	Heavy metals	Horizontal auger; dry excavation	76 152 (100,200 cy)	1995
Milltown Reservoir	Montana	Arsenic, copper	Excavation	1,770,800 (2,330,000 cy)	
Onondaga Lake	New York	PAH, PCB, mercury, others	Hydraulic cutter; mechanical	1,640,080 (2,158,000 cy)	2014

Table 1. Summary of Major U.S. Remedial Dredging Projects (cont'd).

Project	Location	Contaminant(s) of Concern	Dredge Method	Volume Dredged (m^3)	Completion Date
Orion Project 1	New Jersey		Closed-bucket clamshell	76,000 (100,000 cy)	2000
Port of Long Beach IR Site 7 Naval Base Remediation	California	PCBs, metals	Clamshell	532,000 (700,000 cy)	2010
Port Hueneme CAD Site Development	California	PCBs, TBT, metals	Clamshell and hydraulic cutter	760,000 (1,000,000 cy)	2009
Rhine Channel	California	PCBs, metals, DDT	Clamshell	76,000 (100,000 cy)	2011
St. Lawrence River	New York	PCBs	Horizontal auger; mechanical	10,070 (13,250 cy)	1995
Town Branch Creek (Phase I)	Kentucky	PCBs	Dry excavation	70,680 (93,000 cy)	1998
United Heckathorn Superfund Site	California	DDT	Mechanical bucket	82,080 (108,000 cy)	1997
Waukegan Harbor (Outboard Marine)	Waukegan	PCBs	Hydraulic cutter	39,000 (50,000 cy)	1992
East Waterway Phase 1 Removal Action, Port of Seattle	Washington	PCBs, metals, PAH	Mechanical clamshell	197,600 (260,000 cy)	2005
Middle Waterway	Washington	Mercury, arsenic, metals, PAH	Mechanical clamshell	82,080 (108,000 cy)	2005
East Waterway Stage 1, Port of Seattle	Washington	PCBs, metals, PAH	Mechanical clamshell	161,120 (212,000 cy)	2003
Black Lagoon/ Detroit River	Michigan	PCBs, PAHs, heavy metals, oil, grease	Mechanical clamshell	87,400 (115,000 cy)	
Bryant Mill Pond	Michigan	PCBs	Dry excavation	110,960 (146,000 cy)	
Commencement Bay, Middle Waterway	Washington	Mercury, arsenic, metals, PAH	Mechanical clamshell	82,080 (108,000 cy)	2005
Commencement Bay, Thea Foss/ Wheeler Osgood Waterway	Washington	Zinc, lead, mercury, PAHs, PCBs, and NAPL	Hydraulic	401,280 (528,000 cy)	

Table 1. Summary of Major U.S. Remedial Dredging Projects (cont'd).

Project	Location	Contaminant(s) of Concern	Dredge Method	Volume Dredged (m^3)	Completion Date
Cumberland Bay (Lake Champlain Basin Program)	New York	PCBs, PAHs, PCDDs, PCDFs	Hydraulic	148,200 (195,000 cy)	2001
Greenlaw Brook/ Butterfield Brook/ Limestone Stream	Maine	Pesticides, PAHs, PCBs, TPHs, lead	Dry and wet excavation	115,520 (152,000 cy)	
Kinnickinnic River	Wisconsin	PCBs and PAHs	Mechanical	126,920 (167,000 cy)	
Newburgh Lake	Michigan	PCBs	Hydraulic cutter; mechanical excavation	446,880 (588,000 cy)	
Pine River	Michigan	DDT	Cofferdam and excavation	486,400 (640,000 cy)	
Ruddiman Creek/Pond	Michigan	Cadmium, chromium, lead, and PCBs	Mechanical	68,400 (90,000 cy)	
Bremerton Naval Complex	Washington	PCBs, PAHs, mercury, arsenic, copper, lead, and zinc	Mechanical	171,000 (225,000 cy)	
Tyler Pond, Edison Pond, Willow Run Sludge Lagoon	Michigan	PCBs	Dry excavation	342,000 (450,000 cy)	
Roebling Steel Co. (Delaware River)	Delaware	PAH, metals		182,400 (240,000 cy)	2013
Atlantic Wood Industries, Elizabeth River	Virginia	PAH		119,320 (157,000 cy) estimated	
Puget Sound Naval Shipyard Complex	Washington	PCBs and mercury		171,000 (225,000 cy)	2005

Notes:
cy = cubic yard
DDT = dichlorodiphenyltrichloroethane
D/F = dioxins and furans
m^3 = cubic meter
NAPL = non-aqueous phase liquid
PAH = polycyclic aromatic hydrocarbon
PCB = polychlorinated biphenyl
PCDD = polychlorinated dibenzodioxin
PCDF = polychlorinated dibenzofuran
ppm = part per million
ROD = Record of Decision
TBT = tributyltin
TPH = total petroleum hydrocarbon
VOC = volatile organic compound

Table 2. Summary of Unit Costs for Key Components of U.S. Environmental Dredging Projects.

Item	Average Cost (US $)	Range of Costs (US $)	
		Minimum Cost	Maximum Cost
Dry Excavation ($/m^3)	92 (70/cy)	13 (10/cy)	177 (135/cy)
Mechanical Dredging ($/m^3)	99 (75 cy)	20 (15/cy)	283 (215/cy)
Hydraulic Dredging ($/m^3)	79 (60 cy)	20 (15/cy)	256 (195/cy)
Water Treatment ($/L)	0.17 (0.045/gal)	0.0132 (0.0035/gal)	0.624 (0.165/gal)
Landfill Disposal ($/m^3)	105 (80/cy)	6.6 (5/cy)	289 (220/cy)
Special (TSCA) Disposal ($/m^3)	263 (200/cy)	13 (10/cy)	631 (480/cy)

Notes:
Costs shown are based on Mohan et al. (2010).
Minimum and maximum range costs should be considered as outliers.
cy = cubic yard
gal = gallons
L = liter
m^3 = cubic meter
TSCA = Toxic Substances Control Act
USD = U.S. dollars

Table 3 presents the summary of environmental dredging costs, split into three tiers (to represent volume ranges). A closer look at the historical cost data of completed environmental dredging projects reveals the following (with respect to the economic advantage in having local dredged material disposal options available for cost-effective dredging projects):

- **Local Disposal**. Where effective local disposal was available for placing the sediments, the total cost of dredging and disposal ranged from $20/cubic meter (m^3; $15/cubic yard [cy]) to $809/m^3 ($615/cy) for projects with at least 7,600 m^3 (10,000 cy) of sediments. Because the one project that had the lowest on-site confined disposal facility cost was implemented in a manner more like a navigational dredging project than an environmental dredging project (i.e., hydraulic dredging and disposal in a nearshore confined disposal facility), it would be prudent to account for a more realistic range of costs in the range of $66/m^3 ($50/cy) to $263/m^3 ($200/cy), when a local disposal facility is available at a reasonable cost within close proximity of the dredge area. Where on-site incineration was needed, costs escalated to the $658/m^3 ($500/cy) to $2,105/m^3 ($1,600/cy) range. For smaller volume projects (less than $8,552/m^3 [6,500 cy]), costs ranged as high as $3,816/m^3 ($2,900/cy).
- **Off-site Disposal.** For projects that included off-site disposal, the costs generally varied from $132/m^3 ($100/cy) to $658/m^3 ($500/cy). For projects that required special (e.g., Toxic Substances Control Act) disposal, total costs were more on the order of $908/m^3 ($690/cy) to $4,026/m^3 ($3,060/cy).

Table 3. Summary of Environmental Dredging Construction Costs[1].

Tier	Remediation Volume Range (m^3)	Range of Observed Costs and Average ($\$/m^3$)
Tier 1	760 to 11,400 (1,000 to 15,000/cy)	263 to 3,815 (1395 average) (200 to 2,900/cy [1,060/cy average])[2]
Tier 2	11,400 to 76,000 (15,000 to 100,000/cy)	52 to 1,039 (382 average) (40 to 790/cy [290/cy average])[3]
Tier 3	greater than 76,000 (greater than 100,000/cy)	26 to 1270 (336 average) (20 to 965/cy [255/cy average])[4]

Notes:
1. Costs shown are based on Mohan et al. (2010). These costs do not include non-construction costs (such as design, planning, permitting, project management, and agency oversight) or source control costs.
2. The higher end denotes projects with small dredging volumes (less than 4,940 m^3 [6,500 cy]), pilot projects with unique local restrictions, or hot spot dredging, and, in some cases, several passes of dredging.
3. Denotes efficient mid-size volume projects, generally dredging, with some backfill/cap after dredging; lower end of the range denotes projects with local, on-site disposal.
4. Efficiencies of (volume) scale influence Tier 3 cost ranges; the higher end denotes a project with on-site incineration and higher levels of contamination than normal, and, in some cases, several passes of dredging.

cy = cubic yard

The authors also reviewed project information from their collective professional experience and generated an approximate order of costs for post-dredged backfill placement. In general, \$50,000 to \$150,000 per acre should be sufficient for most backfill layers (for approximate layer thickness of 0.15 to 0.30 m [0.5 to 1 foot]), noting that local site-specific conditions can affect these costs considerably.

A review of completed projects from a cost and schedule perspective, and comparing them specifically with the cost estimate developed during the selection of the remedial approach (e.g., feasibility study) reveals that sediment remediation projects tend to cost more and take longer to complete than expected (Figures 4 and 5). There are three key aspects to this observation.

- First is that cost and schedule data from completed projects needs to be carefully considered and integrated in developing estimates during remedy evaluations for future projects such that decisions are made using the most accurate information possible.
- Second, and just as importantly, effective project management and control of these factors are needed during remedy implementation to align projects better with the original schedule and cost estimates.
- Finally, experienced construction professionals or contractors are rarely engaged to perform constructability reviews during the feasibility study and conceptual design phases.

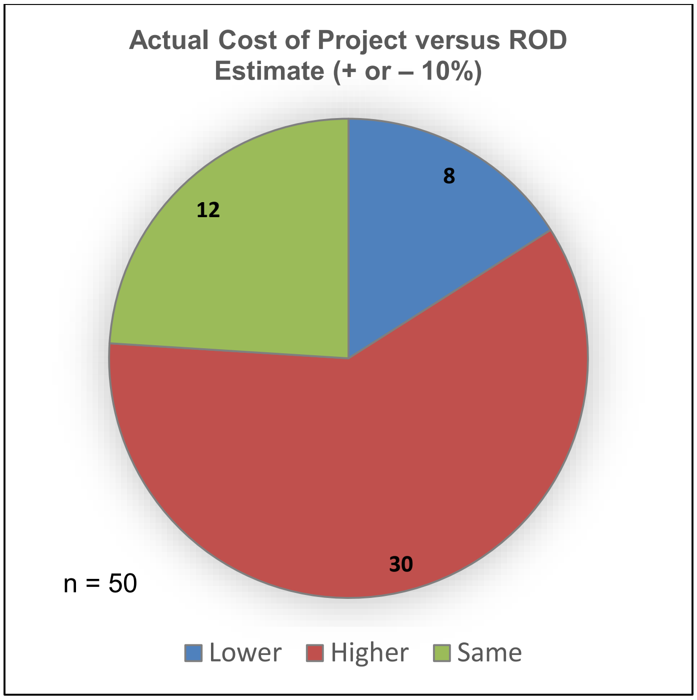

Figure 4. Comparison of Estimated and Actual Costs for Completed Remediation Projects.

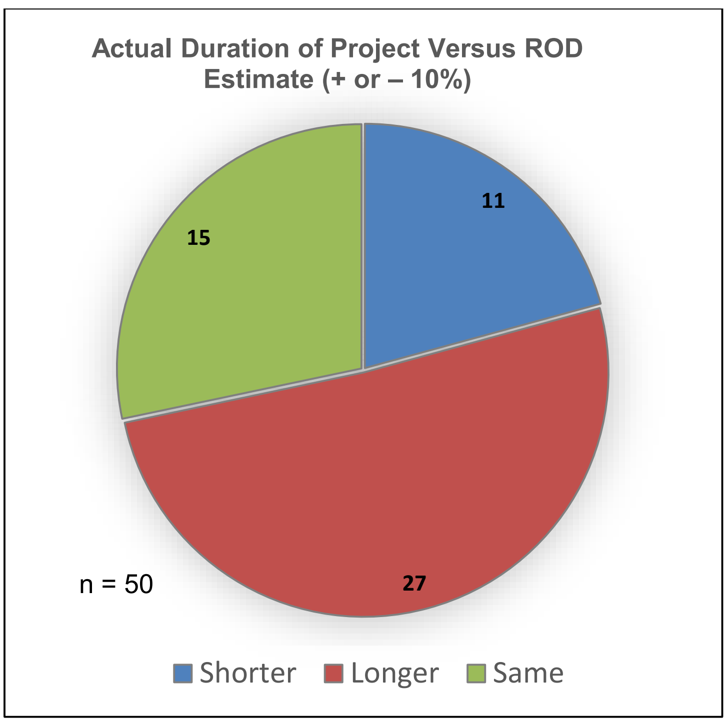

Figure 5. Comparison of Estimated and Actual Schedule for Completed Remediation Projects.

LESSONS LEARNED FROM COMPLETED PROJECTS

A review of completed environmental dredging projects in the United States clearly demonstrates that thorough characterization of site conditions is critical to effectively designing and implementing successful projects. Inadequate site characterization can increase the frequency of undisturbed residuals encountered at the base of the dredge cut (Figure 6), which can cause delays, result in higher costs, and can potentially lead to failure to meet cleanup levels. To be successful, environmental dredging projects also need to be developed using an integrated approach, ensuring that dredging operations are compatible with materials handling, transport, treatment, and disposal. Sometimes multiple dredge types may be used to optimize operations, depending on the specific project goals (for example, a relatively large dredge is often more appropriate for production cuts, whereas a smaller dredge may be more optimal for thin cuts and residuals passes). Management actions to improve overall project effectiveness should be thoroughly considered, including the use of appropriate control measures, post-dredge residual management, and other best management practices (BMPs).

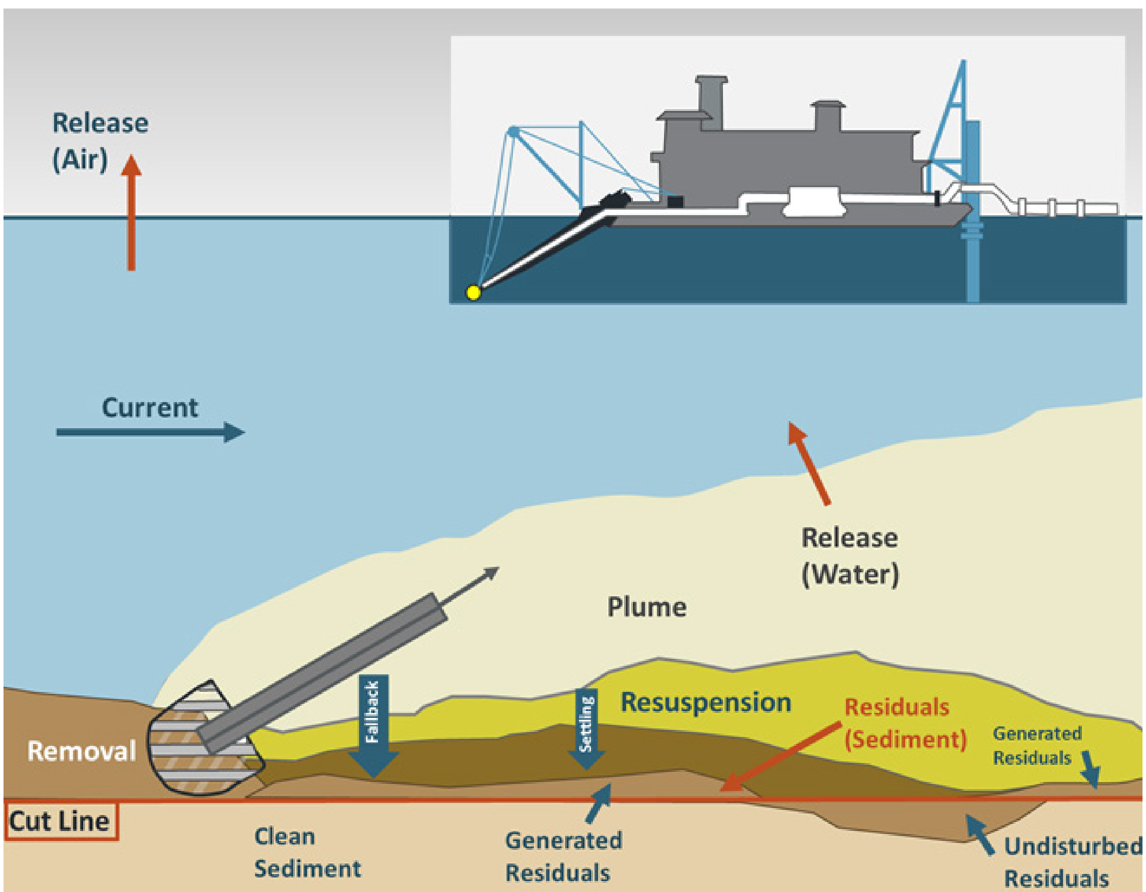

Figure 6. Four Rs of Environmental Dredging (adapted from USACE, 2008).

As discussed in Bridges et al. (2010), all environmental dredging operations leave some residual contaminated sediment behind (Figure 6). This is not surprising given the limitations of even the most modern dredging equipment, the variable distribution of contamination found in many sites (including relatively high levels at depth from legacy releases), and the limited degree of pre-dredging characterization that has been performed at some environmental dredging sites. The inevitability of post-dredging residuals and their influence on risk has been increasingly recognized over the last decade. Recent technological innovations in statistically based site characterization, survey and dredging equipment, and BMPs for reducing residuals have shown some improvements over conventional equipment and practices, but residuals are still unavoidable. Because the purpose of environmental dredging is to reduce contaminated sediment risks, dredging residuals are a continuing concern.

The state of practice in modeling dredging processes is not sufficient to make precise predictions of post-dredging residual contaminant concentrations, but empirical approaches based on detailed case study information can provide good estimates. Detailed pre- and post-dredge characterization data collected at some of the higher profile environmental dredging projects (e.g., Hudson River, Lower Fox River, and Ashtabula River) suggest that the average concentration of contaminants in generated residuals will approximate the average sediment concentration over the entire dredge cut profile (e.g., USEPA, 2010). Generated residuals have been estimated using mass balance calculations on more than 30 environmental dredging projects, including the Hudson River, Lower Fox River, Ashtabula River, and Esquimalt Harbor projects that used statistically based pre- and post-dredge sampling programs to provide particularly high confidence in the generated residual characterization (Patmont and Palermo, 2007; Patmont et al., 2015). At those sites, generated residuals represented approximately 1% to 11% of the mass of contaminants or solids dredged over the entire design cut. Undisturbed residuals can result in leaving behind additional contaminated sediment.

The nature and extent of generated residuals are related to multiple environmental factors, including sediment geotechnical and geophysical characteristics, variability in contaminant distributions, and physical site conditions such as the presence of bedrock, hardpan, debris, or other obstructions. Operational factors that likely affect generated residuals include dredging equipment size and type, number of dredge passes, selection of intermediate and final cutline elevations, allowable overdredging, dredge cut slopes, accuracy of positioning, operator experience, and the sequence of operations (Bridges et al., 2008, 2010; Palermo et al., 2008; Fuglevand and Webb, 2009). However, sediment liquidity appears to be the most important site factor determining the amount of residuals generated at environmental dredging projects. Sediment with low bulk density (e.g., water content exceeding the geotechnical liquid limit) has the highest potential to generate residuals, as slope failure, sloughing, and spillage processes that occur with even the most modern dredging equipment lead to the generation of fluidized mud during dredging operations (Figure 7). Further complicating factors in the dredging process (e.g., the presence of debris in the sediment bed or underlying rock/hardpan) can make environmental dredging process and achievement of risk-based cleanup levels very difficult as well as costly because dredging is less effective in these difficult environments.

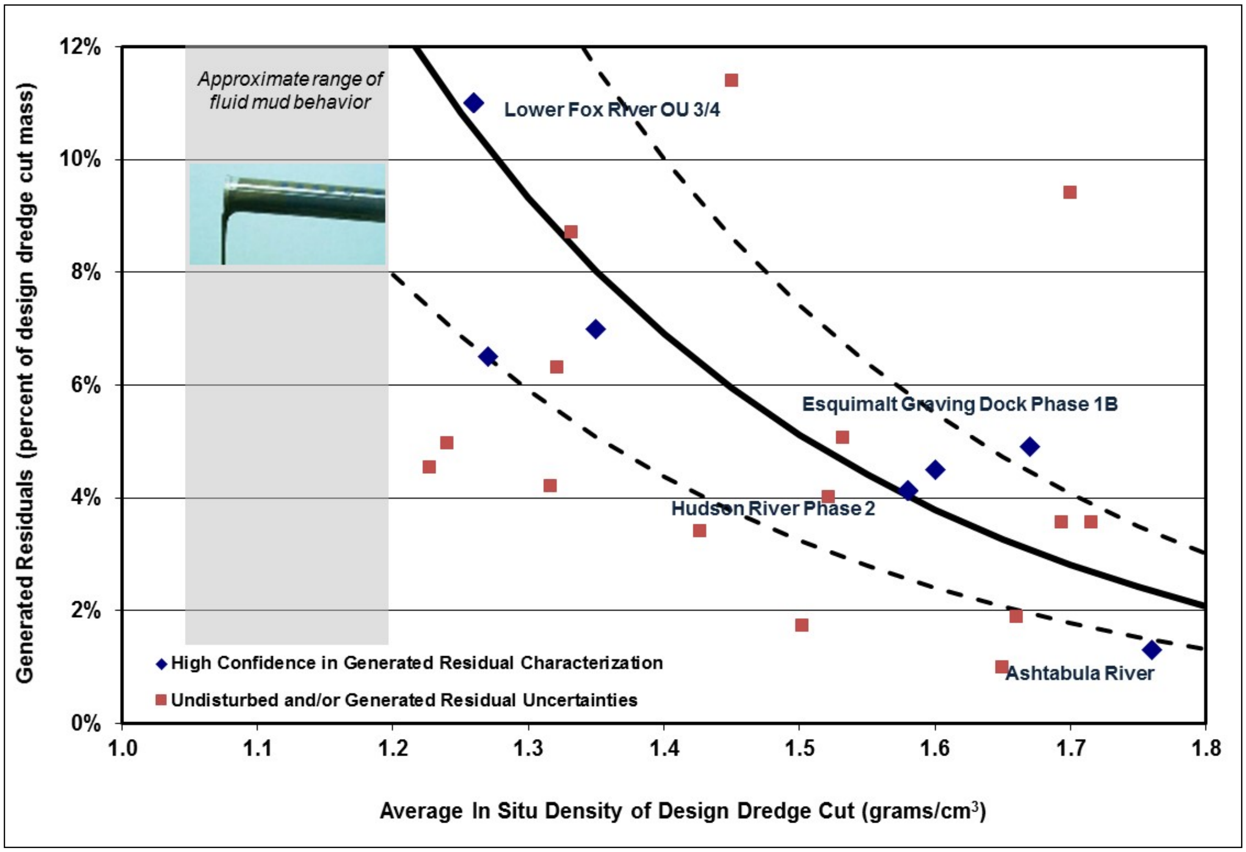

Figure 7. Generated Residuals Case Studies and Regression Relationship (from Patmont et al., 2015).

Based on column settling tests, sediment transport modeling, and detailed post-dredge sampling data collected on the better characterized environmental dredging projects (e.g., Patmont and Palermo, 2007; Patmont et al. 2015), most resuspended sediments settle close to the dredge relatively quickly (in a matter of minutes to an hour); however, finer particles may be transported into the far field (outside of project area). Contaminant releases associated with dredging can occur in particulate, dissolved, or volatile fractions, with each characterized by a different transport and/or exposure pathway. Particulate-associated contaminants are often released by the dredge head in the form of fluid mud and, once in the dissolved phase, they can travel into the far field and increase contaminant exposure-related risk.

Even when the most modern dredging equipment and post-dredge residual BMPs are used, short-term sediment resuspension and associated contaminant release still limits the effectiveness of environmental dredging. Environmental dredging operations unavoidably resuspend sediment, releasing dissolved contaminants into the water column and generating residuals that may or may not be confined to the dredge footprint and amenable to BMPs. Thus, environmental dredging results in short-term and potentially longer-term risks.

Table 4. Environmental Dredging Release Case Studies[1].

Project	Environmental Dredging Activity	Best Managemen t Practices	Source of Release Estimate	Indicator of Contaminant Mass Released	Primary Reference
1999 – 2000 Fox River	62,320 m^3 (82,000 cy) hydraulic	Operational BMPs/silt curtains	Water quality monitoring	Average 2% (about 30% dissolved)	Steuer, 2000
2004 Duwamish/ Diagonal	53,200 m^3 (70,000 cy) mechanical	Operational BMPs	Fate/transport and food web modeling to simulate measured fish tissue PCBs	Midpoint 3% (range: 1% to 6%)	Stern, 2007
2005 Grasse River	19,000 m^3 (25,000 cy) hydraulic	Operational BMPs/silt curtains	Water quality monitoring	Average 3% (>50% dissolved)	Connolly et al., 2007
2005 Lower Passaic River	3,040 m^3 (4,000 cy) mechanical	Operational BMPs/rinse tank	Water quality monitoring	Average 3% to 4% (range: 1% to 6%)	Lower Passaic River Restoration Project Team, 2009
2009 Hudson River	209,000 m^3 (275,000 cy) mechanical	Operational BMPs/silt curtains	Water quality monitoring	Average 3% to 4% (about 80% dissolved)	Anchor QEA and Arcadis, 2010
2011 to 2015 Hudson River	174,800 m^3 (2,300,000 cy) mechanical	Operational BMPs	Water quality monitoring	Average 1% (about 80% dissolved)	GE and Anchor QEA, unpublished data

Notes:
1. Preliminary data summaries; subject to revision.
BMP = best management practice
cy = cubic yard
m^3 = cubic meter

Resuspension is the process of dislodgement and dispersal of sediment into the water column where it may be transported and dispersed through the water column (Figure 6). Resuspension may also result in short-term release of dissolved contaminants into the water column, primarily by contaminant desorption or porewater release from resuspended sediments, dredging residuals, or other fluid layers with high suspended solids concentration (e.g., fluid mud or the nepheloid layer; Bridges et al., 2010). The degree of resuspension and release at environmental dredging projects is influenced by site-specific sediment conditions (e.g., currents/waves, debris, and bedrock), as well as operational factors (e.g., dredge cut thickness, dredge speed/production, and operator skills). However, even when the most modern BMPs are used, environmental dredging release rates (expressed as the percent of dredged contaminant mass released to the water column; largely in the dissolved phase) have been relatively consistent across environmental dredging projects. Table 4 provides a summary of case studies regarding documented releases related to contaminated sediment dredging projects, mostly focused on PCBs. The release rates observed across these studies are generally in the range of 1% to 4%, with most of the release being in the bioavailable dissolved form. As demonstrated by these case studies, there are no documented differences in release rates between projects that use barrier controls (e.g., silt curtains) and those that do not.

Many environmental dredging projects conducted to date have resulted in significant residuals and/or releases during remedial construction, as evident through chemical monitoring of surface water quality and/or fish tissue before, during, and after construction. For example, fish tissue PCB concentrations at the Commencement Bay Nearshore/Tideflats Superfund Site in Tacoma, Washington, increased during environmental dredging operations and have persisted for a decade after the major dredging events (Figure 8; West et al. 2016). There are also concerns that diffuse, non-point sources of PCBs from the watershed may not have been fully controlled prior to cleanup. Similar results have been observed at a wide range of other environmental dredging projects (Bridges et al., 2010; Patmont et al., 2013).

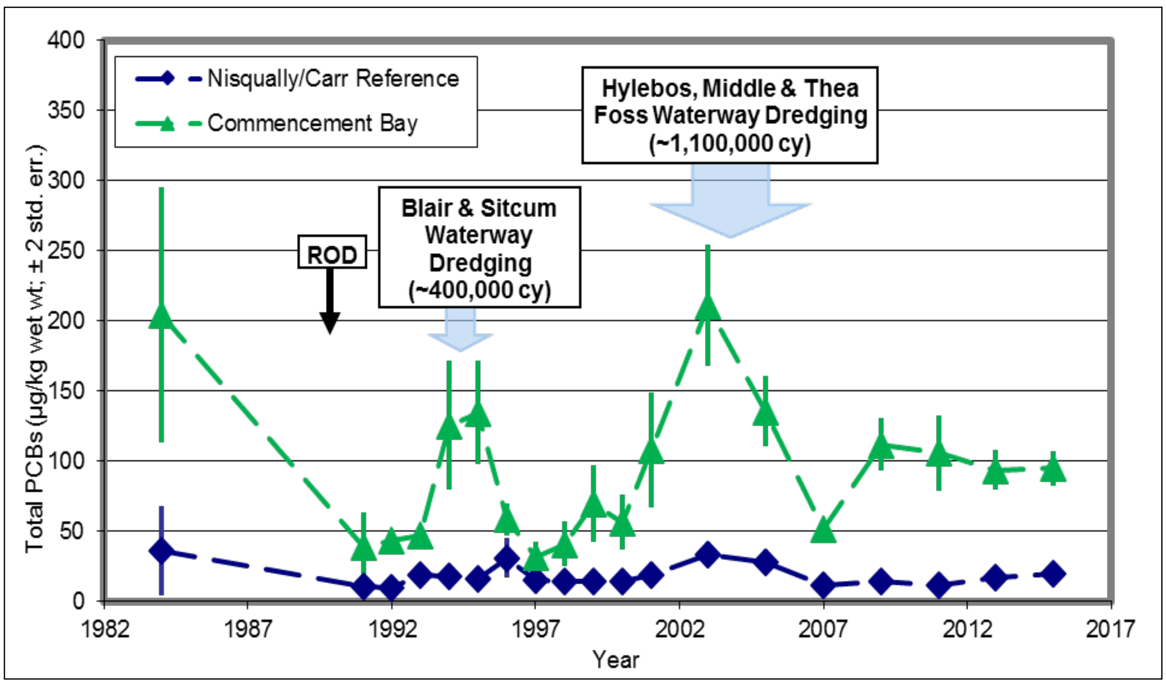

Figure 8. Dredging-related Increases in Fish Tissue Concentrations: Commencement Bay Nearshore/Tideflats Superfund Site, Washington

Finally, experiences from completed environmental dredging projects have also shown that additional residual dredging to remove relatively low-density residual sediments is inefficient and often ineffective (Patmont and Palermo 2007; NAS 2007). Moreover, BMPs aimed at controlling resuspension and transport of sediment away from the project area show mixed success in preventing contaminant migration. For these reasons, residual contamination or releases following environmental dredging must be anticipated and considered in the remedy selection and design process.

IMPLICATIONS FOR FUTURE PROJECTS

During the feasibility study stage of a sediment cleanup project, it is important to evaluate the comparative advantages and disadvantages of each remedial technology and/or alternative in an equitable manner, especially from a short- and long-term risk perspective. A good understanding of the dredging Four Rs processes, as well as the recontamination potential from ongoing sources, is important at a number of different stages of the cleanup process. These evaluations allow decision makers to consider net risk reductions (and increases) during and after alternative implementation and to weigh them against potentially less intrusive remedial technologies (e.g., a hybrid remedy). Environmental dredging is generally appropriate in those situations where it would significantly improve net risk reductions and provide net environmental benefits compared to other alternatives, and where the additional cost and implementation considerations of dredging relative to less invasive technologies is not disproportionate to its additional protectiveness (Bridges et al., 2012).

During remedial design, an understanding of the sources and characteristics of likely residuals, resuspension, and release can be important for developing appropriate equipment selection and operation/management protocols (e.g., the decision between re-dredge passes and post-dredge cover). Dredge plan development should focus on achieving realistic removal goals (e.g., achieving design elevations) and facilitating the implementation of appropriate adaptive management plans to achieve risk-based remedial goals. Limited cleanup dredging passes; post-dredge residuals covers, backfill, or in some cases armored caps; and post-removal data analyses are important components of a successful adaptive management plan. However, the process must begin with careful pre-design characterization and subsequent data analyses, including geostatistical methods where appropriate, which have proven to be useful in reducing the potential for undisturbed residuals at environmental dredging sites. Other proven models are also available to estimate the nature and extent of releases during environmental dredging, including impacts to water quality and fish tissue. The use of model-predicted, post-remedy conditions allows for an assessment of residual risks and provides an opportunity to optimize the design prior to construction, thus improving the effectiveness of the overall action.

It is important to realize that even with appropriate planning, careful dredge plan design, and good construction BMPs, releases and residuals are still expected at environmental dredging projects. During the design phase, an adaptive management plan should be developed to establish the framework for timely evaluation of various management options for the effective management of dredging-related releases and residuals. Though releases are unavoidable and are often difficult to manage, residual management options (RMOs) can be developed to effectively and efficiently achieve the project cleanup goals. These RMOs should be developed during remedial design so that field decisions can be made in a timely manner to prevent extended downtime during construction. A well-structured decision framework can be developed prior to construction and utilized in the field for identifying appropriate RMO approaches based on the results of post-dredge confirmation sample results. Such a decision framework should consider site conditions (including hardpan and debris), selected equipment and operational mode, engineering features (such as structures, utilities, offsets), estimated residual layer thickness, residual mass, density and concentrations, ratio of generated residuals to undisturbed residuals, and cost.

An evaluation of the above variables will help identify appropriate RMOs to effectively address post-dredge conditions. RMOs implemented on other projects generally include MNR, additional dredging passes with varying required cut thicknesses, and placement of sand covers and engineered caps (Patmont and Palermo, 2007). Depending on the specific RMO selected, additional sediment verification sampling may need to be performed to verify the effectiveness of the action and to determine whether or not subsequent work is required to meet remedial goals. The general conditions under which these RMOs should be implemented, as well as the pros and cons of these options, are discussed below.

- **MNR.** MNR is an appropriate RMO to consider at sites where future sedimentation and/or chemical degradation rates can be reasonably forecasted, therefore allowing a reasonable estimate of residual chemical concentration decay within an acceptable time frame. MNR generally applies to sites where residuals concentrations are marginally above the remediation level.
- **Additional Dredging Passes.** At some sites, additional dredging is desirable to address residual sediments above the action level. RMOs that include additional dredging can be effective at some sites, but are often inefficient and costly. The additional dredging passes are typically most effective when they are used to remove a deeper deposit of undisturbed residuals that may have been missed by the initial site characterization. Accordingly, one of two dredging RMOs may be implemented:
    - **Cleanup pass.** A cleanup pass is a dredge pass set at an elevation in such a way as to attempt to remove only a thin surficial layer of material, with the intent of removing a layer of reconsolidated generated residuals (allowing sufficient time for reconsolidation as practicable) and a minimal thickness of underlying clean material.
    - **Additional production pass.** One or more production passes target thicker layers of residuals, especially undisturbed residuals. This action would only be needed for cases in which the initial site characterization was incomplete and the setting of the initial production dredge cut elevation left a considerable thickness of contaminated sediment.
- **Backfill, Sand Covers, and Engineered Caps.** For sites where post-dredge conditions do not warrant re-dredging, backfill, sand covers, and engineered caps can be cost-effective and protective alternatives. Depending upon the nature and extent of the residuals, a backfill or sand cover may be used to enhance natural recovery processes and meet secondary project goals, such as habitat enhancement. Where higher levels of residuals contamination are identified within impracticable dredge areas (e.g., underlying hardpan or adjacent sensitive structures), engineered isolation caps may be designed and constructed to provide a protective solution to residual contamination.

KEY LESSONS LEARNED

A closer review of completed remediation projects reveals the following points that should be applied to the design and implementation of future projects:

- Mass removal does not necessarily imply risk reduction. In fact, just the opposite may be true.
- Use modeling tools and real site conditions to predict and manage for residuals and resuspension in the field.
- Remedial dredging is most efficient when it is combined with a post-dredge management plan such as placement of a backfill layer for restoration.
- Obtain a reliable set of pre-construction baseline data for post-construction verification purposes.
- Good documentation of design is key for effective communication. Develop clear and concise plans and specifications—avoid ambiguity.
- Perform the design/constructability review with a set of contractors who would likely bid on the project.
- Choose new and modern equipment, whenever feasible.
- Clearly define specifications for dredging, capping and backfilling, including performance and long-term verification goals.
- Use BMPs in the field to control the Four Rs.
- Provide a clear and concise measurement and payment clause. If multiple measurements are used, specify which takes precedence, in case of conflict.
- Track construction progress closely; track using multiple methods including volume, aerial extent, and earned value.
- Select the best qualified contractor, and communicate frequently on project expectations and actual progress made.
- Incentivize the contractor; do not penalize. Success, if shared, is a strong motivator.

SUMMARY AND CONCLUSIONS

Over the past 30 years, environmental dredging has been the tool of choice selected by North American federal and state regulators for implementing environmental cleanups in the aquatic environment; however, review of selected remedies in the last decade in comparison to previous periods has indicated a shift in USEPA's approach to remedy selection. Remedy decision documents have increasingly included hybrid remedies that implement a combination of dredging, capping, and MNR, acknowledging that dredging alone may not be adequate (or cost effective) to achieve net risk reduction or relatively low remediation levels. This is further underscored by the recent industry trend of inclusion of post-removal backfill layers during the planning of cleanup projects.

Understanding and appropriately planning for residual contamination that may remain following dredging are critical components of successful environmental remediation projects. Recent efforts focused on characterizing the effectiveness of environmental dredging projects throughout North America have led to advances in understanding the processes leading to dredging residuals. Consideration of the limitations of dredging equipment and dealing with residual contamination following environmental dredging should be anticipated and considered in the remedy selection and design process, with dredge plan development (and equipment selection) aimed at achieving efficient and reasonable removal goals, and with facilitating the implementation of appropriate adaptive management plans for recovery in the longer term.

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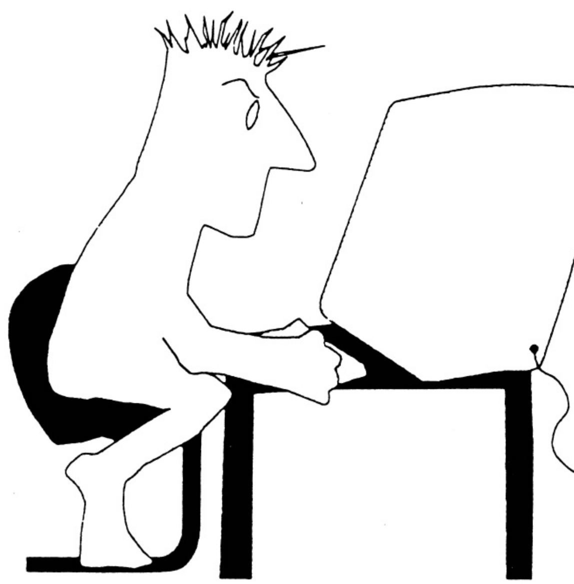

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