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Bucket dredge using a Cable Arm® clamshell in the Lower Passaic River, NJ.

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EDITOR'S NOTE

Now in its 19th year, the Journal of Dredging is gaining traction. This issue marks the Journal's third consecutive quarterly publication containing multiple manuscripts. Sufficient manuscripts are under review to publish issues in July and October 2021. But, plenty of space remains in upcoming as well as in future issues. Garnering sufficient high-quality submissions to maintain a consistent publication schedule remains our most significant challenge. I hope that you will consider submitting a manuscript for consideration. As editor, I am committed to a fair and thorough review process. If you have information about an interesting project, informative data, or any other publication ideas, but need help getting it into a publishable manuscript, please reach out to me; I will be glad to help. We need your submissions!

This issue of Western Dredging Association's (WEDA) Journal of Dredging contains two interesting manuscripts. The first provides a technically sound basis for analyzing slurry transport in inclined pipes. The results are very useful for estimating slurry flows from deep depths through an inclined pipe. The second paper discusses a range of approaches to increase beneficial use, specifically in the United States, significantly compared to the long-term historical rate of about 30%. This paper is particularly timely given the U.S. Congress' call in the Water Resources Development Act of 2020 to prioritize beneficial use. I appreciate Mr. Craig Vogt shepharding this manuscript through the review process in a manner that helped me avoid potential conflicts of interest as a co-author.

The quality of any journal depends on the effort reviewers invest in providing objective, critical feedback to authors. Our reviewers have been outstanding and responsive, allowing us to maintain a relatively expedient publication schedule. Further, their reviews have been constructive, helping authors improve their manuscripts prior to publication. As an author, I really appreciate it when someone invests their time to help me increase the quality of a publication. As an editor, I am especially appreciative of our reviewers.

If you have suggestions for the journal or questions about potential submissions, please contact me.

Don Hayes
Editor, WEDA Journal of Dredging
April 2021

DOMINATING FACTORS IN SLURRY TRANSPORT IN INCLINED PIPES

Sape A. Miedema[1], F. Wang[2], G. Hong[3], and X. Chen[4]

ABSTRACT

In deep sea mining, the valuable materials will often be transported to the surface by means of slurry transport through pipelines, using centrifugal pumps to generate the pressure. The slurry transport pipeline has vertical, but also inclined trajectories. It is thus of interest what are the dominating factors in slurry transport in inclined pipes. Here this is investigated for Newtonian settling slurries. Experiments to investigate the dominating factors in slurry transport in inclined pipes were carried out in the CCCC National Engineering Research Center of Dredging Technology and Equipment, Shanghai, China. These experiments were carried out in a D_p=0.3 m pipe with sand with a d_{50} of 0.77 mm, concentrations up to 16%, inclination angles up to 44° and line speeds up to 7 m/s.

The physics of slurry transport can be divided into 5 main flow regimes. Each flow regime has its dominating physics. The stationary bed regime is based on bed friction, the sliding bed flow regime on sliding friction, the heterogeneous flow regime on collisions and collision intensity, the homogeneous flow regime on wall friction and the sliding flow regime on sliding friction. So, each flow regime requires its own approach how to deal with inclined pipes. Models in literature most often multiply the so-called solids effect with the cosine of the inclination angle, without considering different flow regimes, which is considered here as incorrect. Because different flow regimes respond differently, also the transitions between the flow regimes will depend on the inclination angle. It should be noted however that the potential energy term always dominates the hydraulic gradients measured.

Keywords: Slurry transport, inclined pipes, flow regimes.

INTRODUCTION

The research question here is, what is the influence of the inclination angle on the hydraulic gradient, on the Limit of Stationary Deposit Velocity (LSDV) and on the Limit Deposit Velocity (LDV). The effect of inclined pipes is expressed based on the length of the pipe, not the horizontal distance. The hydraulic gradient is a dimensionless number, used by most researchers to express pressure losses in pipes. By dividing the pressure losses by the carrier liquid density and the length of the pipeline, a very convenient dimensionless number is found.

$$i=\frac{\Delta p}{\rho_l g \Delta L} \quad \text{with} \quad i_l=\frac{\Delta p_l}{\rho_l g \Delta L}=\frac{\lambda_l\left(\frac{\Delta L}{D_p}\right)\left(\frac{1}{2}\rho_l v_{ls}^2\right)}{\rho_l g \Delta L}=\frac{\lambda_l v_{ls}^2}{2 g D_p} \qquad (1)$$

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[1] Associate Professor, Delft University of Technology, Mekelweg 2, 2628 CD, Delft, The Netherlands, T: ++31-15-2788359, Email: s.a.miedema@tudelft.nl.

[2] Senior engineer, CCCC National Engineering Research Center of Dredging Technology and Equipment, China. Email: wangfeixin@cccc-drc.com.

[3] Senior engineer, CCCC National Engineering Research Center of Dredging Technology and Equipment, China. Email: hongguojun@cccc-drc.com.

[4] PhD Candidate, Offshore and Dredging Engineering, Delft University of Technology. Email: x.chen-1@tudelft.nl.

Another very convenient dimensionless number is the relative solids effect, given by:

$$E_{rhg}=\frac{i_m-i_l}{R_{sd}C_v}=\frac{\Delta p_m-\Delta p_l}{\rho_l g \Delta L R_{sd} C_v} \quad \text{with} \quad \mathrm{R}_{sd}=\frac{\rho_m-\rho_l}{\rho_l}=\frac{\rho_m}{\rho_l}-1 \qquad (2)$$

Before focusing on the DHLLDV Framework, first several models/equations from literature are shown.

The Heterogeneous Flow Regime, Durand and Condolios and Gibert.

The basic equation for the solids effect of Durand and Condolios (1952) and Gibert (1960) for inclined pipes, is adding the cosine of the inclination angle according to:

$$i_{m,\theta}=i_l+sin(\theta)\,(1+R_{sd}C_{vt})+i_l(81)\left(\frac{v_{ls}^2\sqrt{C_x}}{gD_pR_{sd}}\right)^{-3/2} C_{vt}\,cos(\theta)^{3/2} \qquad (3)$$

The first term in this equation is the Darcy Weisbach hydraulic gradient for the carrier liquid. The second term is the potential energy term for both the carrier liquid and the solids. The third term is the solids effect term. So, the solids effect is multiplied with the cosine of the inclination angle to the power of 3/2. This means the solids effect is decreasing with an increasing inclination angle, whether the inclination is upwards or downwards. It should be mentioned that the hydraulic gradient is based on the length of the pipe and not on the horizontal component of the length.

The Heterogeneous Flow Regime, Worster and Denny.

Worster and Denny (1955) have a slightly different approach. They state that the hydraulic gradient in an inclined pipe equals the sum of the hydraulic gradients of the horizontal component and the vertical component. This gives the following equation:

$$i_{m,\theta}=i_l+sin(\theta)\,(1+R_{sd}C_{vt})+i_l(81)\left(\frac{v_{ls}^2\sqrt{C_x}}{gD_pR_{sd}}\right)^{-3/2} C_{vt}\,cos(\theta) \qquad (4)$$

The difference with Durand and Condolios (1952) and Gibert (1960) is the power of the cosine. In both cases, the equations match the hydraulic gradient of a horizontal pipe if the inclination angle equals zero and a vertical pipe if the inclination angle equals 90 degrees, whether the inclination is upwards (positive inclination angle) or downwards (negative inclination angle). However, in both cases, the Equivalent Liquid Model (ELM) component for a vertical pipe is missing.

The Heterogeneous Flow Regime, Wilson et al.

For inclined pipes, Wilson et al. (2006) modified the equation for horizontal pipes, matching the reasoning of Worster and Denny (1955), but with the use of the power M according to:

$$i_{m,\theta}=i_l+sin(\theta)\,(1+R_{sd}C_{vt})+\frac{\mu_{sf}}{2}\left(\frac{v_{50}}{v_{ls}}\right)^{M} R_{sd}C_{vt}\,cos(\theta)^{M} \qquad (5)$$

The power M has a value of 1.7 for uniform or narrow graded sands and decreases to 0.25 for very broad graded sands. For narrow graded sands the influence of the inclination angle is similar to the Durand and Condolios (1952) and Gibert (1960) approach with a power of 1.5 versus 1.7 for Wilson et al. (2006). For medium graded sands with a power around 1, the influence is like the Worster and Denny (1955) approach.

The Sliding Bed Regime, Doron et al.

Doron et al. (1997) investigated the influence of inclined pipes, based on their 2LM and 3LM models (LM=Layer Model). Basically, they multiplied the sliding friction with the cosine of the inclination angle, and they added the potential energy term, which is proportional with the sine of the inclination angle. They carried out experiments with inclination angles from -7 to +7 degrees. The resulting data however is dominated by the potential energy term, because of the small inclination angles.

DISCUSSION OF LITERATURE

After adding the potential energy terms to the hydraulic gradient in a correct way, the pipe inclination effect can be considered, by multiplying the solids effect term with the cosine of the inclination angle to a power ranging from 1.0 to 1.7. Different researchers give different powers, most probably because the models are either empirical or have different physical backgrounds. This implies that the solids effect reduces to zero for a vertical pipe, which is doubtful, especially for very small particles giving homogeneous flow (ELM). One would expect an equation of the following form:

$$i_{m,\theta} = i_l\left(1 + \alpha R_{sd} C_{vs} \sin(\theta)^{\beta_1}\right) + \sin(\theta)\,(1 + R_{sd} C_{vs}) + E_{rhg} R_{sd} C_{vs} \cos(\theta)^{\beta_2} \tag{6}$$

The first term on the right-hand side is the Darcy Weisbach friction, including the mobilized ELM (the homogeneous solids effect) corrected for the inclination angle. The second term is the potential energy term. The third term is the solids effect ($E_{rhg)}$ corrected for the inclination angle. So, where the solids effect decreases with the inclination angle, the homogeneous solids effect increases. In this form a vertical pipe shows mobilized/reduced ELM behavior, which is observed by Newitt et al. (1961). Other flow regimes were not considered. Although this equation is a big improvement compared to the equations from literature, it does not yet distinguish explicitly between the flow regimes.

DHLLDV FRAMEWORK MODELING

The DHLLDV Framework combines the 5 flow regimes into one hydraulic gradient or relative solids effect curve. Figure 1 shows the definitions used in a cross section of the pipe used for the stationary and sliding bed flow regimes. A short summary of each flow regime is given, since Miedema (2017) already explained the detailed derivation for each flow regime.

Pure Carrier Liquid in an Inclined Pipe

The hydraulic gradient for pure carrier liquid in an inclined pipe can now be determined with:

$$i_{l,\theta} = i_l + \sin(\theta) \tag{7}$$

So apparently, the hydraulic gradient increases with the sine of the inclination angle (Figure 2). This also means that a downwards slope with a negative inclination angle gives a negative sine and thus a reduction of the hydraulic gradient. In this case the hydraulic gradient may even become negative.

Stationary Bed Regime in an Inclined Pipe

Since the bed is not moving, the friction between the bed and the pipe wall compensates for the weight component of the bed. The hydraulic gradient can now be determined with:

$$i_{m,\theta} = \frac{\tau_1 O_1 L + \tau_{12} O_{12} L}{\rho_l A_1 L g} + \sin(\theta) = i_m + \sin(\theta) \tag{8}$$

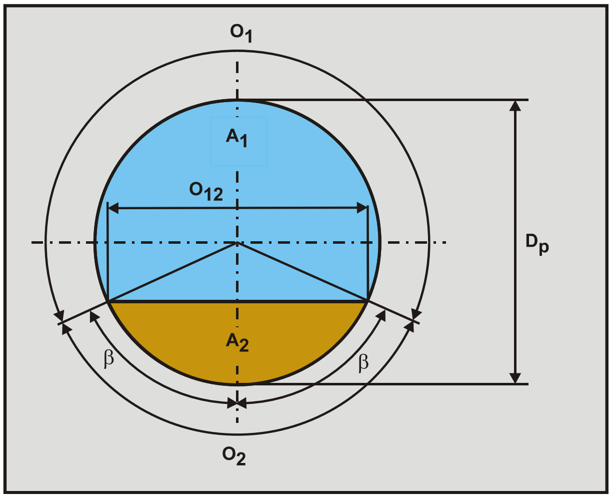

Figure 1. Definitions.

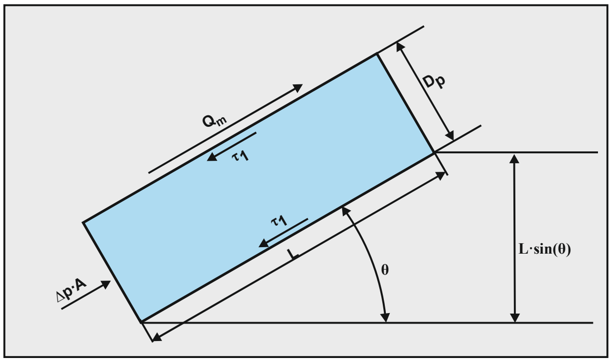

Figure 2. Pure carrier liquid in an inclined pipe.

which is the hydraulic gradient of a stationary bed in a horizontal pipe plus the sine of the inclination angle. The weight of the solids does not give a contribution to the hydraulic gradient, since the solids are not moving. See Figure 3: The stationary bed regime in an inclined pipe.

Sliding Bed Regime in an Inclined Pipe

The hydraulic gradient for the sliding bed regime is:

$$i_{m,\theta} = i_l + sin(\theta)\,(1 + R_{sd} C_{vs}) + R_{sd} C_{vs} \mu_{sf}\, cos(\theta) \tag{9}$$

The relative excess hydraulic gradient or relative solids effect, $E_{rhg,\theta}$, is now:

$$E_{rhg,\theta} = \frac{i_{m,\theta} - i_{l,\theta}}{R_{sd} C_{vs}} = \mu_{sf}\, cos(\theta) + sin(\theta) \tag{10}$$

See Figures 4 and Figure 5: A sliding bed in an inclined pipe. The friction velocity u_* is defined as $\sqrt{(\lambda/8)}\cdot v_{ls}$, a measure for the friction on the pipe wall and also a measure for the thickness of the viscous (laminar) sub layer.

Heterogeneous Regime in an Inclined Pipe

In an inclined pipe the effective terminal settling velocity perpendicular to the pipe wall gives a potential energy term of (β is part of the hindered settling model):

$$S_{hr,\theta} = S_{hr}\, cos(\theta) = \frac{v_t \left(1 - \frac{C_{vs}}{\kappa_C}\right)^{\beta}}{v_{ls}}\, cos(\theta) \tag{11}$$

For the kinetic energy losses, the angle of attack has to be adjusted in an inclined pipe. The angle of attack is defined as the ratio between the terminal settling velocity and the velocity at the thickness of the viscous sub layer, giving (see Figure 6):

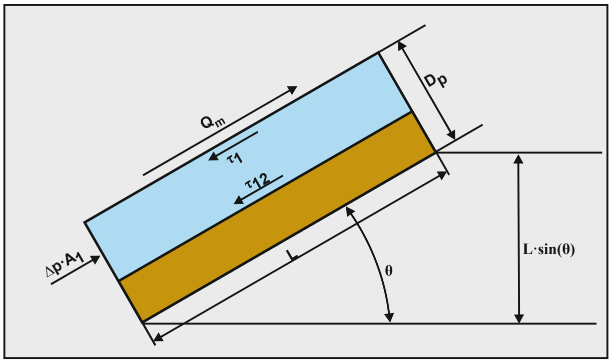

Figure 3: The stationary bed regime in an inclined pipe.

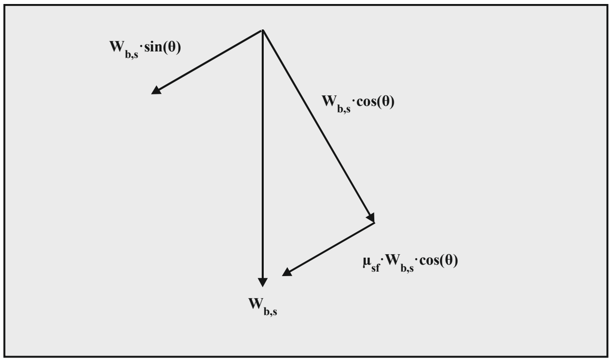

Figure 4: The submerged weight components and the sliding bed friction force.

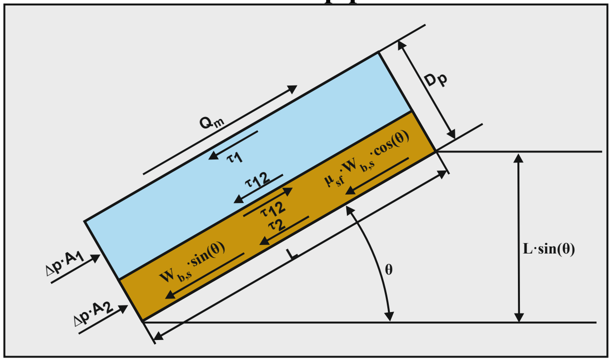

Figure 5: A sliding bed in an inclined pipe.

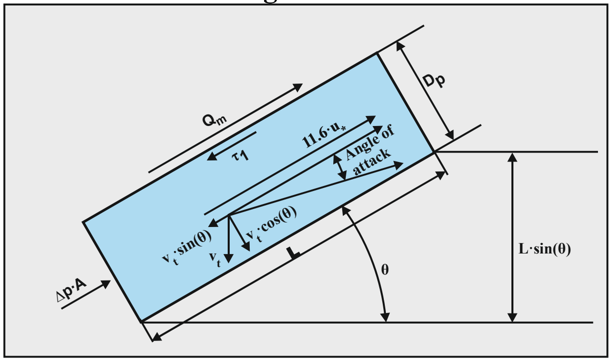

Figure 6: Heterogeneous flow in an inclined pipe, the angle of attack.

$$S_{rs,\theta} = c\left(\frac{\delta_v}{d}\right)^{2/3}\left(\frac{v_t\cos(\theta)}{11.6u_*-v_t\sin(\theta)}\right)^{4/3}\left(\frac{v_t}{\sqrt{gd}}\right)^2 \tag{12}$$

So, for very small particles with $v_t << 11.6\cdot u_*$, the kinetic energy losses are proportional to the cosine of the inclination angle to a power of 4/3. For larger particles, the second term in the denominator becomes significant resulting in different behavior of a positive versus a negative inclination angle. Apart from this, also the lifting of the mixture has to be added, giving:

$$\begin{gathered} i_{m,\theta} = i_l + \sin(\theta)\left(1+R_{sd}C_{vs}\right) + \left(S_{hr,\theta}+S_{rs,\theta}\right)R_{sd}C_{vs} \\ E_{rhg,\theta} = S_{hr,\theta}+S_{rs,\theta}+\sin(\theta) \end{gathered} \tag{13}$$

Literature shows a power of the cosine between 1 and 1.7. Here a more complicated formulation is found. Considering that the potential energy losses are much smaller than the kinetic energy losses, a power of about 4/3 is found for small particles, while larger particles will show a smaller power depending on the terminal settling velocity (see equation (**12**)). The higher the terminal settling velocity, the smaller the power. Theoretically this power may even become zero when nominator and denominator decrease in the same way with increasing inclination angle.

Homogeneous Regime in an Inclined Pipe

For an inclined pipe, only the lifting of the mixture must be added, giving:

$$i_{m,\theta} = i_l\left(1+\alpha_E R_{sd}C_{vs}\right) + \sin(\theta)\left(1+R_{sd}C_{vs}\right) \tag{14}$$

$$E_{rhg,\theta} = \alpha_E i_l + sin(\theta)$$

Sliding Flow Regime or Fully Stratified Flow in an Inclined Pipe

The sliding flow regime behaves the same as the sliding bed regime, since both regimes are dominated by sliding friction, so:

$$i_{m,\theta} = i_l + sin(\theta)\,(1 + R_{sd} C_{vs}) + R_{sd} C_{vs} \mu_{sf}\, cos(\theta) \tag{15}$$

The relative excess hydraulic gradient or relative solids effect $E_{rhg,\theta}$ is now:

$$E_{rhg,\theta} = \frac{i_{m,\theta} - i_{l,\theta}}{R_{sd} C_{vs}} = \mu_{sf}\, cos(\theta) + sin(\theta) \tag{16}$$

The Limit Deposit Velocity

The Limit of Stationary Deposit Velocity is affected by the pipe inclination. In an ascending pipe, the cross-sectional averaged line speed has to be higher compared to a horizontal pipe in order to make a bed start sliding. In a descending pipe this line speed is lower. It is even possible that in a descending pipe the bed will always slide because of gravity. The Limit of Stationary Deposit Velocity is at the transition of the stationary bed regime and the sliding bed regime. The Limit Deposit Velocity, defined as the line speed above which there is no stationary or sliding bed, is determined by either the potential energy losses or a limiting sliding bed. In both cases this is affected by the cosine of the inclination angle, the component of gravity perpendicular to the pipe wall. Since in both cases the Limit Deposit Velocity depends on the cube root of this cosine, the Limit Deposit Velocity will decrease according to Miedema (June 2016):

$$v_{ls,ldv,\theta} = v_{ls,ldv}\, cos(\theta)^{1/3} \tag{17}$$

Because of the cube root of this cosine, this means that for angles up to 45° the reduction is less than 10%.

DISCUSSION OF MODELING

For the stationary bed regime, only the potential energy term of the pure liquid must be added to the hydraulic gradient of the mixture (basically the pure liquid hydraulic gradient in the restricted area above the bed). For all other flow regimes, the potential energy term of the mixture must be added, together with a correction of the so-called solids effect. The result of this is a higher line speed for the intersection point of the stationary bed curve and the sliding bed curve. So, in general an increase of the Limit of Stationary Deposit Velocity (LSDV) with increasing inclination angle. This may however also result in omission of the occurrence of a sliding bed for an inclined pipe, where a sliding bed would occur in a horizontal pipe. This makes sense, since a higher line speed is required to make a bed start sliding, there is the possibility that the bed is already fully suspended before it could start sliding. With negative inclination angles, a stationary bed may never occur if the arctan of the sliding friction coefficient of the sand with the pipe wall is smaller than the inclination angle. Usually this sliding friction angle or angle of external friction will be about 20°. So, if the descending inclination angle is smaller than -20°, the LSDV does not exist and even at zero-line speed the bed is already sliding. This is also the reason why the Wilson et al. (2006) graph for the correction for inclined pipes starts at -20°.

In the sliding bed/sliding flow regime and the heterogeneous regime, the hydraulic gradient is lower for an inclined pipe compared with a horizontal pipe, if the potential energy term of the mixture (static head) is not considered, especially for small particles in the heterogeneous regime. For the heterogeneous regime, there is a difference between ascending and descending pipes, due to the term with the angle of attack in the kinetic energy losses. The decrease in an ascending pipe is smaller than in a descending pipe and could even give a small increase in an ascending pipe at low line speeds. The transition line speed of the heterogeneous flow regime to the homogeneous flow regime will also decrease with increasing inclination angle.

In case of a sliding bed one may expect more stratification in an ascending pipe compared to a descending pipe, due to the higher line speed in an ascending pipe to make the bed start sliding. In other words, a higher shear stress on the bed is required in an ascending pipe, resulting in a thicker sheet flow layer at the top of the bed.

The hydraulic gradients of the inclined pipes are determined per meter of inclined pipe and not per meter of horizontal pipe. In order to find the correct hydraulic gradient curves for an inclined pipe, one first has to determine the hydraulic gradient curves for each flow regime individually. The resulting curve can be found by comparing flow regime curves with the line speed as a variable.

1. If the sliding bed hydraulic gradient (SB) is smaller than the stationary (fixed) bed hydraulic gradient (FB), the sliding bed hydraulic gradient (SB) is chosen, otherwise the stationary (fixed) bed hydraulic gradient (FB). The resulting curve is named the **FB-SB** curve, or in a descending pipe with an angle smaller than about -20°, the **SB** curve.
2. In the case of sliding flow (SF, large particles), $\mathbf{d>0.015 \cdot D_p}$ according to Wilson et al. (2006), this is also the final curve (see Miedema (2018a) and (2018b) for a more detailed criterion). This curve is named the **FB-SB-SF** curve, or in a descending pipe with an angle smaller than about -20°, the **SB-SF** curve. If there is no sliding flow (small and medium sized particles) steps 3 and 4 must be taken.
3. If the heterogeneous flow regime hydraulic gradient (He) is smaller than the FB-SB hydraulic gradient, the heterogeneous hydraulic gradient (He) is chosen, otherwise the FB-SB hydraulic gradient. The resulting curve is named the **FB-SB-He** curve, or in a descending pipe with an angle smaller than -20°, the **SB-He** curve. Depending on the parameters (particle and pipe diameter), it is possible that this curve does not contain a sliding bed regime. In that case the resulting curve is the **FB-He** curve. The particles will be so small that sliding flow will not occur in this case.
4. If there is no sliding flow and the homogeneous flow regime hydraulic gradient (Ho) is larger than the FB-SB-He hydraulic gradient, the homogeneous hydraulic gradient (Ho) is chosen, otherwise the FB-SB-He or FB-He hydraulic gradient. The resulting curve is named the **FB-SB-He-Ho** curve, or in a descending pipe with an angle smaller than -20°, the **SB-He-Ho** curve.

It may be clear that the resulting hydraulic gradient curves do not respond in a single way to the inclinations angle, since each flow regime has its own characteristic behavior. This implies that the models from literature are not useable, since the Durand and Condolios (1952) , Worster and Denny (1955) and Wilson et al. (2006) models are created only for the heterogeneous flow regime and constant transport concentration, while the Doron and Barnea (1997) model was created for a sliding bed and constant spatial concentration. The reality seems to be more complicated.

VALIDATION

De Vreede (2018), carried out experiments at the National Engineering Research Center for Dredging (NERCD) in Shanghai. The experiments were carried out with a flow loop with a pipe diameter of 300 mm. It contains a measurement section of over 110 meters, part of which is inclinable. Pipe inclination angles of 17.9, 28.9 and 44 degrees were tested with slurry concentrations up to 15 % at flow velocities between 2 and 7 m/s. The sand used in the experiments had a d_{50} of 0.77 mm on average. The flow velocities (line speeds), delivered concentrations, total pressures, differential pressures and pump data were recorded.

Conducting these experiments on this scale under controlled laboratory conditions is a unique research. Figure 7 gives a schematic display of the test setup.

In Figure 7 the slurry would "start" at the slurry tanks (1) (not displayed). Upstream from the slurry tanks, the water reservoir is located. The slurry tanks and water reservoir are connected via a set of pipes and valves. The pump is located at 2, downstream from the reservoirs in the figure. Directly after the pump a section that serves as a U-loop (3) is found. The U-loop is outfitted with 2 differential pressure meters (one on each leg) and an ultrasonic density meter. After the U-loop, the pipe is led through a water basin (4) that can serve as cooling section. From the cooling system, the pipe is led upwards where the electromagnetic flow meter (5) is attached to the vertical ascending leg of the vehicle crossing. Directly downstream from the vehicle crossing, the inclinable segment (6) starts with the ascending section, then a 180 degree turn and the descending section. Several differential pressure meters and total pressure sensors are attached to it. The horizontal section (7) begins right after the inclinable segment downstream from the descending section. This horizontal section includes differential pressure meters and total pressure sensors. The horizontal pipe has a Perspex observation section built in to monitor sliding or stationary beds. After the horizontal measurement section, the second 180 degree turn (8) is located which leads the flow led back to the slurry tanks. The ascending and descending legs of the inclinable section have a combined maximum length of approximately 50 meters depending on the inclination angle. At inclination angles over 18 degrees, the inclinable section is shortened to fit under the roof of the laboratory. The horizontal measurement section excluding the inclinable section is a little under 60 meters long. Except for the connections at the slurry reservoir, the pipe diameter of the whole setup is 300 mm. Figure 8 shows the inclinable sections with inclination angles of 20, 30 and 45 degrees, both ascending and descending. Because the top of the inclinable section did not completely fit in the building, the angles used were slightly smaller, 17.9, 28.9 and 44 degrees. The lengths of the inclinable sections are 11.5 m, 17.5 m and 26.5 m. A detailed description of the experimental setup including the transducers and measurement methods used can be found in de Vreede (2018). The facility is shown in Figure 9.

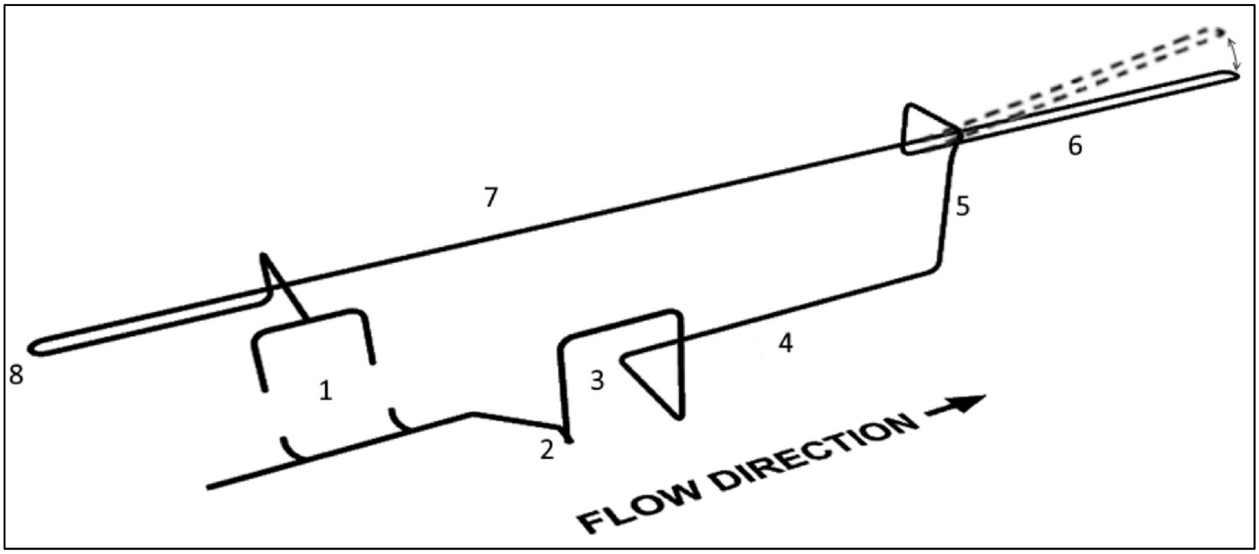

Figure 7: Schematic display of the test setup (source: de Vreede (2018)).

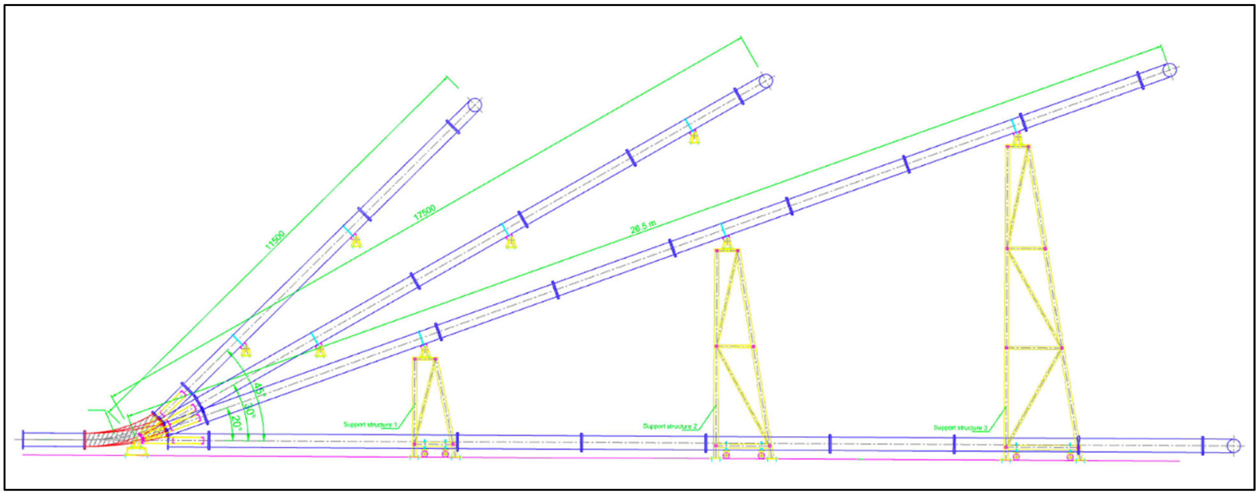

Figure 8: The inclinable section with inclination angles of 20, 30 and 45 degrees (source: de Vreede (2018)).

The experiments were carried out with intended constant delivered concentrations of 0%, 2.5%, 5%, 7.5%, 10% and 12.5%. In reality, it was difficult to obtain constant delivered concentrations during the experiments. Based on the way the experiments were carried out, an almost constant amount of solids in the whole system, the assumption of an almost constant spatial volumetric concentration is more realistic. This spatial concentration is also required in the DHLLDV model described here. Still there are differences in the concentration between the experiments at different inclination angles. Since the inclinable section contains both the ascending and the descending pipe and the hydraulic gradients were measured simultaneously, there may have been a difference in the spatial concentrations between the ascending and descending pipes. It is likely that the ascending pipe had a slightly higher spatial concentration compared with the descending pipe, especially at low line speeds.

Figure 9: The testing facility with the inclined loop.

The experimental data has been corrected for these effects, based on the potential energy component of the hydraulic gradient, since this component does not depend on the modelling of the solids effect. The resulting hydraulic gradients are shown in Figure 10, Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15. The actual spatial volumetric concentrations used in the graphs are 0%, 2%, 5%, 7.5%, 10% and 13.5%.

Figure 10 shows the hydraulic gradient curves and experimental data for pure liquid. The pipe wall roughness is calibrated based on these experiments, resulting in a good match. So, the theoretical assumption of the potential energy term for all inclined pipes seems to be valid. It should be mentioned here that it is always advised to check experimental data of something known, since there may be errors in the measurement.

The data points in the ascending pipe show a very good correlation with the theoretical curves, while the data points in the descending pipes show more scatter. Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15 show the hydraulic gradient curves and experimental data for the mixtures. Based on the theory and the way the experiments were carried out, one may expect the following phenomena:

1. In the ascending pipes there will be a fixed bed regime at low line speeds, followed by the heterogeneous regime and the homogeneous regime (FB-He-Ho). The sliding bed regime will not occur due to the combination of particle and pipe diameters and the spatial concentrations. So, there is expected to be a direct transition from the fixed bed regime to the heterogeneous regime.
2. In the descending pipes there may be some fixed bed regime at very low line speeds at an inclination angle of -17.9°, followed by the sliding bed regime, the heterogeneous regime and the homogeneous regime. The inclination angle of -17.9° is already close to the expected friction angle of 20°. For the inclination angles of -28.9° and -44°, the sliding bed will already occur at zero line speed (compare with a brick on an inclined slope, the brick will start sliding if the inclination angle is larger than the friction angle). This sliding bed regime is followed by the heterogeneous regime and the homogeneous regime (SB-He-Ho).
3. Because of the layout of the circuit one may expect some accumulation of solids in the horizontal pipe sections at very low line speeds, resulting in a decrease of the spatial concentration in the inclinable sections. This will result in slightly lower hydraulic gradients at these low line speeds in the ascending pipe and slightly higher hydraulic gradients in the descending pipes, especially at the higher spatial concentrations.
4. Because of possible deceleration and accumulation in the ascending pipe and acceleration in the descending pipe, the spatial concentration in the ascending pipe may be slightly higher than in the descending pipe, resulting in some underestimation of the hydraulic gradient in the ascending pipe and in absolute value overestimation in the descending pipe, based on the overall average spatial concentration.

CONCLUSIONS AND DISCUSSION

Models from literature multiply the so-called solids effect with the cosine of the inclination angle to a power between 0.25 and 1.7, based on the heterogeneous flow regime only or the sliding bed regime only. These models do not take the homogeneous (reduced) Equivalent Liquid Model (ELM) into consideration for very high inclination angles. The consequence is, that there is no solids effect in vertical pipes, which is doubtful.

The use of the cosine of the inclination angle on the solids effect for the sliding bed regime seems appropriate, a good first estimate. However, for the heterogeneous flow regime this is more complicated, resulting in a difference for an ascending compared to a descending pipe. In this case an ELM component containing the sine of the inclination angle should be added.

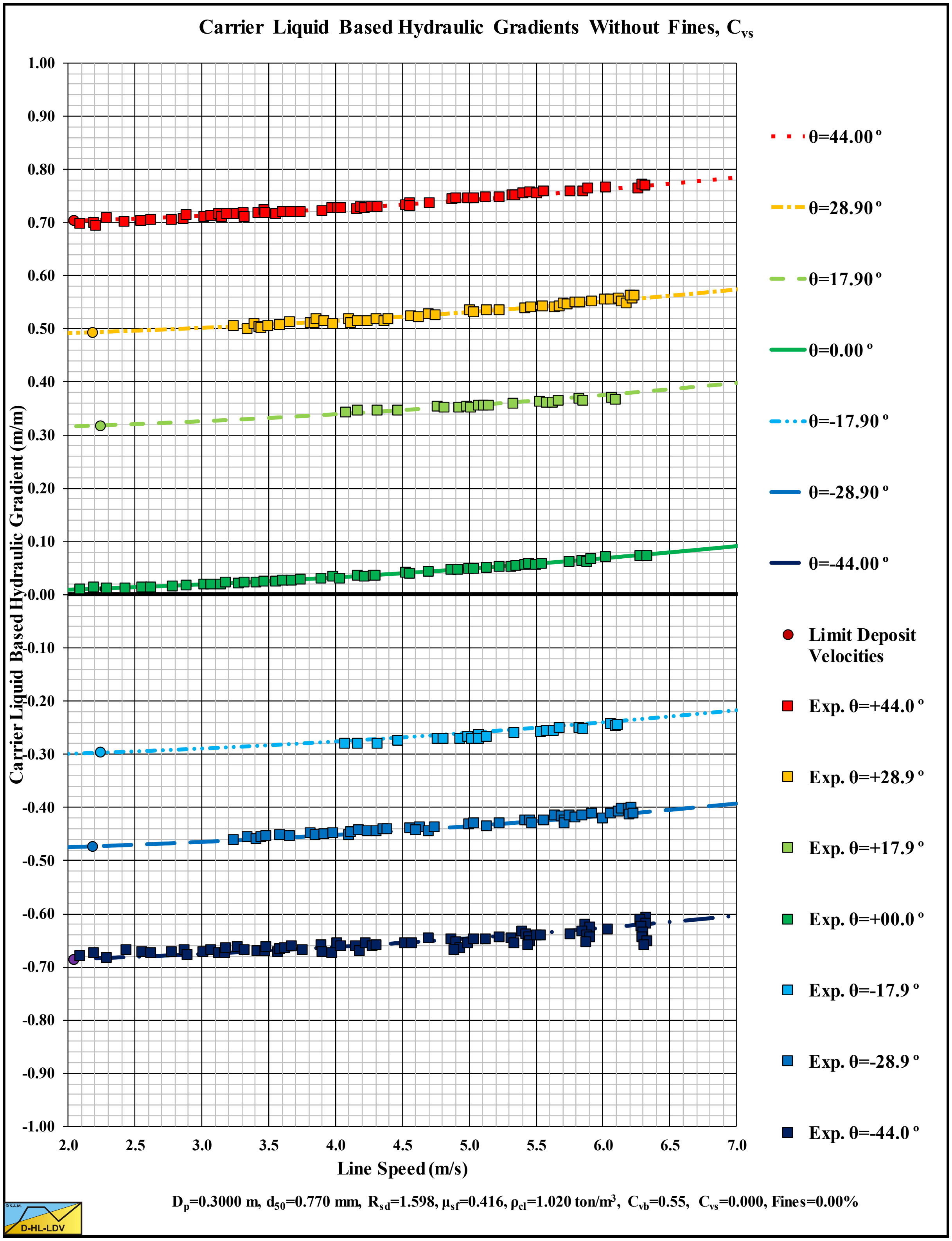

Figure 10. Inclined pipes C_{vs}=0.0%, experiments versus DHLLDV.

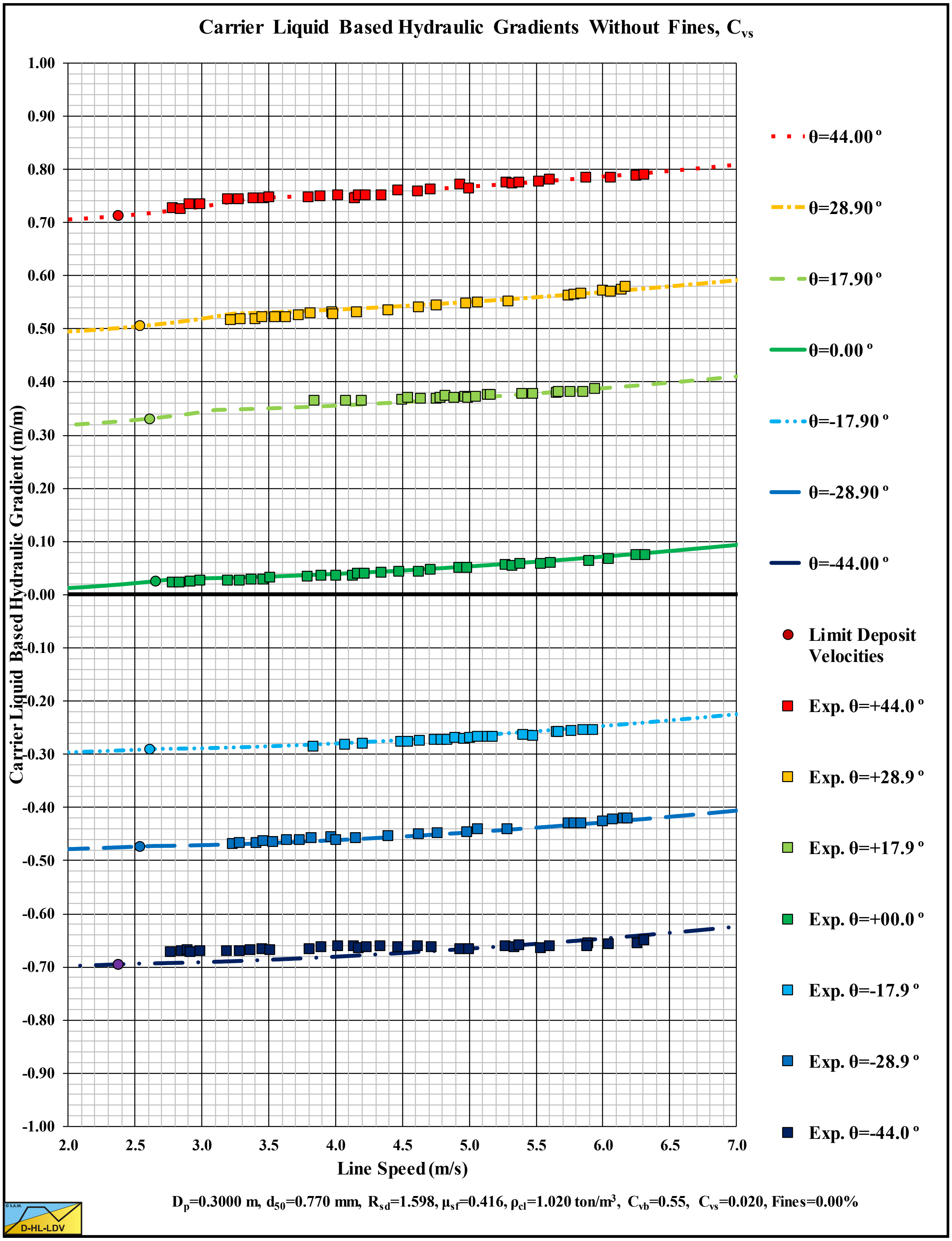

Figure 11. Inclined pipes C_{vs}=2.0%, experiments versus DHLLDV.

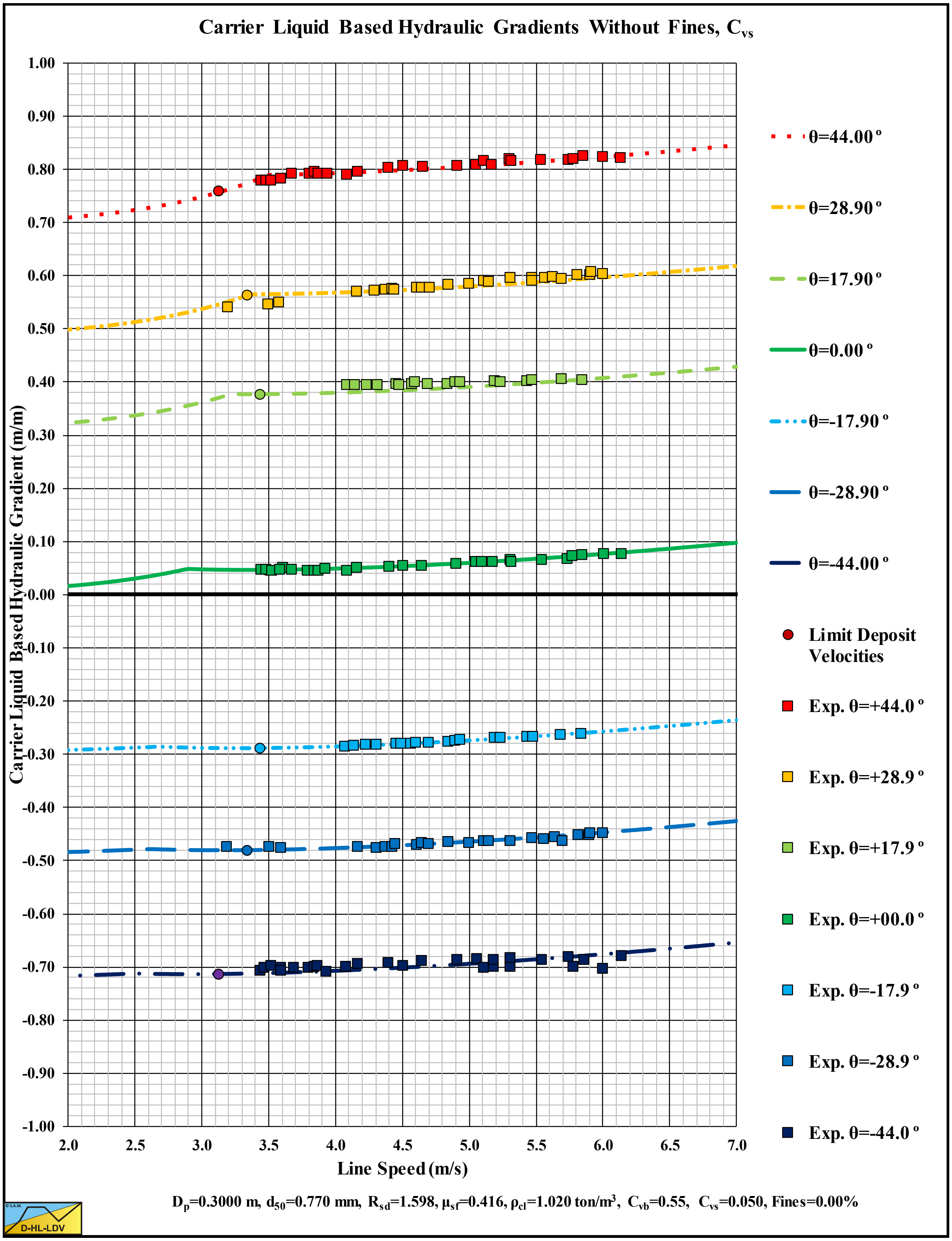

Figure 12. Inclined pipes C_{vs}=5.0%, experiments versus DHLLDV.

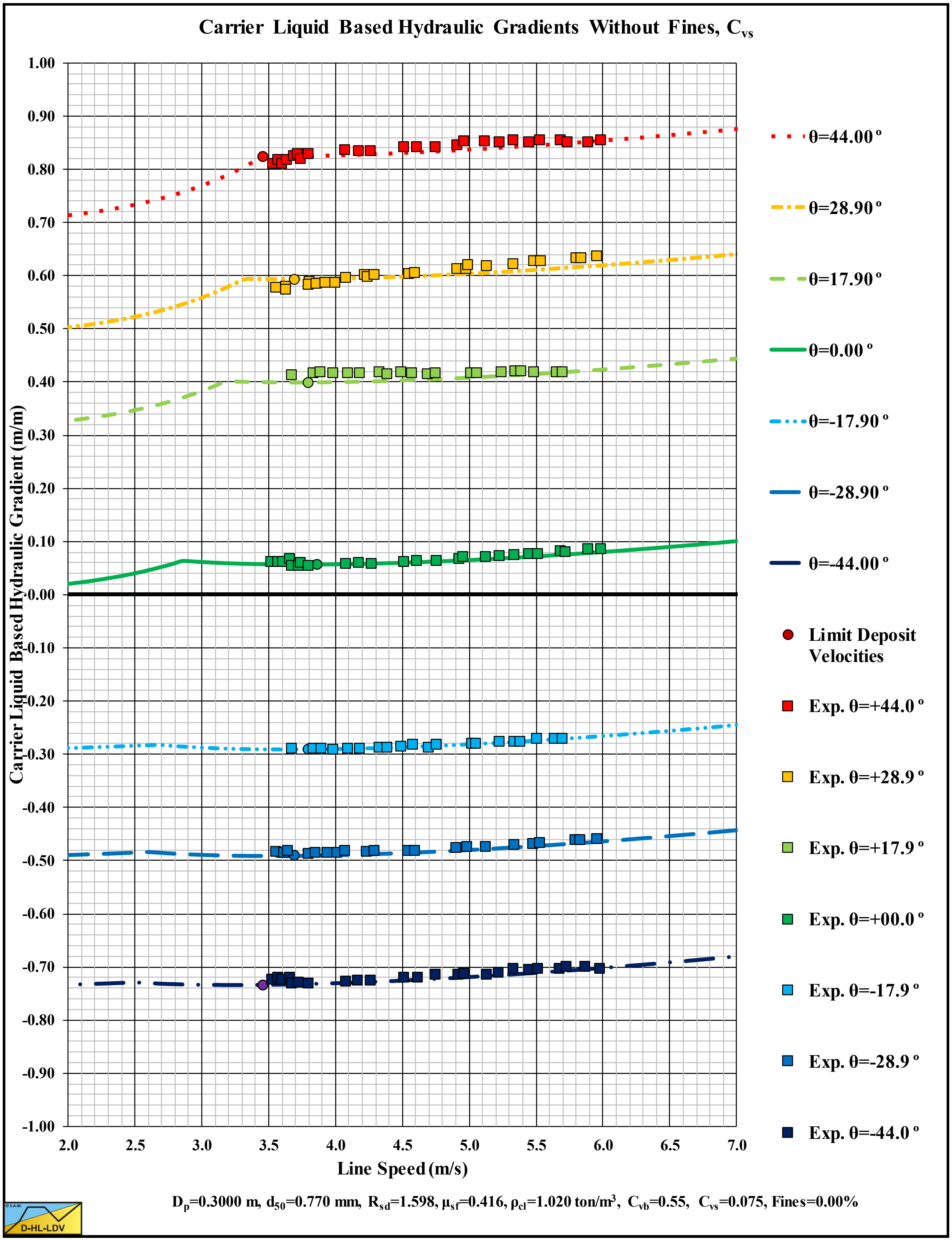

Figure 13. Inclined pipes C_{vs}=7.5%, experiments versus DHLLDV.

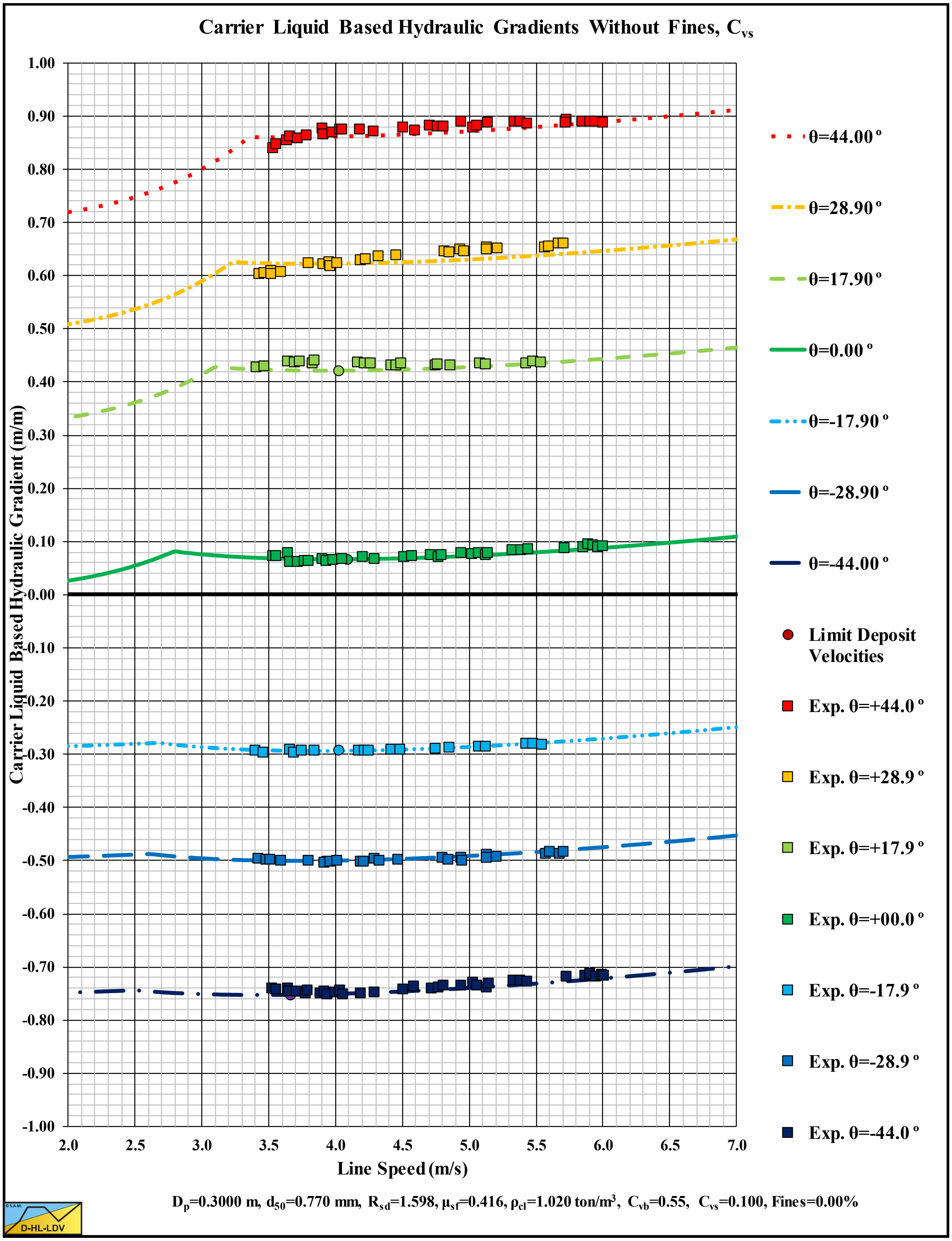

Figure 14. Inclined pipes C_{vs}=10.0%, experiments versus DHLLDV.

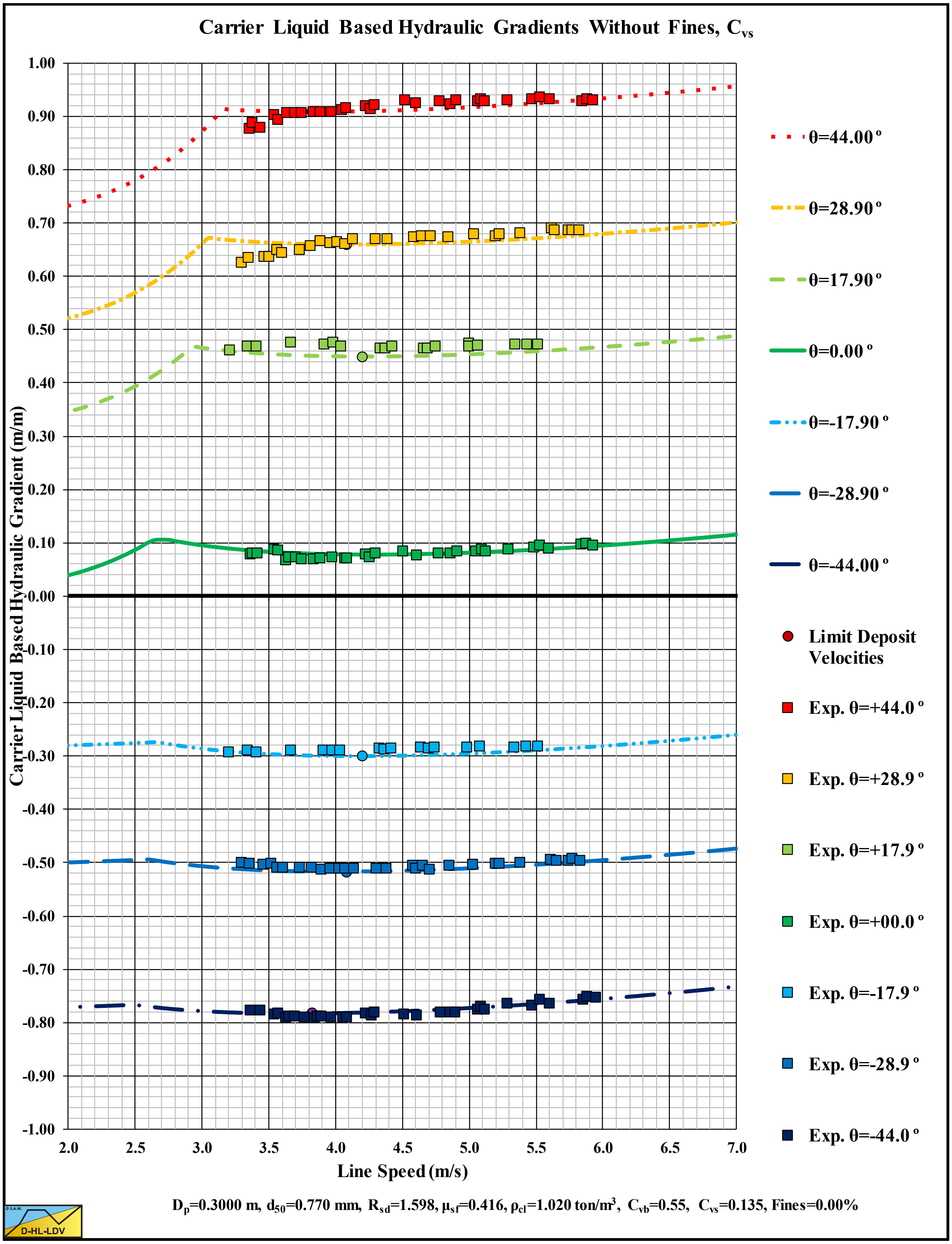

Figure 15. Inclined pipes C_{vs}=13.5%, experiments versus DHLLDV.

A proper model for inclined pipes should consider the different flow regimes individually and then combine the flow regime hydraulic gradients, based on which flow regime will occur at which line speed. The effect of the inclination angle may be different for the different flow regimes. Also, the transition line speeds between the different flow regimes depend on the inclination angle.

Since the occurrence of the different flow regimes depends strongly on the particle and pipe diameters and the line speed, this also has a dominant effect on the occurrence of the flow regimes in inclined pipes.
In an ascending pipe a bed will start sliding at a higher line speed and transit to heterogeneous flow at a lower line speed, with the possibility that there is no sliding bed at all, while there would be in a horizontal pipe. So, the line speed range of the sliding bed is reduced, possibly to zero. In a descending pipe the opposite will occur, with the possibility that there is a sliding bed from line speed zero up to the transition to heterogeneous transport.

The validation with the de Vreede (2018) experiments (CCCC National Engineering Research Center of Dredging Technology and Equipment, Shanghai, China) show a good correlation. However, it should be stated that the potential energy terms are dominating, and it is very difficult to identify the exact behavior of the solids effect. A good correlation means that the theoretical offset of the hydraulic gradient because of the potential energy matches the experiments, but also the shape of the theoretical hydraulic gradient curve matches the experiments, with sometimes some explainable deviation at low line speeds.
Now one could say, deduct the potential energy term and then compare the solids effect with the theory. This is possible; however, this would increase the scatter of the experimental data enormously in percentage. Also, because a small error in the spatial concentration would be magnified in the solids effect. Because the data have been taken largely in the heterogeneous regime, above 3.5 m/s, it is difficult to see if predictions of the LSDV/LDV are correct.

The approach chosen in the DHLLDV Framework as described here, determining hydraulic gradient curves for each flow regime and then combine/construct the resulting hydraulic gradient curve, seems to work very well.

REFERENCES

Doron, P., Simkhis, M., and Barnea, D. (1997). Flow of solid liquid mixtures in inclined pipes. International Journal of Multiphase Flow, Vol. 23, No. 2., 313-323.

Durand, R., and Condolios, E. (1952). Etude experimentale du refoulement des materieaux en conduites en particulier des produits de dragage et des schlamms. Deuxiemes Journees de l'Hydraulique., 27-55.

Gibert, R. (1960). Transport hydraulique et refoulement des mixtures en conduites. Annales des Ponts et Chausees., 130(3), 307-74, 130(4), 437-94.

Miedema, S. A. (2016). Slurry Transport: Fundamentals, A Historical Overview and The Delft Head Loss and Limit Deposit Velocity Framework. (1st Edition ed.). (R. C. Ramsdell, Ed.) Miami, Florida, USA: Delft University of Technology.

Miedema, S. A. (2017). Slurry transport in inclined pipes. Dredging Summit and Expo (p. 15). Vancouver, Canada: WEDA.

Miedema, S. A. (2018a). Slurry transport, fully stratified flow in the sliding flow regime. Dredging Summit and Expo (p. 15). Norfolk, Virginia, USA.: WEDA.

Miedema, S. A. (2018b). Slurry transport, the sliding flow regime or fully stratified flow. Submitted to: Terra et Aqua, 8.

Newitt, D. M., Richardson, J. F., and Gliddon, B. J. (1961). Hydraulic conveying of solids in vertical pipes. Transactions Institute of Chemical Engineers, Vol. 39., 93-100.

Vreede, M. d. (2018). Hydraulic transport in inclined large diameter pipelines. Delft, the Netherlands: Delft University of Technology.

Wilson, K. C., Addie, G. R., Sellgren, A., and Clift, R. (2006). Slurry transport using centrifugal pumps. New York: Springer Science+Business Media Inc.

Worster, R. C., and Denny, D. F. (1955). Hydraulic transport of solid materials in pipelines. Institution of Mechanical Engineers (London), 563-586.

NOMENCLATURE

A, A_p	Cross section pipe	**m^2**
A_1	Cross section restricted area above the bed	**m^2**
A_2	Cross section bed	**m^2**
c	Proportionality constant	**-**
C_{vb}	Bed volumetric concentration	**-**
C_{vs}	Spatial volumetric concentration	**-**
d	Particle diameter	**m**
E_{rhg}	Relative excess hydraulic gradient without pipe inclination	**-**
$E_{rhg,\theta}$	Relative excess hydraulic gradient with pipe inclination	**-**
g	Gravitational constant (9.81)	**m/s^2**
i_l	Hydraulic gradient liquid without pipe inclination	**-**
$i_{l,\theta}$	Hydraulic gradient liquid with pipe inclination	**-**
i_m	Hydraulic gradient mixture without pipe inclination	**-**
$i_{m,\theta}$	Hydraulic gradient mixture with pipe inclination	**-**
L	Length of pipe	**m**
O_1	Circumference restricted area above the bed in contact with pipe wall	**m**
O_2	Circumference of bed with pipe wall	**m**
O_{12}	Width of the top of the bed	**m**
p	Pressure in pipe	**kPa**
R_{sd}	Relative submerged density of solids	**-**
S_{hr}	Settling velocity Hindered Relative without pipe inclination	**-**
$S_{hr,\theta}$	Settling velocity Hindered Relative with pipe inclination	**-**
S_{rs}	Slip Ratio Squared without pipe inclination	**-**
$S_{rs,\theta}$	Slip Ratio Squared with pipe inclination	**-**
u_*	Friction velocity	**m/s**
v_{ls}	Line speed	**m/s**
v_t	Terminal settling velocity	**m/s**
v_{sl}	Slip velocity solids	**m/s**
$v_{ls,ldv}$	Limit Deposit Velocity without pipe inclination	**m/s**
$v_{ls,ldv,\theta}$	Limit Deposit Velocity with pipe inclination	**m/s**
W_b	Weight of the bed	**ton**
$W_{b,s}$	Submerged weight of the bed	**ton**
x	Distance in pipe length direction	**m**
α_E	Homogeneous lubrication factor	**-**
β	Richardson and Zaki hindered settling power	**-**
δ_v	Thickness viscous sub-layer	**m**
ρ_b	Density of the bed including pore water	**ton/m^3**
ρ_s	Density of the solids	**ton/m^3**
ρ_l	Density of the liquid	**ton/m^3**
ρ_m	Mixture density	**ton/m^3**

τ_1	Shear stress between liquid and pipe wall	**kPa**
τ_{12}	Shear stress on top of the bed	**kPa**
θ	Inclination angle (positive upwards, negative downwards)	**o**
μ_{sf}	Sliding friction coefficient	**-**
κ_C	Concentration eccentricity factor	**-**

DATA AVAILABILITY

All data and models generated or used during the study are included in the manuscript. The data can be found in the graphs, the models in the equations.

OVERCOMING BARRIERS TO BENEFICIAL USE OF DREDGED MATERIAL IN THE US

Kristin Searcy Bell†1, Brandon M. Boyd2, Staci L. Goetz3,*
Donald F. Hayes2, Victor S. Magar1, Burton Suedel2

ABSTRACT

Thousands of projects have successfully used millions of cubic meters of dredged material for beneficial use applications since the concept was introduced in the 1970s. Most projects have been technical successes, though some were unable to achieve sufficient financial success to be sustainable. Despite those successes, currently less than 40% of dredged material in the US is used beneficially. Limited Federal budgets, as well as state and local sponsor budgets, discourage the use of more costly beneficial use alternatives, even if those alternatives are more environmentally sustainable. Incompatible project timing and volume inconsistencies between dredging projects and beneficial use projects also discourage increased beneficial use. These barriers must be overcome if beneficial use of dredged material is to become standard practice. A more holistic evaluation of beneficial use and disposal options is needed, considering both short-term and long-term benefits and costs. Cost differentials will narrow as disposal costs increase and conventional disposal capacities decrease. Furthermore, increasing the recognition of the sediment's *value* in the ecological health of our aquatic ecosystems with a desire to improve sustainability in view of sea level rise will generate creative opportunities and encourage innovative partnerships. Local and regional beneficial use advocacy groups can foster collaboration, communication, advanced planning, and coordination between stakeholders; these steps can bridge the gap between the timing of projects and volume differentials, and further support beneficial use projects in general. This paper discusses barriers to beneficial use of dredged material in the US and strategies to overcome them. Given that only a small fraction of dredged material is unsuitable for reuse without treatment, a logical goal is for all dredged material in the US to be used beneficially unless chemically unsuited to remain in the environment. While that laudable goal may not be achievable in the short term, identifying mechanisms to overcome economic and institutional barriers will facilitate expansion of beneficial use opportunities.

Keywords: sediment, sustainable infrastructure, resiliency, Engineering with Nature®, habitat development

INTRODUCTION

Dredged sediment has been used beneficially as long as dredging has occurred. The beneficial use of dredged material can be used for engineering or environmental purposes, including construction materials, beach nourishment, flood protection, or habitat creation. Dredged "spoils" were used historically to raise expansive areas of marshes and swamps adjacent to existing shorelines above the high-water tide to create new land (Kennish 2002; Wong 2019). The Tokyo Haneda Airport, where construction started in 1931, is just one example of many important infrastructure features resulting from such efforts (Watabe and Sassa 2016). Similar examples exist in virtually every major port city. Such projects resulted from a combination of convenience and cost. Landfill projects provided a nearby location to place dredged material and the resulting filled land had value

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[1]* All authors contributed equally to this paper and are listed in alphabetical order.
† Corresponding author, ksbell@ramboll.com
[1] Ramboll, 333 West Wacker Drive, Suite 2700, Chicago, IL, 60606, USA
[2] US Army Engineer Research and Development Center, 3909 Halls Ferry Rd, Vicksburg, MS, 39180, USA
[3] Ramboll, 234 West Florida St, Fifth Floor, Milwaukee, WI, 53204, USA

where the swamps and marshes were assumed to have none. In addition, the proximity to shipping and nearshore industrial activities bolstered newly created land values.

The concept of dredged material beneficial use became more formalized during the 1970s and 1980s. Environmental regulations made sediment disposal more complicated and increased sediment disposal costs, particularly when associated with constructing new dredged material placement facilities. These societal and economic pressures made beneficial use more attractive. Construction of many successful beneficial use projects helped extend existing placement capacity of existing facilities while new solutions were pursued. This period culminated with the Engineer Manual 1110-2-5026 (USACE 1987) that summarized a host of successful strategies for dredged material beneficial use. Funded by the Dredging Operations and Environmental Research (DOER) program, the USACE recently revisited several USACE beneficial use projects constructed in the late 1970s to document their long-term successes and trajectories; these projects were initially documented by Newling and Landin (1985). The findings show that all projects produced ecological (e.g., habitat development) or engineering (e.g., shoreline resiliency) benefits. Drake Wilson Island is one successful example that continues to provide benefits, as summarized in the Engineering With Nature Atlas Volume 2 (https://ewn.el.erdc.dren.mil/atlas.html). The long-term success demonstrated by this project demonstrates that the technical capacity to successfully implement beneficial use has been available for decades.

With the successful application of beneficial use, dredged material drew increasing interest in the 1990s as a potential resource, especially in urban areas where soil sources are scarce. For example, the New Jersey Department of Transportation (NJDOT) conducted numerous demonstration projects related to the use of dredged sediment for mine reclamation, highway embankment construction, and other uses (Yozzo et al. 2004). They also evaluated a host of treatment technologies that could reduce chemical concentrations in dredged material to levels suitable for different beneficial uses.

Despite a long history of successful beneficial use projects (see for example Bridges et al. [2018] and https://budm.el.erdc.dren.mil/), beneficial use is not practiced on a widespread and consistent basis. Bridges (2018) asked, “What would it take to reach 100% beneficial use?” This paper investigates potential feasibility, cost, and institutional barriers that currently restrict achieving this goal and identifies potential solutions for overcoming these barriers and expanding beneficial use. Portions of this paper are excerpted from a forthcoming update on the PIANC (2009) international standard of practice on sediment beneficial use.

CATEGORIZING BENEFICIAL USES AND BENEFICIAL USE TRENDS

Dredged material consists primarily of super-saturated granular particles typical of most soils and sediment—gravel, sand, silt, and clay. Although some dredged material contains elevated concentrations of chemical contaminants, the vast majority of navigational dredged material does not. Thus, almost any need for additional soil or sediment provides a potential opportunity for using dredged material.

PIANC (2009) defines sediment beneficial use as *any use of dredged material rather than mere disposal is regarded as use.* This definition allows consideration of the widest range of options available to the port operator, contractor or other proposer seeking to use dredged material from dredging operations. The Central Dredging Association (CEDA 2019) defined sediment beneficial use as *the use of dredged or natural sediment in applications that are beneficial and in harmony to human and natural development*. While also broad, this definition focuses on sediment uses that benefit society and the natural environment. It places a greater burden on decision makers to consider societal and ecological benefits of sediment use. USACE (1987), USEPA and USACE (2007a) and USACE (2015), and Childs (2015) identified multiple beneficial use categories in an attempt to better understand and expand beneficial use opportunities. Those uses are listed in Table 1. Here, we define beneficial use as *using dredged sediment to achieve additional benefits beyond the purposes related to its removal, including other economic, environmental, or social benefits*.

While these approaches categorize beneficial use by application or technology, the USACE Regional Sediment Management (RSM) Database (USACE 2020) uses a simplified version of Child’s (2015) approach and categorizes beneficial use based on location where sediment is applied rather than type: i.e., beach, in-river, and

Table 1. Comparison of attempts to categorize beneficial use alternatives by previous efforts.

USACE (1987)	USEPA and USACE (2007a) and USACE (2015)	Childs (2015)
Habitat development	Habitat restoration and development	Upland placement for ecological habitat
Beach nourishment	Beach nourishment	Beach or nearshore placement for shoreline protection or beach nourishment
Parks and recreation	Parks and recreation	Placement for upland land development
Agriculture, forestry, and horticulture	Agriculture, forestry, horticulture, and aquaculture	Shallow water placement for wetland, marsh, or habitat
Strip mine reclamation and solid waste management	Strip-mine reclamation and solid waste management	Unconfined aquatic placement
Construction and industrial use	Construction/industrial development	Island placement for benefits
Multiple purpose	Multiple-purpose activities	Ocean placement for beneficial use
Material transfer		Upland placement for soil reuse
Shoreline stabilization and erosion control		Confined in-water placement for beneficial purpose
Aquaculture		

littoral; open water, upland, and wetland. Child's categories are used in the Great Lakes Beneficial Use manual (GLDT 2020).

USEPA and USACE (2007a) estimated that only 20-30% of the total volume dredged in the US is being used beneficially. Unfortunately, the data to differentiate beneficial use rates for channel maintenance as compared to channel deepening or other new work are not available. Since 1997, USACE has tracked dredge volumes and sediment beneficial use (USACE 2020). Figure 1 shows annual dredged volumes and beneficial use volumes from 1997 through 2017. The data show an average of 38% beneficial use for sediment removed from federal navigation channels between 1998 and 2017. For 2004-2006, beneficial use is closer to 30%, reasonably consistent with the conclusions drawn by USEPA and USACE (2007a). Other years are closer to 40% or 50% beneficial use.

While the volume of beneficial use in the US, 50 to 80 million cubic meters (MCM) annually, is impressive, Figure 1 also shows the potential for redirecting an additional 80 MCM annually to beneficial uses in lieu of disposal. The National Research Council (1994) estimated that only 5% of maintenance dredged material in the US is unsuitable for open water placement. More recent or specific citable data were not identified, but it is believed that only a very small portion would have restrictions on beneficial use or require treatment because of sediment contamination.

Encouraging the expansion of beneficial use will be especially important in upcoming decades, as dredged material placement options reach capacity in many areas and open water placement is under increasing scrutiny. Societal pressures, regulations, and space limitations make open water disposal and the permitting and construction of new placement facilities increasingly difficult and expensive. For example, the closure of the "Mud Dump" disposal site in New York / New Jersey Harbor in 1992 resulted in a dredging crisis for the State of New Jersey that spurred the region toward beneficial use (Maher et al. 2013). The closure of this open water disposal site put into jeopardy New Jersey's ability to conduct maintenance dredging and to implement new capital projects, like the planned deepening of entrance channels to the Port of New York and New Jersey. This eventually led to numerous policy changes, including regulatory overhaul and the establishment of policies that supported innovative techniques to manage dredged material, such as a greater investment in beneficial use. More recently, the State of Ohio banned open water disposal in Lake Erie starting July 2020, also leading to

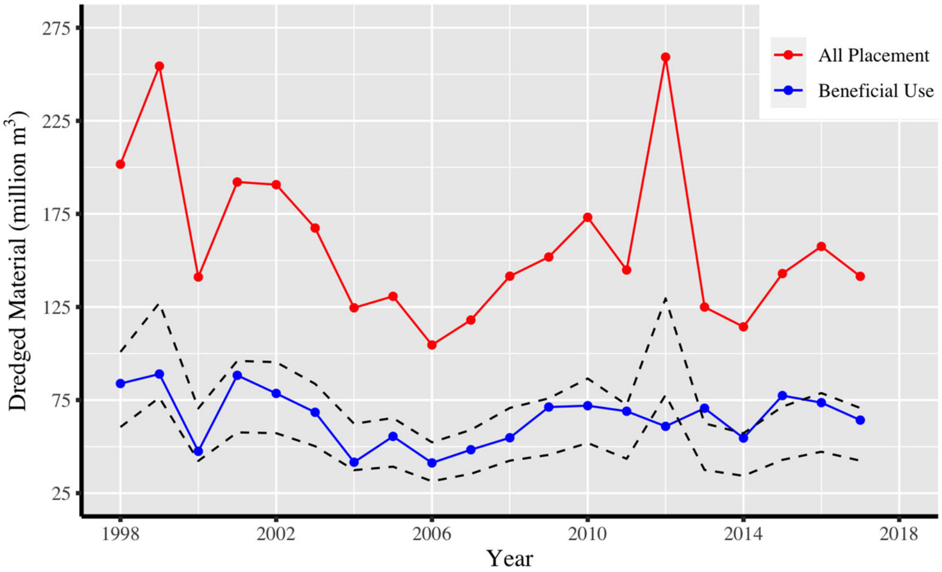

Figure 1. Dredging placement for USACE navigation dredging from 1998 to 2017. Dashed lines represent 50 and 30% thresholds of all dredged material placed and are shown to demonstrate what percentage beneficial use is of all placement. Data from the USACE RSM BU Database (https://rsm.usace.army.mil/BUDB).

increased focus on beneficial use alternatives, particularly as capacity in conventional disposal facilities (e.g., CDFs) is exhausted.

Beneficial use also has drawn recent interest thanks to two popular trends - increasing recognition of sediment as a valuable resource in a healthy aquatic ecosystem, and a push for increasing infrastructure sustainability (e.g., improved habitat and coastal resilience). Sediment loss or changes in natural sediment inputs can adversely affect riverine, estuarine, and coastal ecosystems and sea level rise can add to the effects in coastal ecosystems, such that an environmentally and ecologically motivated focus has been cast on beneficial use. Techniques that can accomplish resupply of sediment include sediment bypassing, thin-layer placement, and nearshore placement. Consistent with this observation, the RSM database shows that between 1998 and 2020 almost half (47.1%) of the sediment beneficial use (approximately 616 MCM) has been returned to river systems. An additional 16.8% (220 MCM) was used to restore or enhance wetland environments, 13.2% (173 MCM) was placed on beaches, 11.1% (145 MCM) was placed within the littoral zone, 10% (131 MCM) was used beneficially in upland locations, and 1.8% (24 MCM) was used beneficially in open water. “Strategic” unconfined placement (e.g., placing sediment within riverine or coastal environments) must consider long-term and system-wide watershed benefits and impacts. Benefits can include wetland nourishment and habitat maintenance, while negative impacts may include increased long-term sediment management needs (i.e., more dredging) and negative habitat impacts if areas are overwhelmed by increased sediment loads.

Over the last decade, progress in documenting sediment beneficial use also has been realized. CEDA (2021) and USACE (2021) both developed web sites dedicated to beneficial use, communicating recent advances and best practices. Highlights of technical progress include: using thin layer placement to restore coastal habitat; building dikes, foreshores, and marshland to decrease wave impact (i.e., improving resiliency), thus reducing the need for conventional dike construction; developing strategic and large-scale beach and dune nourishment to improve coastal resiliency; harvesting clean dredged material previously placed in confined disposal facilities (CDFs) to increase CDF storage capacity; and strategic and beneficial placement of dredged material distant from the original placement area.

PIANC (2009) summarized beneficial use experiences achieved since their 1992 report. Their primary objectives were to document the experiences gained, examine constraints on use, and make recommendations to increase beneficial use by providing a template to encourage sediment beneficial use as an alternative to disposal. In the decade since PIANC (2009) was published, many gains and advances have been realized, and documentation of beneficial use practices has increased. These advances have been influenced by key events and publications. Notably, in 2008, PIANC published a position paper on Working with Nature (WwN; PIANC 2008), followed by a Guide for Applying Working with Nature to Navigation Infrastructure Projects (PIANC 2018). Soon after the 2008 position paper, Building with Nature (BwN) and Engineering With Nature (EWN®) were launched, both of which are initiatives to implement WwN and are developing and demonstrating, through multiple dredging projects, the capabilities needed to achieve sustainable, triple-win project outcomes (see for example, De Vriend and Van Koningsveld 2012; Bridges et al. 2014, 2018). In 2018, the International Association of Dredging Contractors (IADC) and CEDA jointly published a guide on delivering dredging projects that enhance economic, social, and environmental values in a sustainable manner (Laboyrie et al. 2018). In 2015, the United Nations released its Sustainable Development Goals, a call for action to promote prosperity while protecting the environment, as part of its 2030 Agenda for Sustainable Development (United Nations 2019). Climate change impacts to waterborne transport infrastructure recently came to the forefront, prompting the need to develop adaptation measures (PIANC 2020). Collectively, these documents promote the advancement of beneficial use and the ongoing implementation of nature-based solutions to promote natural and increasingly resilient aquatic ecosystems.

BARRIERS TO EXPANDING BENEFICIAL USE

Creative sediment management alternatives are critical to support navigation dredging as further constraints on low-cost conventional management alternatives are imposed. Conventional disposal sites have finite capacity while open water placement continues to come under increasing scrutiny. These factors, combined with an increasing awareness of the importance of sediment in maintaining coastal resiliency, provide the impetus for creating additional opportunities for beneficial use. Identifying barriers and means to overcome them is necessary for expanding beneficial use opportunities.

Technical Barriers

Multiple technical barriers discourage beneficial use of dredged material. Example barriers include physical characteristics of dredged material incompatible with requirements for use, differences between dredged material volume available and sediment volumes required, the presence and potential need to remove contaminants, and the distance between dredging projects and beneficial use opportunities.

Physical Characteristics and Characterization

Physical characteristics of dredged materials vary widely, sometimes even within the same project area. For example, as energy associated with sediment suspension and transport changes geographically, seasonally, and over time, the segregation of particle sizes within an estuary or port facility can occur. Looking only at average particle size distributions may not give a sufficiently accurate characterization of dredged material and what portions of that material are suitable for various uses, particularly where particle size distributions are heterogeneous. Therefore, sufficient sediment sample collection and characterization needs to be conducted as part of the beneficial use project design. Complicating matters, dredging and dredged material handling can further segregate sediment particles as coarse sediment particles tend to settle more rapidly than fine particles.

Volume Incompatibility and Project Timing

Volume incompatibilities and unaligned project timing can also discourage beneficial use. If the volume of sediment required for a potential beneficial use is more than the volume of sediment available from dredging, the projects may be incompatible unless the beneficial use project is scalable. Many examples exist where a beneficial use project receives sediment from multiple dredging projects or over multiple dredging cycles. This spreads costs over multiple projects. Conversely, if the dredged material volume is in excess of that required for a beneficial use, the dredging project may need to bear the costs and risks associated with obtaining permits for and using multiple placement areas. To accommodate the potentially different timelines for beneficial use and dredging projects, alternative placement or staging options may be employed.

The US mined 80 to 120 million metric tons of sand and gravel annually from 2015 to 2019 (Statista 2020). Why is dredged material not used in lieu of mining, resulting in a financially beneficial partnership for all parties? The sporadic nature of dredging complicates commercial opportunities. Sand and gravel suppliers need inventory on-hand at all times to match demands. Dredging produces large volumes over short periods, and then may not produce additional sand for several years. Most sand and gravel suppliers do not have the capacity to hold material on site for an extended period. Thus, it is more prudent for them to generate their own inventory on a consistent basis even if it costs more to do so. CDFs also offer a potentially underused opportunity to reclaim sand, so long as the CDF material is uncontaminated and has properties of interest to the user. Harvesting clean sand from a CDF also can have the added benefit of increasing CDF capacity for sediment that does not have immediate or long-term use potential.

Inconsistent Sediment Quality

Inconsistent quality also limits dredged sediment beneficial use. Dredged material almost always contains some fines. Coarse materials are more valuable when segregated by size, so additional processing may be necessary. For some potential uses, the fines must be removed and, often, disposed of in an appropriate facility (CDF). Many suppliers have separation capabilities but may not be able to handle the large flow rates over short periods associated with dredging. Few suppliers have the capacity to manage large volumes and required processing and storage requirements, limiting commercial opportunities.

Sediment Contamination

Sediment known to have elevated contaminant levels pose additional concerns. Contaminants tend to bind preferentially to fine particles, making organically rich fines particularly challenging to beneficial use. If contamination is present, preprocessing may be required before dredged material can be used safely. Preprocessing comes in many forms, but separation and treatment are the most common. The goal of separation is usually to separate the lesser-contaminated sand particles for beneficial use whilst reducing the net volume of contaminated sediment that must be disposed.

Treatment of Dredged Material

The selected treatment process or degree of treatment required for beneficial use depends on the physical and chemical characteristics of the dredged material, the nature of the contaminants, and the purpose for which it is being used. Barriers lay in the capital and operational costs associated with the treatment, the level of treatment required, and storage capacity needed for the dredged materials. Contamination is a continuum and most dredged sediments are “suitable” for some kind of beneficial use without having to apply expensive remediation-like treatment technologies, although physical separation is often warranted. Categories of contaminant treatment technologies and associated considerations for each technology are provided below:

- **Solids Separation.** Separation of sand from fines is typically conducted to achieve a target grain size class of the dredged material or to isolate the fine fraction which typically contains a high fraction of the contaminants. Separation can be conducted via low-energy methods, which are typically much less expensive than other treatment methods described below.

- **Chemical Immobilization and Stabilization.** Contaminants can be immobilized and stabilized by adding pozzolanic materials, such as Portland cement, lime, fly ash, or slag. These materials react with the dredged material and bind particles and contaminants, which reduces contaminant leaching potential (Maher et al. 2013; PIANC 2009).

- **Thermal Treatment.** Thermal processes include desorption and capture at relatively low temperatures, and contaminant destruction at high temperatures. High-temperature products include bricks or lightweight aggregate. While technically feasible, thermal treatment costs are high, in part because the high-water content in sediment consumes substantial thermal energy.

- **Bioremediation.** Microorganisms can degrade some organic contaminants if provided sufficient time and proper conditions, typically by spreading the dredged material over large areas of land and stimulating the biodegradation via aeration. Bioremediation is contaminant- and site-specific and may not be suitable for heterogeneous material from routine navigational dredging. Bioremediation requires large areas of land, and associated costs include the need for aeration and potential amendments, including carbon sources.

Economic Barriers

For all types of dredging, costs have increased historically; according to the USACE, the cost per cubic meter increased two and a half fold between 1963 and 2018 (USACE Navigation Data Center 2021). Direct costs for beneficial use as compared to disposal vary greatly depending on site-specific conditions, including the characteristics and volume of dredged material, location and capacity of disposal facilities, transport of the dredged material, and production rate of treatment facilities (PIANC 2009). Direct costs associated with the beneficial use of dredged material are often higher than for conventional sediment disposal, thus resulting in a significant disadvantage for beneficial use. PIANC (2009) suggested that the following potential requirements be considered as part of a beneficial use project when developing project cost estimates:

- **Material Testing -** Testing of the chemical and physical properties of the dredged material is needed to determine the suitability of the material for beneficial use and any treatment requirements. Chemical and physical characterization requirements for beneficial use can be more comprehensive than the testing required for disposal.

- **Treatment -** For beneficial use of dredged material, physical processing, such as the separation of fines, or contaminant treatment may be required. The associated costs vary depending on the dredged material characteristics, type of treatment, scale, and either the ultimate disposal costs or the market value of an end product. Simple technologies such as natural sand separation and land-farming (bioremediation) are relatively inexpensive if the necessary land is available. Stabilization has relatively moderate costs and can be used to improve the geotechnical quality of the dredged material (PIANC 2009). Thermal immobilization treatment costs are much higher. The market value of potential end-products should be considered in determining net costs.

- **Permitting -** Existing placement areas typically have permits in place, having completed required environmental impact studies and assessments before opening. In contrast, beneficial use sites usually require new permits. Required environmental studies and assessments must be completed as part of the project. Not only can these studies be expensive, they can take significant time to complete. The permitting process adds additional time, especially when regulators have limited experience with beneficial use or a new use is proposed. Even for relatively simple projects, permitting can take one to two years and the outcome may be uncertain. Time, cost, and uncertainty associated with permitting discourage the development of new beneficial use sites.

- **Risk Assessment -** Many dredging projects operate on strict schedules and budgets. Such logistical constraints are especially true for maintenance dredging projects, which represent many opportunities for beneficial use. Beneficial uses often carry additional financial or schedule risks not associated with conventional sediment disposal. Many of those risks have been discussed above. Every project must balance the benefits of beneficial use with additional risks associated with using dredged sediment. The decisions to use dredged materials must be based on site-specific considerations and risk assessments and on possible mitigation measures.

- **Liaility -** Liability concerns can discourage beneficial use of dredged sediment, especially for uncontrolled uses. For example, sediment could be resourced from a placement site (e.g., from a CDF) for residential or commercial uses. However, some agencies and project owners fear potential liability for future impacts resulting from sediment-bound contaminants, even if they are not aware of them or were not involved in their generation. Without a widely accepted definition of "clean," many prefer to use quarried materials from a known source rather than dredged sediment or sediment from containment areas.

The vagaries of dredging and dredged material management costs complicate cost comparisons. Dredging and transportation costs vary with competition, fuel price fluctuations, and demand. Local regulations such as dredging windows can exacerbate these variations. Value assessments are even more difficult. Reliable navigation depths are crucial to sustain waterborne commerce, which has long economic tentacles. Quantifying benefits resulting from sediment reuse is even more challenging, especially when they will continue to accrue over decades. Yet, dredging project managers face the dilemma of integrating all three on a routine basis. Moreover, they must do so within constrained budgets that do not reflect anticipated values resulting from dredging projects (Wetta and Hanson 2011). It is not surprising that the most quantifiable of these short-term costs often drives decision-making. Nonetheless, dredging managers are often faced with balancing these values as part of project development, design, and execution. Pandal (1998), McLellan et al. (2001), Yozzo et al. (2014), and Maglio et al. (2020) are examples where cost was a primary factor in sediment management alternative selection.

Institutional Barriers to Expanding Beneficial Use

Institutional barriers to expanding beneficial use can be grouped into three categories: 1) lack of harmonized approaches between state and Federal agency regulations, 2) complex cost-sharing requirements, and 3) public and agency acceptance (GLDT 2020; PIANC 2009). These barriers are examined to identify potential opportunities to facilitate the expansion of beneficial use.

Need for Harmonized Regulatory Approaches

In the US, regulatory requirements for beneficial use differ among States and between State and federal agencies. Regulations must be considered for different regulated environments (e.g., upland, wetland, nearshore, aquatic) and for the products that may be generated using dredged material. Federal guidelines applicable to aquatic (defined as waters of the U.S., occurring below the ordinary high-water mark or marine) and upland placement are summarized in Table 2. Definitions of these environments vary among states, as do the exposure pathways and end-use environmental concerns (Kiel 2018).

Sediment chemical criteria for beneficial use are commonly assessed by bulk sediment chemical concentrations, although elutriate tests, toxicity tests, or modeling may be applied. Sediment quality evaluations may include but are not limited to risk-based evaluations (i.e., risk-based threshold criteria) or comparison to the ambient background sediment concentrations. Federal and regional guidance documents describe testing protocols and evaluation procedures (e.g., USACE 2003; USEPA and USACE 1998; USEPA 2016a and 2016b). USEPA guidance for performing beneficial use evaluations provides a step-wise or phased approach (USEPA 2016a and 2016b).

Table 2. Federal regulations for the placement of sediment (Kiel 2018; GLDT 2020; Illinois Marine Transportation System [IMTS 2020])

Aquatic placement	Upland Placement	Other Federal Regulations for Consideration
Sections 404/401 Clean Water Act (CWA) - suitability for aquatic placement water quality certification in coordination with permitting state; also addresses invasive species or contaminant migration across jurisdictions	Section 402 of CWA also applies for unconfined upland placement and discharge to a waterway with shared jurisdictional boundary can make permitting/testing more complex	Clean Air Act - fugitive dust and equipment emissions (Note that non-attainment may be a particular barrier for large reuse projects)
National Environmental Policy Act (NEPA) - addresses invasive species or contaminant migration across jurisdictions	NEPA	Surface Mining Control and Reclamation Act (SMCRA) -if used for mine land reclamation
Coastal Zone Management Act (CZMA)-where and what populations and activities exist where dredged material is placed or used	CZMA	Water Resources Development Act
Marine Protection, Research, and Sanctuaries Act (MPRSA) - prohibits the dumping of material into the ocean that would unreasonably degrade or endanger human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities	Endangered Species Act (ESA)- where and what populations and activities exist where dredged material is placed or used	Water Resources Reform and Development Act of 2014 (WRRDA)
	RCRA- solid waste management rules (depending on handling/permitting)	Rivers and Harbors Act
	Toxic Substances Control Act (TSCA) – polychlorinated biphenyls (PCBs) > 50 milligram per kilogram (mg/kg) confined disposal facility (CDF) or upland only (depending on handling/permitting)	National Historic Preservation Act

Some states regulate dredged sediment as soil or solid waste while others regulate it as sediment. Table 3 summarizes state approaches to beneficial use that was compiled from previously developed compendia (Kiel 2018, GLDT 2020, IMTS 2020) and state guidance (e.g., San Francisco Bay Regional Water Quality Control Board, SFWQCB 2000). The table includes states where criteria apply, if any, to aquatic or upland placement. Guidance and regulations for these same states are summarized in Table 4.

Many waterways also serve as state boundaries. Inconsistencies between neighboring states can impact coordination and the period of project execution. If chemical criteria for material beneficial use differ among states, there may be uncertainty regarding which laws prevail for a given project. Connecting waterways may also have differing environmental windows, or periods of the year when dredging and open water placement may occur due to ecological considerations. The Great Lakes Beneficial Use Testing Manual proposed a holistic, risk-based approach that dredged material be evaluated based on potentially impacted environments (aquatic or upland), jurisdictional authorities (federal or State), receptors at risk (human or ecological) and pathways of exposure (water, soil contact, food chain, air, etc.)," for environmental acceptability for beneficial use. This approach is consistent with USEPA guidance (2016a), which was developed to help states make beneficial use

Table 3. State guidelines for the placement of non-hazardous sediment (Maher et al. 2013; Kiel 2018; GLDT 2020; Illinois Marine Transportation System [IMTS 2020])

State	Aquatic Placement in Waters of the U.S.		Upland Placement	
	Sediment quality guidelines or water quality limits	**Soil/waste limits**	**Sediment quality guidelines or water quality limits**	**Soil/waste limits**
California[a]	•		•	
Illinois	•		•	
Iowa	N/A	N/A	N/A	N/A
Indiana	•			•
Kentucky	•			•
Ohio[a]	•		•	
Oregon	•		•	
Pennsylvania	N/A	N/A		•
Maryland	•		•	
Michigan	•		•	
Mississippi	•		•	
Missouri	•		•	
Minnesota	•			•
New Jersey	•		•	•
New York	•			•
Texas	•		•	
Washington	•			•
Wisconsin	N/A	N/A		•

[a] sediment and water quality limits include toxicity testing or bioassays

Notes: • = applicable; blank = unregulated/no framework; N/A = not applicable, no beneficial use allowed.

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

California	The Long-Term Management Strategy for the Placement of Dredged Material in the San Francisco Bay Region (USACE et. al 2001) presents long-term dredging, disposal and beneficial reuse strategy for the San Francisco Bay area. An objective of the plan was for LTMS agencies to apply their policies in a coordinated and comprehensive manner.
Illinois	For dredging projects with discharges to waters of the State or hydraulic dredging projects the Facility Evaluation Unit-Permit Section, Division of Water Pollution Control of Illinois EPA makes placement decisions. Testing procedures are contained within 35 Ill. Adm. Code 395. Either the Facility Evaluation Unit-Permit Section or the Permit Section of Illinois EPA's Bureau of Land make determinations for other dredging projects. No permit is required for upland beneficial use of mechanically dredged materials that are placed away from surface water and that do not discharge to waters of the State. (IMTS 2020)
Iowa	A joint federal-state dredging permit process requires physical and chemical characterization for water quality certification where projects will discharge dredged material to waterways. Most projects for habitat restoration and environmental cleanup manage dredged material in confined disposal facilities or upland landfills. Iowa Administrative Code 567-108 Beneficial Use Determinations (ITMS 2020) allows for sediment beneficial use as fill or alternative cover provided it is stabilized to meet criteria.
Indiana	Indiana Department of Natural Resources (IDNR) and Department of Environmental Management (IDEM) use the policy document, Remediation Closure Guide (WASTE-0046-R1-NPD), and statutory closure guide IC 13-12-3-2 and IC 13-25-5-8.5 are used to make beneficial use decisions. Site specific screening levels that incorporate institutional and engineering controls or generic screening levels may be used. (GLDT 2020; IMTS 2020)
Kentucky	Beneficial use is a permit-by-rule activity from the Kentucky Energy and Environment Cabinet Division of Water. (IMTS 2020).

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

Ohio	The Ohio Environmental Protection Agency Division of Material and Waste Management (DMWM), Beneficial Use Unit is the agency responsible for upland beneficial use. Placement for dredged material from harbor and navigation dredging activities is regulated under Ohio Administrative Code Chapter 3745- 599. Other beneficial use requests are considered on a project-specific basis. (GLDT 2020)
Oregon	Oregon Department of Environmental Quality has standing beneficial use determinations (BUD) for dredged sediment approved by the department's water quality program for unconfined in-water placement based on chemical screening. Dredged sediment that is not approved by the department's water quality program for in-water placement that are below risk-based screening levels or natural background managed in accordance with state requirements consistent with Chapter 340 Division 41. Other determinations are made on a case-by-case basis.[1]
Pennsylvania	Upland beneficial use evaluations use generic 10-5 risk-based soil screening concentrations, which follows USEPA toxicity criteria hierarchy for protection of human health. Pennsylvania Department of Environmental Protection: Administrative Code, 2011, Chapter 250, Administration of Land Recycling Program. (GLDT 2020)
Maryland	The Maryland Department of the Environment guidance document Innovative Reuse and Beneficial Use of Dredged Material (2019) includes regulations and permitting requirements for beach nourishment and marsh creation. The guidance also provides a risk-based framework that incorporates chemical concentrations, exposed populations, exposure duration and pathway(s) for other beneficial uses for which regulation and permitting requirements are less prescriptive.
Michigan	Michigan Department of Environment, Great Lakes, and Energy (EGLE) is the regulating agency for dredged material placement and evaluation. Uncontaminated dredged material (or greater than 90% sand) and dredged material that meets the Part 201, Environmental Remediation, generic residential criteria are not regulated solid wastes and can be used upland, without restriction from the solid waste regulations (Tittabawassee and Saginaw Rivers excepted). Otherwise, materials may be used upland under authorized restrictions or are required to be managed as solid waste.
Mississippi	Coastal Wetlands Protection Law Act, Title 49, Chapter 27, Mississippi Code § 49-27-61 requires beneficial use if greater than 2,500 cy will be removed, if BU sites are available, and materials are compatible. The guidance document, Master Plan for Beneficial Use of Dredged Material for Coastal Mississippi (CH2MHill 2011) identifies priority coastal zone BU areas, outlines permitting regulations, and provides testing guidance. In general, permits require upland confinement of dredged material unless otherwise permitted.
Missouri	Most dredged material is placed in-water; however, the Department of Natural Resources permits beneficial use for habitat restoration, mine reclamation, agriculture, and landfill generation. A state "MOG698" permit is required for placement of dredged material in a disposal facility. (IMTS 2020)
Minnesota	Dredged material is categorized by the Minnesota Pollution Control Agency into one of three management levels depending on sediment characterization results, including grain size and chemistry screened against Soil Reference Values. Dredged material may require a State Disposal System (SDS) permit for beneficial use, depending on sediment source and project volume. Other Projects in unspecified areas should follow the guidance, Managing dredge materials in the State of Minnesota (2014).
New Jersey	New Jersey gives priority to acceptable beneficial uses of dredged material over other dredged material management/disposal alternatives (Maher et al. 2013). Testing protocols for projects vary with dredge volume, sediment physical and chemical characteristics, and the type and nature of the beneficial use. Guidance is provided for the evaluation of raw dredged material and the creation and usage of processed dredged material (PDM).
New York	An upland BUD will be made for dredged material under New York State's Department of Environmental Conservation Solid Waste Management Facilities Regulations, 6 NYCRR Part 360. The BUD provides for a specified use at a location as fill, cover, topsoil, aggregate, or to allow its sale or distribution for these uses. The more protective of the soil cleanup objectives (SCOs) in 6 NYCRR Part 375, Environmental Remediation Programs Regulations, are used to evaluate dredged material. The Identification and Listing of Hazardous Wastes under 6 NYCRR Part 371 may also be relevant. (GLDT 2020)
Texas	The restoration of topsoil through placement of dredged solids is encouraged (TWDB 2005). Texas General Land Office issues leases, easements, and permits for projects on state-owned coastal lands. Additionally, Texas Parks and Wildlife Department is responsible for the management and protection of marl, sand, gravel, and shell located within the tidewater limits, with the exception of oil and gas lease activities, or navigation projects. Wetland loss is considered an opportunity for beneficial use.

Table 4. Select Examples of Beneficial Use State Guidance and Regulations Summary

Washington	Dredged Material Evaluation and Disposal Procedures User Manual (USACE et al. 2018) provides an interagency approach to the management of dredged material in Washington State. The manual is a framework for characterizing proposed dredged material for unconfined aquatic disposal suitability and characterizing proposed post-dredge surface material for compliance with state regulations. The Washington State Sediment Management Standards (SMS) and Model Toxics Control Act (MTCA) are used to evaluate sediment quality for non-navigation projects.[1]
Wisconsin	The Wisconsin Department of Natural Resources promotes the use of dredged material that minimizes harm to the environment and benefits municipal construction projects. Sampling protocols are provided in Wis. Admin. Code 347.01. Risk-based soil screening criteria are used to evaluate proposed beneficial use project. (GLDT 2020, IMTS 2020)

[1] In addition, the Sediment Evaluation Framework (SEF) for the Pacific Northwest describes procedures for the risk-based sediment assessment of potential contaminant-related environmental impacts of dredging and the aquatic placement of dredged material in inland waters and the disposal of dredged material in ocean waters. The SEF guidance was developed for the Pacific Northwest region, including the States of Washington, Oregon and Idaho.

determinations. The USEPA guidance allows flexibility to integrate within existing evaluation frameworks and regulatory programs but acknowledges these factors, public perceptions, and market conditions may factor into the final determination.

Working with the Federal Standard to Select the Least-Costly Dredge Alternative

Local sponsors and stakeholders are common advocates for beneficial use. Cost sharing between the federal government and non-federal partners is common for most federally-funded dredging projects. Prior to revised wording in Section 125 of the *Water Resources Development Act of 2020 (WRDA2020)*, the Federal Standard prohibited USACE from paying for alternatives associated with maintenance dredging other than the least-cost acceptable option, unless another entity (e.g., a local sponsor, state, or other entity) paid the difference (USEPA 2021a). The Federal Standard defined the costs associated with maintenance dredging projects but did not dictate the disposal or placement option for a project (GLDT 2020). Historically, this standard imposed substantial cost constraints on beneficial use projects when beneficial use alternatives were more costly than conventional disposal methods. New-work dredging projects may be held to a different standard based on national economic development (NED) benefits. The differing approaches to regulation complicate the assessment of dredged material for a given use, which can result in an unwillingness on the part of project proponents to fully consider beneficial use. Regulatory factors that would need to be harmonized to expand beneficial use were summarized in GLDT (2020). It states that, to avoid unnecessary additional testing or duplication of testing, WRDA 2020 modified the Federal Standard verbiage, requiring that a water resources development project:

> *…fully identifies and analyzes national economic development benefits, regional economic development benefits, environmental quality benefits, and other societal effects.*

Essentially, WRDA 2020 requires new projects to consider the extent to which a project *produces benefits that are in excess of the estimated costs*. The new approach may be the byproduct of WRDA 2016 (Section 1122), which created a beneficial use pilot program, initially allowing ten maintenance dredging projects across the country that could reflect broader societal values while not having to be constrained by the Federal Standard. WRDA 2020 fosters the same consideration of natural and nature-based alternatives as structural alternatives and allows USACE to consider other environmental or economic benefits not directly related to the dredging project. Historically, without additional funding for channel maintenance to cover increased costs, USACE Districts have been reluctant to embrace higher cost alternatives even if the net benefits are greater. The impact of this new Federal Standard language has yet to be realized, though it is not difficult to imagine its transformational nature on sediment management decisions.

Maher et al. (2013) argues for upland disposal sites that "the reality of disposal options without beneficial use is that they are not sustainable; by definition any disposal site will eventually fill up." Maher et al. (2013) proposed a different standard of evaluation for the Federal Standard based on "sediment value" or the "value of a cubic yard." This value would factor in not only the navigational benefit, but the cost of sediment management and cost offsets realized by the beneficial use beneficiary as well. This approach leads to an evaluation of the sustainability of placement options that may be the most appropriate way to assess which alternative is "least costly" (i.e., not only least expensive, but also the least costly to the beneficiary and to the environment).

Public and Agency Acceptance

An important step in successfully implementing beneficial use on a wider scale is through educating the public and regulators on sediment management and beneficial use risks and benefits. There is a general perception that the public has a relatively poor understanding of environmental risks resulting from the dredged material use (PIANC 2009). Some jurisdictions classify dredged material as "waste," regardless of source, content, or quality. Consequently, waste management regulations and restrictions apply, which increases scrutiny and permitting requirements because the dredged material is assumed to be harmful. The perception that dredged material is a waste to be disposed, rather than a resource to be used purposefully, does not favor beneficial use. In contrast, other jurisdictions classify dredged material as a "mineral resource." While this puts dredged material in a more positive light, mineral resource regulations often require market prices for mineral uses, which may also inhibit beneficial use.

The perception of dredged material as waste also feeds into the "NIMBY" (not in my back yard) syndrome that sometimes pervades the permitting process. As long as the perceptions of regulators and communities are negative toward dredged material, it will be a challenge to grow the practice of beneficial use. Raising public awareness will improve the stakeholder commitment of resources (USEPA and USACE 2007b). Beneficial use diverts cleaner sediment from filling limited disposal (e.g., CDF, landfill) space, so that space can be conserved for material that is not able to be used beneficially, including contaminated material. Also, the appropriate beneficial use of dredged materials is consistent with USEPA's Sustainable Materials Management program (USEPA 2016b).

New Jersey Department of Transportation (NJDOT) and the New Jersey Department of Environmental Protection (NJDEP) have worked together since 1996 to implement a dredged material management plan inclusive of a beneficial use policy without compromising economic development or environmental protection (Maher et al. 2013). Economic advantages include turning sediment into feedstock to produce blended cement and a manufactured aggregate material by using processes that simultaneously remove contaminants to safe levels (Maher et al. 2013). Processed dredged material is more widely used than treated dredged material in NY/NJ Harbor. Millions of cubic yards have been processed and placed upland in the past two decades. This has resulted in the remediation and development of numerous contaminated sites. Since Superstorm Sandy in 2012, clean navigational dredged material has been used to improve coastal resiliency and to restore and enhance habitat.

Maryland Department of Environment (MDE) published guidance in 2019 on the innovative uses of dredged sediment such as soil amendments, engineered fill, or to create aquatic habitat. The guidance document arose out of the Dredged Material Management Act of 2001, which prioritized beneficial use and innovative reuse alternatives over other traditional dredged material placement methods.

Both New Jersey and Maryland are examples of the synergy between cultural acceptance of beneficial use, public and agency acceptance, and the role of legislation to support and even promote beneficial use. Wider implementation of policies to promote beneficial use could have a large impact on public acceptance and the proportion of sediment that can economically be dredged, beneficially used, and diverted from landfill placement (Figure 2).

EXPANDING BENEFICIAL USE OPPORTUNITES

Despite the successful history of beneficial use, the increasing constraints on disposal facilities, and the increased recognition of sediment value, disposal of dredged material continues to be the default approach. However,

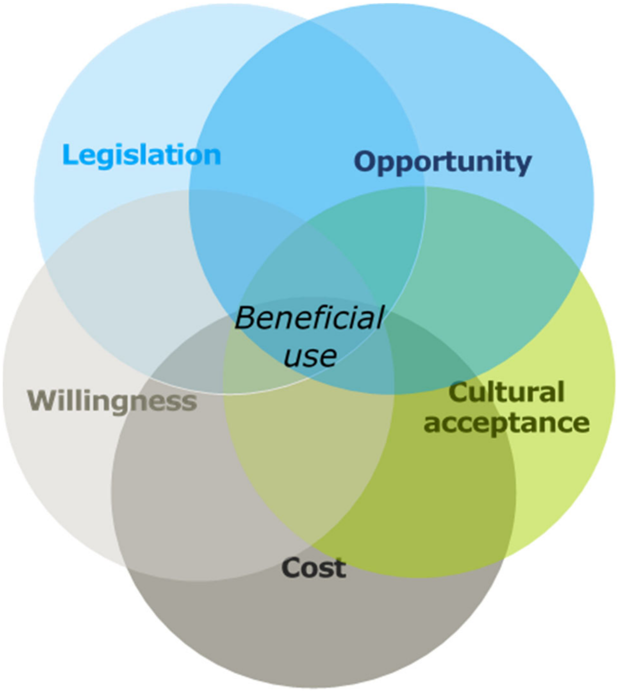

Figure 2. Overlap of critical dredged material components required to facilitate increased beneficial use.

identifying and implementing solutions to the existing economic, logistical, and institutional constraints will facilitate the transition from dredged material disposal to beneficial use. The viable solutions will need to be amendable to a variety of site-specific and project-specific conditions, such as maintenance dredging projects versus new work, uncontaminated material versus highly-contaminated material, and USACE-led projects versus non-USACE projects.

Overcoming Cost Barriers

For the beneficial use of dredged material to be competitive against disposal options, social, sustainability, and environmental factors should be considered in addition to cost, including cost offsets realized by the beneficial use customer. By conducting a more comprehensive and holistic assessment, the net benefits beyond direct and immediate monetary cost savings are evaluated. For example, the beneficial use option may result in increased business and employment within a location and provide long-term environmental benefits if the dredged material is used to improve habitats, such as shoreline restoration or wetland creation. This approach is also consistent with the EWN® principles. These are benefits and values that need to be considered in a long-term comprehensive evaluation and are often not realized in the upfront cost evaluation when comparing beneficial use against sediment disposal.

Many beneficial use projects today incorporate three success pillars of sustainability - economic value, social gain, and environmental benefit (CEDA 2019). The three pillars of sustainability are shaping how beneficial use projects are being implemented successfully. Examples of how the three pillars are being implemented in practice include: coupling dredged sediment supply and demand (e.g., Kleirijperij, Mud Motor in the Netherlands); making advancements in adaptive management (e.g., Markerwadden in the Netherlands); evaluating project value through quantification of ecosystem services (e.g., Prins Hendriks Dike, Horseshoe Bend in the US); acknowledging the role of dredgers, dredging, and dredged sediment to reduce CO_2 emissions and sequester carbon; and positioning dredging projects in ways that fit within a circular economy as prescribed in recent legislation driving sediment use (e.g., Netherlands) (Bridges et al. 2014; CEDA 2019; van Eekelen and Bouw 2020).

Beneficial use in the US is highest where economically advantageous partnerships exist, projects have strong local advocacy, and sediment characterization is consistent with available beneficial use options. Historically, successful beneficial use projects have typically been cost neutral for the dredging project while providing environmental benefits and/or increasing sustainability. Moving forward, increased focus on value (WRDA 2020) allows new projects to consider social and environmental benefits in addition to costs.

Overcoming Barriers through Policy

Policy established at the federal, state, and local levels can further support the establishment, coordination, and implementation of beneficial use projects. Historically, the Federal Standard had required USACE dredging projects to select the least costly dredged material disposal or placement alternative that meets all federal environmental requirements. This requirement has often discouraged sediment beneficial use projects due to cost constraints. For beneficial use to be applied more widely, policy needs to be developed or updated to support beneficial use application. Such policy changes are already being realized through WRDA 2020, which emphasizes project benefits by stating that the suitability of dredged material for a full range of environmental, economic, and societal beneficial uses should be considered.

At state and local levels, consistent and clear policy and the development of holistic sediment and dredged material management plans can foster a beneficial use mind-set and encourage the implementation of beneficial use projects. States could more actively recognize the additional benefits of dredging and dredged material, beyond navigation. For example, states could establish funding mechanisms to pay the additional costs of beneficial use of dredged materials in recognition of the broader economic gains by the state or local area, such as protection from coastal erosion/sea level rise or habitat and recreation enhancements. Such policy and long-term management plans need to be drafted with input of multiple stakeholders, established, and then implemented. These economic-related policies also facilitate overcoming the cost barriers previously discussed.

Overcoming Barriers through Partnerships

Consistent engagement among the various stakeholders has been demonstrated to be an effective tool in overcoming barriers to beneficial uses. Open communication and established relationships encourage stakeholders to ask questions, express their viewpoint, and understand other viewpoints. Generally speaking, beneficial use is more complicated than traditional placement options. Because beneficial use involves goals beyond just dredged material placement capacity, stakeholders want to suggest desired outcomes and share concerns with respect to their interests. A mechanism and venue for stakeholders to discuss their concerns and work collaboratively towards a consensus creates an opportunity to streamline beneficial use projects. Partnerships across multiple stakeholders can assist in upfront planning and coordination of project schedules. For example, reducing gaps in the timing between dredging projects and beneficial use projects ultimately reduces dredged material storage costs and overall project costs. Several outstanding examples of inter-agency, multi-stakeholder beneficial use partnerships exist; a few of these are provided below.

- At the USACE Portland District, the Portland Sediment Evaluation Team includes membership from USEPA Region 10, Oregon Department of Environmental Quality, Washington Department of Ecology, US Fish and Wildlife Service, and National Marine Fisheries Service and has a 15-year history of engagement that is crucial in moving projects forward (McMillan and Holm 2020).

- The San Francisco Bay Long Term Management Strategy includes USEPA, the USACE, the San Francisco Regional Water Quality Control Board, the San Francisco Bay Conservation and Development Commission and other stakeholders in the region. The goal of this group is to develop new approaches to dredging and dredged material management in the San Francisco Bay region through various objectives, such as conducting dredged material disposal in the most environmentally sound manner; maximizing the use of dredged material as a resource; and establishing a cooperative permitting framework for dredging and dredged material disposal (USEPA 2019).

- The USACE Mobile District participates in the Project Implementation Committee of the Mobile Bay National Estuary Program (http://www.mobilebaynep.com/). This interagency group assesses needs and resources, identifies and plans projects, seeks citizen input, and determines necessary tasks and roles for member agencies. The group's success is attributed to its ability to move such projects forward, the open communication focused on consensus, and a realization that the common goal is to implement successful beneficial use (Mroczko 2020).

- The New York/New Jersey Harbor Regional Dredging Team supports dredging projects in the region by developing comprehensive regional dredged material management plans that identify short-term and long-term disposal alternatives, consider methods to reduce dredging, and maximize beneficial use of dredged materials (USEPA 2021b). The team includes members from USEPA, USACE, New York Department of Environmental Conservation, New Jersey Department of Environmental Protection, the Port Authority of New York and New Jersey, and the New Jersey Department of Transportation.

- In the USACE New Orleans District, beneficial use is often the "least cost" option. Working groups previously focused on raising awareness and educating stakeholders on beneficial use practices and outcomes. Such working groups are no longer necessary to move beneficial use forward in the region. Economics, advocacy, and previous trust-building engagement has moved the practice from being unique to commonplace (Corbino 2020).

PROJECT CASE STUDIES

Case studies of successful beneficial use projects are presented below for the Seven Mile Island Innovation Laboratory and Drake Wilson Island.

Seven Mile Island Innovation Laboratory (SMIIL)

The USACE Philadelphia District, the State of New Jersey, and The Wetlands Institute implemented a collaboration framework by developing SMIIL along the New Jersey Coast (https://wetlandsinstitute.org/smiil/). The object of SMIIL is to transform the concept of dredged material as waste to dredged material as a resource, and to advance and improve dredging and marsh restoration techniques through innovative research, collaboration, knowledge sharing, and practical application consistent with RSM and EWN® principles.

Coastal New Jersey marshes are at risk due to sea level rise, sediment starvation, and marsh platform degradation. These influences contribute to reduced marsh habitat value, reduced coastal resilience, and increased coastal flooding risk. Sediment has become increasingly recognized as an essential resource for the continued health of marsh habitat and for maintaining/increasing coastal resiliency in the face of sea level rise. At issue was how best to advance the beneficial use practice to build on four marsh restoration and habitat creation projects using sediment from the New Jersey Intracoastal Waterway. The SMIIL approach was a marked departure from the traditional practice of dredging and placing the material in confined disposal facilities cut off from the natural sediment system.

The boundaries of the 24-square mile SMIIL were chosen due to the presence of existing and historic dredged material placement sites, confined disposal facilities, federal and state channels including the New Jersey Intracoastal Waterway, and extensive tidal marshes. The project goals focus on maintaining safe navigation channels while retaining dredged sediment in the system to benefit natural ecosystems and coastal communities. A working group was formed and continues to meet to identify and refine both short- and long-term objectives. Monitoring is ongoing and includes the collection of sediment, hydrodynamic, wetland vegetation, and local bird data to inform baseline conditions, initial designs, and beneficial use placement strategies that mimic natural processes and minimize unintended adverse impacts. Adaptive management strategies are in place to support long-term sustainability of dredging and coastal resilience in the region. Lessons learned from implementing this strategy are subsequently being applied in other areas of the SMIIL.

Drake Wilson Island

The USACE is making strides coordinating internally to improve communications across navigation and dredging programs. Such internal coordination enhances the ability of the USACE to align resources and coordinate across programs to improve efficiencies and communications about beneficial use projects. One effective way to promote beneficial use is to document and communicate how both present and past beneficial use projects have been implemented successfully. Drake Wilson Island is an example of a successful historic beneficial use project. The 5-ha marsh created on Drake Wilson Island in Apalachicola Bay (FL) was described by Newling and Landin (1985) then revisited in 2019 via funding by the USACE DOER program.

Prior to 1976, the island was an unmanaged dredged material placement area with low habitat value. In early 1976, sandy clay dredged material from Apalachicola Bay was used to construct dikes around the saline intertidal environment which was subject to long wind fetches and strong currents. Coarse-grained sandy dredged material from the adjacent Two-Mile Federal Channel was placed within the dikes to raise the elevation. Smooth cordgrass and saltmeadow cordgrass were planted between December 1976 and September 1977 to encourage native species establishment.

The marsh habitat creation project provided valuable habitat while preventing erosion into the adjacent navigation channel. Increased habitat diversity was observed relative to adjacent traditional dredged material placement locations. Ninety-seven plant species were observed in 1982 when monitoring was performed to assess the success of this beneficial use project. Newling and Landin (1985) observed various wildlife species using the island, the most notable being wading birds and a large clapper rail population. Figure 3 shows a thriving marsh habitat still in place on Drake Wilson Island as of 2019. Five distinct habitat types were observed on Drake Wilson Island as part of a retrospective monitoring study investigating long-term benefits of historical USACE beneficial use projects (Figure 4). Volume 2 of the Engineering With Nature Atlas provides additional information on the current status of the Drake Wilson Island beneficial use site (https://ewn.el.erdc.dren.mil/atlas.html).

Figure 3. Drake Wilson Island on the north shore of Apalachicola Bay, FL, ca. 2019 (photo credit Nathan Beane USACE ERDC)

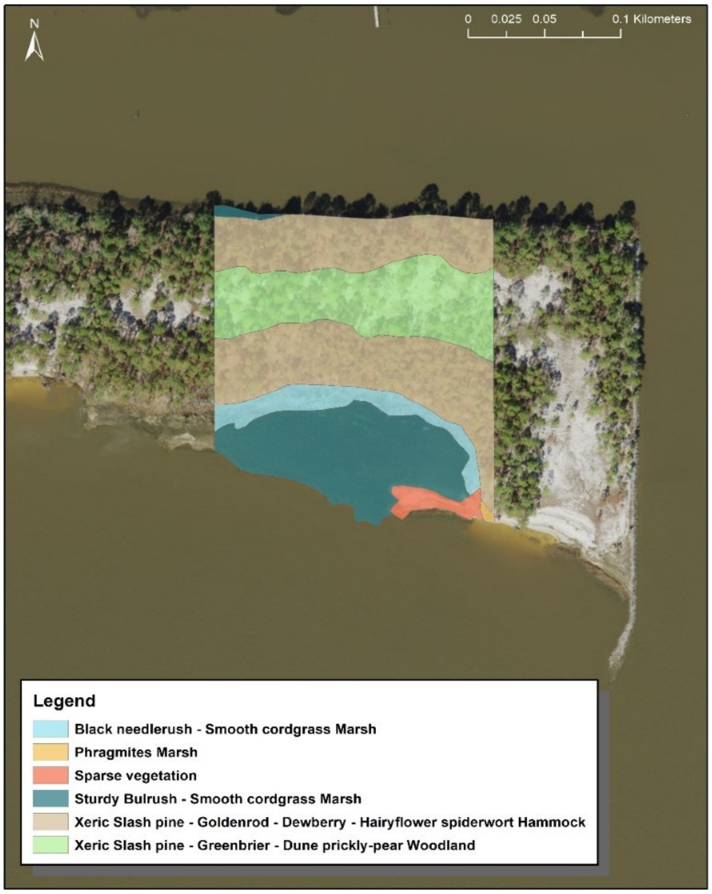

Figure 4. Five distinct habitat types on Drake Wilson Island identified in 2019 as part of a retrospective monitoring study investigating long-term benefits of historical USACE beneficial use projects.

CONCLUSIONS

Increased costs, schedule risks, permitting burdens, potential liability, logistical incompatibilities, and antiquated government policies result in disposal of large volumes of potentially valuable dredged sediments despite many beneficial use opportunities. Recently assembled data show 30 to 40% of dredged material from navigation dredging in the US is used beneficially. The consistency of this percentage over decades suggests the rate of beneficial use will not increase substantially without overt changes that address deterrents.

Historically, for USACE maintenance dredging projects, the Federal Standard is often cited as a rationale for choosing conventional disposal methods over beneficial use when costs for beneficial use exceed the cost of disposal. To increase beneficial use, a more holistic cost evaluation process that considers project value, including societal and ecological benefits, future cost avoidance, and a broader evaluation of cost impacts is needed to provide a more accurate comparison between disposal and beneficial use options. Cost estimates need to account for costs associated with reduced disposal volume capacity, and cost "off-sets" or "avoidance" when the purchase of raw materials is avoided by using dredged material. In addition, the environmental, recreational, and social benefits from habitat restoration/creation, coastal resiliency, and other such benefits afforded from beneficial use should be quantified. Tools like a net-environmental benefit analysis (Efroymson et al. 2003) or ecosystem services analysis (TEEB 2010) can be used to provide a more holistic quantification of value.

Large-scale, long-term beneficial use plans and policies are a potential tool to reduce schedule risks frequently associated with permitting requirements and the burden of obtaining additional permits. Beneficial use projects that provide quantifiable ecological improvements often address waterbody or watershed-wide concerns. These projects are likely candidates for programmatic permits that would reduce project-specific burdens and schedule risks. WRDA 2020 already prioritizes beneficial use over disposal. Additional federal legislation and policy that reduce liability concerns and remove dredged material from characterization as a waste could open additional beneficial use opportunities. Similar legislation at local, regional, and state levels would be even more effective, and could also be used to establish funding mechanisms to pay the additional costs of beneficial use in recognition of the overall, holistic economic advantages in the area.

In many cases, modest adjustments to navigation dredging schedules could significantly reduce sediment volume and project timing mismatches. Making these adjustments without impeding navigability will require up front planning and coordination. USACE and other project sponsors should actively pursue local and regional beneficial use opportunities as part of their local and regional dredged material management plans. These projects could significantly expand placement capacity, which increases the security of future dredging projects, but are often omitted from formal management plans because their timing and capacities are uncertain. Beneficial use working groups, regional dredging teams, and established regional sediment management plans and dredged material management plans have been instrumental in overcoming these schedule constraints or disparities in some areas.

Disposal of dredged material continues to be the standard practice in many areas of the country, such that significant advocacy, promotion, and support of beneficial use projects is needed to bring them to fruition. Local and regional beneficial use and other sediment management groups have increased the rate of beneficial use in some areas of the US, demonstrating how advocacy, collaboration and communication can result in the successful implementation of beneficial use projects. Active communication among stakeholders, including the private sector, non-government organizations, and local, regional, state, and federal regulators, effectively reduces impediments, and facilitates cost sharing often required to overcome increased costs associated with beneficial use. While USACE and their partners, as primary proponents of US navigation dredging, are in a strong position to foster these interdisciplinary groups and develop agency policies that support sustainable navigation infrastructure through increased beneficial use opportunities, this is not only USACE's burden.

Changes to federal and local policy, evaluating sediment disposal options based on environmental, economic and sustainability criteria, and the establishment of multi-stakeholder dredged material management teams at a local level are tools to increase the rate of beneficial use of dredged material. The development of location-specific dredge material management plans can be used to set expectations for the use of dredged material, which can in turn facilitate the coordination of dredge and beneficial use project schedules, establish funding sources to support dredging and beneficial use, and promote long-term societal and ecological benefits. Long-term monitoring of beneficial use projects with an environmental focus is necessary for understanding the changes in the health of coastal habitats that provide essential coastal defense, and for evaluating the overall success and effectiveness of the projects and the beneficial use paradigm.

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REFERENCES

Bridges, T.S. (2018). "Engineering with Nature: Toward Sustainable Systems," Western Dredging Association Gulf Coast Chapter Meeting, November 2018, New Orleans, LA. https://www.westerndredging.org/index.php/information/presentations-library/category/337-2018-in-new-orleans-louisiana?download=1773:national-project-perspectives-on-natural-nature-based-defenses

Bridges, T.S., Lillycrop, J., Wilson, J.R., Fredette, T.J., Suedel, B., Banks, C.J., and Russo, E.J. (2014). "Engineering with Nature Promotes Triple-Win Outcomes," Terra Et Aqua. 135:17-23.

Bridges, T.S., Bourne, E.M., King, J.K., Kuzminski, H.K., Moyniham, E.B., and Suedel, B.C. (2018). "Engineering with Nature®: An Atlas," ERDC/EL SR-18-8. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/27929.

Central Dredging Association (CEDA). (2019). "Sustainable Management of the Beneficial Use of Sediments," http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2019-05-BUS-ip.pdf.

CEDA (2021). https://www.dredging.org/ceda-working-group-on-beneficial-use-of-sediment-wgbu/203. Accessed January 2021.

CH2MHill. (2011). "Master Plan for Beneficial Use of Dredged Material for Coastal Mississippi," Gulf of Mexico Alliance/Habitat Conservation and Restoration Team, National Oceanic Atmospheric Administration Cooperative Award #NOAA GOMA 2003.

Childs, J. L. (2015). "Dredged Material Management Categories for Tracking Beneficial Use," DOER Technical Notes Collection. ERDC TN-DOER-R22, US Army Engineer Research and Development Center, Vicksburg, MS:. https://apps.dtic.mil/docs/citations/ADA619013.

Corbino, J. (2020). USACE New Orleans District. Personal communication. June 30, 2020.

De Vriend, H.J. and Van Koningsveld, M. (2012). "Building with Nature: Thinking, Acting and Interacting Differently," EcoShape, Building with Nature, Dordrecht, the Netherlands.

Efroymson, R.A., J.P. Nicolette, G.W. Suter II. (2003). "A Framework for Net Environmental Benefit Analysis for Remediation or Restoration of Petroleum-Contaminated Sites," Oak Ridge National Laboratory. ORNL/TM-2003/17.

Great Lakes Dredging Team (GLDT). (2020). "Environmental Evaluation and Management of Dredged Material for Beneficial Use: A Regional Manual for the Great Lakes," November.

Illinois Marine Transportation System (IMTS). (2020). "Neighbor State Dredging Review," Draft, February.

Kennish, M. (2002). "Environmental Threats and Environmental Future of Estuaries*,"* Environmental Conservation, 29(1), 78-107. doi:10.1017/S0376892902000061

Kiel, K.G. (2018). "*Beneficial Use of Dredge Material across the Great Lakes: Policies, Environmental Evaluations, and Projects*." Air and Waste Management Association Annual Seminar, January 2018, https://awmanfs.wildapricot.org/resources/Seminar/2018/Karen%20Keil.pdf.

Laboyrie, H.P., Van Koningsveld, M., Aarninkhof, S.G.J., Van Parys, M., Lee, M., Jensen, A., Csiti, A. and Kolman, R. (2018). "Dredging for Sustainable Infrastructure," CEDA/IADC, The Hague, The Netherlands.

Maglio, C., Das, H., & Fenner, F. (2020). "Modal Grain Size Evolution as it Relates to the Dredging and Placement Process - Galveston Island, Texas." Coastal Engineering Proceedings, (36v), papers.7. https://doi.org/10.9753/icce.v36v.papers.7

Maher, A., F. Jafari, W.S. Douglas, and J. Pecchioli. (2013). "The Processing and Beneficial Use of Fine-Grained Dredged Material- A Manual for Engineers," 146 p., New Jersey Departments of Transportation (NJDOT) and Environmental Protection (NJDEP).

Maryland Department of the Environment. (2019). "Innovative Reuse and Beneficial Use of Dredged Material Guidance Document," December 2019.

McLellan, T.N., Maurer, H., Fudge, B., and Heilman, D.J. (2001). "A Decade of Beneficial Use Brazos Island Harbor, Dredging," Proceedings of the WEDA XXI Technical Conference and Texas A&M University 32nd Annual Dredging Seminar, Houston, Texas, June 25-27, 2001.

McMillan, J. and J. Holm. (2020). USACE Portland District. Personal communication. April 13, 2020.

Minnesota Pollution Control Agency. (2014). “Managing dredge materials in the State of Minnesota,” April 2014.

Mroczko, D. (2020). USACE Mobile District. Personal communication. May 7, 2020.

National Research Council. 1994. Restoring and Protecting Marine Habitat: The Role of Engineering and Technology. Washington, DC: The National Academies Press. https://doi.org/10.17226/2213.

Newling, C. J. and M. C. Landin. (1985). “Long-Term Monitoring of Habitat Development at Upland and Wetland Dredged Material Disposal Sites, 1974–1982.” U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, U.S.A. TR D-85-5. NTIS No. AD-A159 106.

Pandal, A.P. (1998). "Beneficial Use of Dredged Material In Protecting the Eroding Coast - A Case Study," Proceedings of the 15th World Dredging Congress, Las Vegas, NV, July 1998.

PIANC. (1992). “Beneficial Uses of Dredged Material: A practical guide,” Report of PIANC Working Group 19, PIANC, Brussels, Belgium.

PIANC. (2008). “Working with Nature,” PIANC Position Paper. October 2008, Revised January 2011, Brussels, Belgium.

PIANC. (2009). *“Dredged Material as a Resource: Options and Constraints,”* EnviCom Working Group 104: PIANC, Brussels, Belgium.

PIANC. (2018). “A Guide for Applying Working with Nature to Navigation Infrastructure Projects, EnviCom,” Working Group 176: PIANC, Brussels, Belgium.

PIANC. (2020). “Climate Change Adaptation Planning for Ports and Inland Waterways,” EnviCom. Working Group 178: PIANC, Brussels, Belgium.

San Francisco Bay Regional Water Quality Control Board (SFBRWQCB). (2000). “Beneficial Reuse of Dredged Materials: Sediment Screening and Testing Guidelines,” May, 2000.

Statista. (2020). https://www.statista.com/statistics/376643/industrial-sand-and-gravel-production-in-the-us. Accessed on September 23, 2020.

TEEB. (2010). The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis of the approach, conclusions, and recommendations of TEEB.

Texas Water Development Board (TWDB). (2005). Dredging vs. New Reservoirs Contract #2004-483-534

United Nations. (2019). *The Sustainable Development Goals Report*. New York. 60 pp. https://unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

U.S. Army Corps of Engineers (USACE). (1987). *Beneficial Uses of Dredged Materia*l. EM 1110-2-5026. Washington, DC. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5026.pdf

USACE. (2003). “Evaluation of Dredged Material Proposed for Disposal at Island, Nearshore, or Upland Confined Disposal Facilities—Upland Testing Manual,” Technical Report ERDC/EL TR-03-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

USACE. (2015). “Dredging and Dredged Material Management,” Engineer Manual 1110-2-5025. U.S. Army Corps of Engineers, Washington, DC.

USACE. (2020). Regional Sediment Management Database, https://rsm.usace.army.mil/BUDB. Accessed 11 February 2021.

USACE (2021). https://budm.el.erdc.dren.mil. Accessed January 2021.

USACE, USEPA, San Francisco Bay Conservation and Development Commission, and SFBRWQCB (2001). “Long-Term Management Strategy for the Placement of Dredged Material in the San Francisco Bay Region.” https://www.spn.usace.army.mil/Portals/68/docs/Dredging/LMTS/entire%20LMTF.pdf.

USACE Navigation Data Center (2021). "Actual Dredging Cost Data for 1963-2018." https://publibrary.planusace.us/#/document/6db4e2a5-20d7-4821-d598-8faf9cd66c6e; federal and industry cost corrected to 2018 dollars. Accessed January 2021.

U.S. Environmental Protection Agency (USEPA). (2016a). A methodology for evaluating beneficial uses of industrial-non-hazardous secondary materials. Office of Resource Conservation and Recovery. EPA 530-R-16-011.

USEPA. (2016b). Beneficial Use Compendium: A collection of resources and tools to support beneficial use evaluations. Office of Resource Conservation and Recovery. EPA 530-R-16-009.

USEPA. (2019). San Francisco Bay Long Term Management Strategy for Dredging. https://www.epa.gov/ocean-dumping/san-francisco-bay-long-term-management-strategy-dredging#:~:text=The%20San%20Francisco%20Bay%20Long,new%20approach%20to%20dredging%20and. Accessed January 2021.

USEPA. (2021a). “The Role of the Federal Standard in the Beneficial Use of Dredged Material,” https://www.epa.gov/cwa-404/role-federal-standard-beneficial-use-dredged-material. Accessed January 2021.

USEPA. (2021b). Managing Ocean Dumping in EPA Region 2. https://www.epa.gov/ocean-dumping/managing-ocean-dumping-epa-region-2#rdt. Accessed January 2021.

USEPA and USACE. (1998). “Great Lakes Dredged Material Testing and Evaluation Manual,” 1076 p.

USEPA and USACE. (2007a). “Identifying, Planning, and Financing Beneficial Use Projects Using Dredged Material, Beneficial Use Planning Manual,” EPA842-B-07-001, October.

USEPA and USACE. (2007b). “Beneficial Uses of Dredged Materials Fact Sheet: Public Involvement and Outreach.” EPA842-F-07-001E.

Van Eekelen, E, and Bouw, M. (Eds.). 2020. Building with Nature: Creating, Implementing, and Upscaling Nature-based Solutions. Ecoshape, nai010 Publishers, Rotterdam.

Watabe, Y.; Sassa, S. (2016). “History of land reclamation using dredged soils at Tokyo Haneda Airport,” Japanese Geotechnical Society Special Publication, Volume 2, Issue 51, Pages 1784-1789, Released January 29, 2016, Online ISSN 2188-8027, https://doi.org/10.3208/jgssp.TC217-04.

Water Resources Development Act of 2016 (WRDA 2016), Pub L. No. 114-322, § 1, 130 Stat. 1645, https://www.congress.gov/114/plaws/publ322/PLAW-114publ322.pdf

Water Resources Development Act of 2020 (WRDA 2020), Pub L. No. 116-260, https://www.congress.gov/116/bills/s1811/BILLS-116s1811eah.pdf.

Wetta, R.B. and Hanson, W.H. "How does dredging effect the economy?," Proceedings of the WEDA XXXI Technical Conference and Texas A&M University 42nd Annual Dredging Seminar, Nashville, Tennessee, June 5-8, 2011.

Wong P.P. (2019). Reclamation. In: Finkl C.W., Makowski C. (eds) Encyclopedia of Coastal Science. Encyclopedia of Earth Sciences Series. Springer, Cham. doi: 10.1007/978-3-319-93806-6_254.

Yozzo, D.J., Wilber, P., Will, R.J. (2004). "Beneficial use of dredged material for habitat creation, enhancement, and restoration in New York–New Jersey Harbor," Journal of Environmental Management 73: 39–52.

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