APPENDIX F

CONVEYANCE SYSTEM HEADLOSS CALCULATIONS

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DRAFT

TECHNICAL MEMORANDUM

January 22, 2010

To: Onondaga Lake Sediment Management Intermediate Design Submittal

From: Jamie Fettig, Ajish Nambiar, and Adam Mickel; Parsons

Subject: Preliminary Slurry Pipeline Hydraulic Analysis

INTRODUCTION

As part of the remediation activities in and around Onondaga Lake, it has been proposed to dredge portions of the Lake bottom sediments. The dredged sediment slurry will be transported via an approximately 19,826 feet high-density polyethylene (HDPE) pipeline to a remote Sediment Consolidation Area (SCA) for dewatering and consolidation. Booster pump stations will be positioned along the pipeline approximately every 4000-6000 ft.

Design related activities associated with the slurry pipeline system will include a system hydraulic analysis and a sediment critical velocity analysis for the dredged slurry. The results from the two analyses will be used to select the optimal pipe size and rating, pump horsepower requirements, and slurry flow velocity requirements. The analysis will include the following components:

1. Preliminary headloss calculations and system curves;
2. Required pipeline slurry velocities; and
3. Pump power requirements.

SYSTEM ANALYSIS

The following analyses will be performed as part of the overall system hydraulic analysis:

1. Selection of the headloss calculation method;
2. System headloss calculations and system curves;
3. Slurry velocity calculations; and
4. Booster pump power requirements.

Headloss Calculations and System Curve

The approach, method, and development of the system curves are described in this section.

Method Approach

The slurry pipeline will be analyzed as a complete system (from the first booster pump to the SCA discharge) as well as individual reaches between booster pump stations. For the purposes of this package, only the system analysis will be considered. The total headloss through the system is the sum of three separate headloss components: (1) friction loss; (2) minor loss and; and (3) static headloss.

Friction Loss Calculation Method

Various methods have been used in computing the headloss for a slurry pipeline application. Many of these incorporate the effects of slurry solids on friction loss and have been empirically-derived. The following methods will be examined as a means to calculate the friction headloss for the proposed slurry pipeline:

1. Darcy-Weisbach
2. Durand
3. Newitt
4. Hazen-Williams

Darcy-Weisbach Method

The Darcy-Weisbach method of calculating friction losses in piping systems is derived via dimensional analysis and is given by Equation 1 (Equation 7.83, Herbich 2000)

$$h_f = SG_m \cdot f \frac{L}{D}\frac{V^2}{2g} \qquad \text{Eq}^{\underline{n}}\ 1$$

Where, h_f = headloss due to friction (ft.)
SG_m = specific gravity of the pumped slurry
L = length of pipe (ft.)
D = inner pipe diameter (ft.)
V = pipeline velocity (ft/sec)
g = Acceleration due to gravity (ft/sec^2)
f = Darcy-Weisbach friction factor, read from the Moody Diagram

Durand Method

The Durand method incorporates the physical properties of the slurry solids in its formula. This is accounted in the formula by introducing the sediment drag coefficient and is given in Equation 2 (Equation 7.86 Herbich, 2000):

$$h_{f,m} = 81C_v h_f \left[(SG_s - 1)\frac{gD}{V^2}(\frac{1}{\sqrt{C_D}} \right] + h_f \qquad \text{Eq}^{\underline{n}}\ 2$$

Where, $h_{f,m}$ = headloss due to friction in the slurry pipeline (ft.)
h_f = headloss due to friction in an equivalent pipe flowing with clean water (ft.)
C_v = concentration of the slurry by volume
SG_s = specific gravity of solid particles
C_D = sediment drag coefficient

Newitt Method

The Newitt method is similar to the Durand method in that it includes a term to account for the additional headloss contributed by the solids in the slurry pipeline. Specifically, the particle terminal settling velocity is factored into the Newitt calculation. The equation is given in Equation 3 (Equation 7.88, Herbich 2000):

$$h_{f,m} = h_f \left[1100C_v (SG_s - 1)\frac{gD}{V^2}\frac{v_t}{V} + 1 \right] \qquad \text{Eq}^{\underline{n}}\ 3$$

Where, v_t = terminal particle settling velocity (ft/sec)

Hazen-Williams Method

The Hazen-Williams equation is an empirically-derived equation and is given in Equation 4:

$$h_f = \frac{4.57L}{C^{1.853}D^{4.87}}Q^{1.852} \qquad \text{Eq}^{\underline{n}}\ 4$$

Where, C = Hazen-Williams roughness coefficient
Q = System flowrate (ft^3/sec)

The roughness coefficient is an empirical constant that describes the pipe and fluid travelling through the system. For fluids containing solids, this coefficient can be read from plots, such as from Turner, Figure 7.31, Herbich, 2000.

The headloss of an equivalent pipe flowing with clean water can be calculated via any headloss equation. For this analysis the Hazen-Williams method will be applied to calculate the clean water headloss for the slurry pipe headloss calculation.

Minor Losses

The minor losses through the system will be quantified as fractions of velocity head, according to Equation 5 (Equation 7.94, Herbich).

$$h_l = k_l \frac{V^2}{2g} \qquad \text{Eq}^{\underline{n}}\ 5$$

Where, h_l = Total minor headloss
k_l = Total minor loss coefficient through reach (sum of individual minor loss coefficients)

This approach will be used when calculating the minor losses throughout the hydraulic analysis. During this analysis, three types of minor losses were considered and were obtained from Table 2.6, Haestad Methods, 2003:

1. Wide-radius bend (k_l = 0.20)
2. Plug valve (k_l = 1.10)
3. Check valve (k_l = 4.00)

The type and quantity of minor losses assumed in this preliminary analysis of the pipeline system are as follows.

Type	Quantity
Wide-Radius Bend	17
Plug Valve	9
Check Valve	1

System Curves

System headloss curves were developed for the slurry pipeline using the headloss formulas as discussed above. The pipeline was assumed to be 19,826 feet, 16-inch nominal diameter (12.30-inch inner diameter) SDR 9 HDPE throughout the analysis. The proposed pipe routing given in drawings 444853-101-C-001 through 444853-101-C-019 and the hydraulic profile given in drawing 444853-200-C-025 were utilized when calculating the headlosses through the system. In addition, the flow characteristic calculations given in Appendix D of the Onondaga Lake Dredging, Sediment Management, & Water Treatment Initial Design Submittal (IDS) were referenced as appropriate.

Specific gravity of the slurry mixture and the slurry concentration by volume were obtained using the following equations: (Equation 7.13 & 7.15, Herbich, 2000).

$$C_w = SG_s \frac{(SG_m - SG_f)}{SG_m (SG_s - SG_f)}$$ Eq$^{\underline{n}}$ 6

$$C_v = \frac{SG_m}{SG_s}(C_w)$$ Eq$^{\underline{n}}$ 7

Where, C_W = slurry concentration by weight
C_V = slurry concentration by volume
SG_S = specific gravity of solids
SG_f = specific gravity if the carrying fluid (i.e., water)
SG_m = specific gravity of slurry

The calculations were made for a slurry concentration of 10% solids by weight. Assuming 0.2 mm sand sized particle for analysis with solids specific gravity of 2.65 the slurry concentration by volume was calculated to be about 4%. Sediment drag coefficient and terminal settling velocities were calculated for a 0.2 mm sand sized particle and are shown in the calculations sheets.

A plot comparing the results obtained via each of these methods is given in the system curve (HL comparison) sheet of this package. Friction losses calculated via the Darcy-Weisbach method resulted in the lowest estimate of headloss for the methods compared. Values for friction losses calculated via the Durand method and Newitt method were similar and were slightly greater than the Darcy-Weisbach method. Headloss calculations obtained by the Hazen-Williams formula were greater than the other methods by about 20%.

A broader particle size distribution tends to have a lower solids effect (Wilson *et al*, 2006) and given the significant amount of percentage fines in the Onondaga Lake sediment the actual headloss may be assumed to be slightly lower than that calculated above.

For the purposes of this submittal, the Hazen-Williams formula was used to compute the potential system pump horsepower requirements which equates to a factor of safety of 1.23.

Pipeline Critical Velocity/Deposition Velocity

Critical velocity (or the deposition velocity) for a sediment grain size is the velocity at which the sediment will be removed from suspension and will settle in the pipeline or roll along the bottom of the pipeline. Slurry transport through a pipeline may be achieved by three flow regimes: 1. homogenous flow, 2. heterogeneous flow, and 3. fully stratified flow. In homogenous flow, uniform solid concentration prevails throughout the section of the pipeline. In a heterogeneous slurry flow, higher concentrations of solids are found towards the bottom section of the pipeline. The lighter solids are generally in suspension and the heavier solids may saltate (roll or bounce along the bottom of the pipeline) depending upon the flow velocity in the pipe. Fully stratified flow is achieved when all the solids are deposited on the bottom of the pipeline and is transported as a moving bed. The most economical method of slurry transport is considered to be in the heterogeneous regime (Herbich, 2000).

Heterogeneous flow is achieved when the slurry mixture velocity is greater than the critical velocity and lower than the transitional velocity. Transitional velocity is the velocity between the homogenous and heterogeneous regime. The ratio of particle diameter to pipe diameter is also important in determining the presence of heterogeneous flow in the pipeline (Wilson *et al.*, 2006). From their experiments, Wilson *et al.*, 2006, estimated that the upper limit for particle size, for which a heterogeneous flow may occur, is 0.015D where D is the diameter of the pipe. They also estimated the flow to be stratified for particle diameter above 0.018D.

For a carrier fluid that does not differ significantly from water it may be assumed that the upper limit for homogenous flow is 150 µm (Wilson *et al.*, 2006). As was calculated during earlier hydraulic analyses, the concentration by volume that is expected during the design is approximately 4% and may be considered significantly low as compared to slurries that are usually transported in the mining industry (approximately 25-30%). Based on this data it may be assumed that all fines (< 0.075 mm) that will be pumped through the pipeline will flow as homogenous non-settling slurry for the flow velocities anticipated in the slurry pipeline.

For this analysis, 16-inch SDR 9 pipe has been considered with an inner diameter of 12.302 inches. The upper limit up to which a heterogeneous flow will occur is calculated as 0.015D which for a 12.302-inch ID pipe is calculated to be 4.7 mm. 0.075 - 4.75 mm is the size range for sand defined by USCS (Unified Sieve Classification System) and as such it may be assumed that the transport of sand and fines will be either in homogenous or a heterogeneous flow regime. Particle diameter above 4.7 mm will be transported as a moving bed along the bottom of the pipeline.

Table 1 through 3 on the sediment data sheet shows the sediment data from the pre-design investigation studies that were conducted at Onondaga Lake. Table 3 shows the weight-based percentage of the fine sand sized particles (0.075 – 0.425 mm), total sand sized particles (0.075 – 4.75 mm) and total gravel and sand sized particles (0.075 – 75mm), . Settling sediment for the sake of this analysis is considered to be all sediments that are larger than 0.075 mm. It is seen from table 3 that total weight of fine sand (0.075 – 0.425 mm) is about 55% of the total weight of all settleable solids (sand and gravel 0.075 – 75 mm). From these sediment data it is assumed that a d_{50} of 0.425 mm is a reasonable estimate for preliminary critical velocity calculations.

Critical velocities for heterogeneous flow of sediment with d_{50} of 0.425 mm flowing through SDR 9 16-inch is calculated using the Durand and Condolis equation (1952) and is shown in Equation 8 and 9 (Equation 7.79, Herbich, 2000).

$$V_{c,hor} = F_L \left[2g \left(\frac{SG_s - SG_f}{SG_f} \right) D \right]^{1/2} \qquad \text{Eq}^{\underline{n}}\ 8$$

$$V_{c,inc} = V_{c,hor} + \Delta_D \left(\sqrt{2g\left(SG_s - 1\right)D}\right) \qquad \text{Eq}^{\underline{n}}\ 9$$

Symbol	Description
$V_{c,\ hor}$	Critical velocity in the horizontal section
$V_{c,inc}$	Critical velocity in the inclined section
F_L	Coefficient that is a function of slurry concentration by volume
D	Inside diameter of of pipe in feet
g	Acceleration due to gravity in ft/sec^2
Δ_D	Factor affecting angle of inclination on durand deposition parameter (Fig 7.29, Herbich 2000)
C_w	Slurry concentration by weight (Assumed to be 10%)
C_v	Slurry concentration by volume
SG_s	Specific gravity of solids (2.65 assumed for fine sand)
SG_f	Specific gravity of the carrying fluid (i.e., water), assumed to be 1.0
SG_m	Specific gravity of slurry
V_t	Particle settling velocity in ft/sec (Fig. 7.22, Herbich 2000)

From Figure 7.27, Herbich 2000, F_L for a 4% slurry concentration by volume and for grain diameter of 0.425 is estimated to be 1.1. Assuming 8% slope for the inclined part of the pipeline and using Figure 7.29, Herbich, 2000, the Δ_D is estimated to be 0.1

Using Durand's equation the critical velocity in the horizontal section of the pipe is calculated to be 11.5 ft/sec and in the inclined section of the pipeline is calculated to be 12.5 ft/sec. Critical velocity is also determined using the nomograph by Wilson *et al*, 1997, shown in figure 7.28 in Herbich 2000. A critical velocity of approximately 12 ft/sec is estimated from the nomograph.

Transitional flow is calculated using equation 7.82 in Herbich 2000 and is given as:

$$v_{th} = \left(1800 gDv_t\right)^{1/3} \qquad \text{Eq}^{\underline{n}}\ 10$$

Where, D is the pipe ID (in.) and;

V_t is the terminal settling velocity (ft/sec) for the 0.425 sand sized particle and is obtained from figure 7.22, Herbich, 2000.

The transitional velocity from the above equation for a sediment grain size of 0.425 mm is calculated to be 22 ft/sec.

Velocity for a 16-inch SDR 9 pipe with ID of 12.302 inches and for a flow of 5000 GPM is calculated to be 13.5 ft/sec. This flow velocity lies between the transitional velocity and the critical velocity that was calculated above.

Further review and analysis of assumptions for the sediment grain size (d_{50}) and critical velocity will be conducted as the design progresses.

HDPE Pipe Derating

HDPE pipe has been proposed to be used for the pipeline. Based on the system hydraulic analyses an appropriate SDR for the pipe meeting the system pressure requirements will be selected. The pipe diameter will also be selected so that a velocity above critical velocity can be maintained in the pipeline.

Additional de-rating for erosion/abrasion tolerance will be applied to the pipe. "Dredging applications of High Density Polyethylene Pipe" Pankow V.R, 1987, was referred to analyze the fate of HDPE pipes used in dredge slurry transport applications. The tests were conducted at the U.S Army Engineer Waterways Experiment Station (WES) Vicksburg, Mississippi. Two 20-foot-long sections of 30-inch ID, SDR-32.5, HDPE pipes were used for the experiment. The HDPE pipe sections were installed in the discharge line of the Port of Portland cutter-suction type, 30-inch hydraulic dredge. About 2.6 million cubic yards of sediment was dredged over a period of 6 months. Slurry of 15% concentration by volume and with an average velocity of 18 ft/sec (range of 13 to 25 ft/sec) was pumped through the HDPE sections. The dredge material ranged from fine sands to 2-inch diameter smooth river rock.

Test results showed that the wear on the HDPE pipes was a function of the type of the material dredged and the velocity. About 30% of wear along the bottom of the pipeline was noted during the period when heavier sediment was being dredged and minimal wear when finer material was being dredged. Wear in the pipeline ranged anywhere between 1.1% and 29.9% and was closely associated with the dredged material type.

Based on these test results and taking into consideration the type of material that is expected in the sediments from Onondaga Lake, a de-rating factor of 10% is assumed as a reasonable erosion/abrasion allowance for design purposes at this stage of the design. Table 1 shows the pressure ratings with and without a 10% derate for commercially available DR schedules of HDPE pipe.

Table 1: Commercially available HDPE pressure ratings

HDPE Spec.	Internal Pressure Rating		Internal Pressure Rating with 10% Derating	
	(psi)	(ft. H_2O)	(psi)	(ft. H_2O)
DR 7	265	612	239	551
DR 9	200	462	180	416
DR 11	160	370	144	333
DR 17	100	231	90	208

Booster Pump Power Requirements

The system headloss curves were used to generate potential booster pump power requirements. The following equation was used to calculate the power requirements:

$$P = \frac{Q \cdot \gamma \cdot H_L}{550\varepsilon}$$

Where, P = Power input required (HP)
Q = Flowrate (ft^3/sec)
γ = Specific gravity of the fluid being pumped (lb/ft^3)
ε = Pump efficiency

The power required to pump 10% dredge slurry by weight through a 16-inch SDR 9 pipe with 70% pump efficiency and at the rate of 5000 gpm is estimated to be 1930 hp. With an accuracy of
-10/+20% for the current level of design the pump horsepower is estimated to be between 1740 – 2320 hp.

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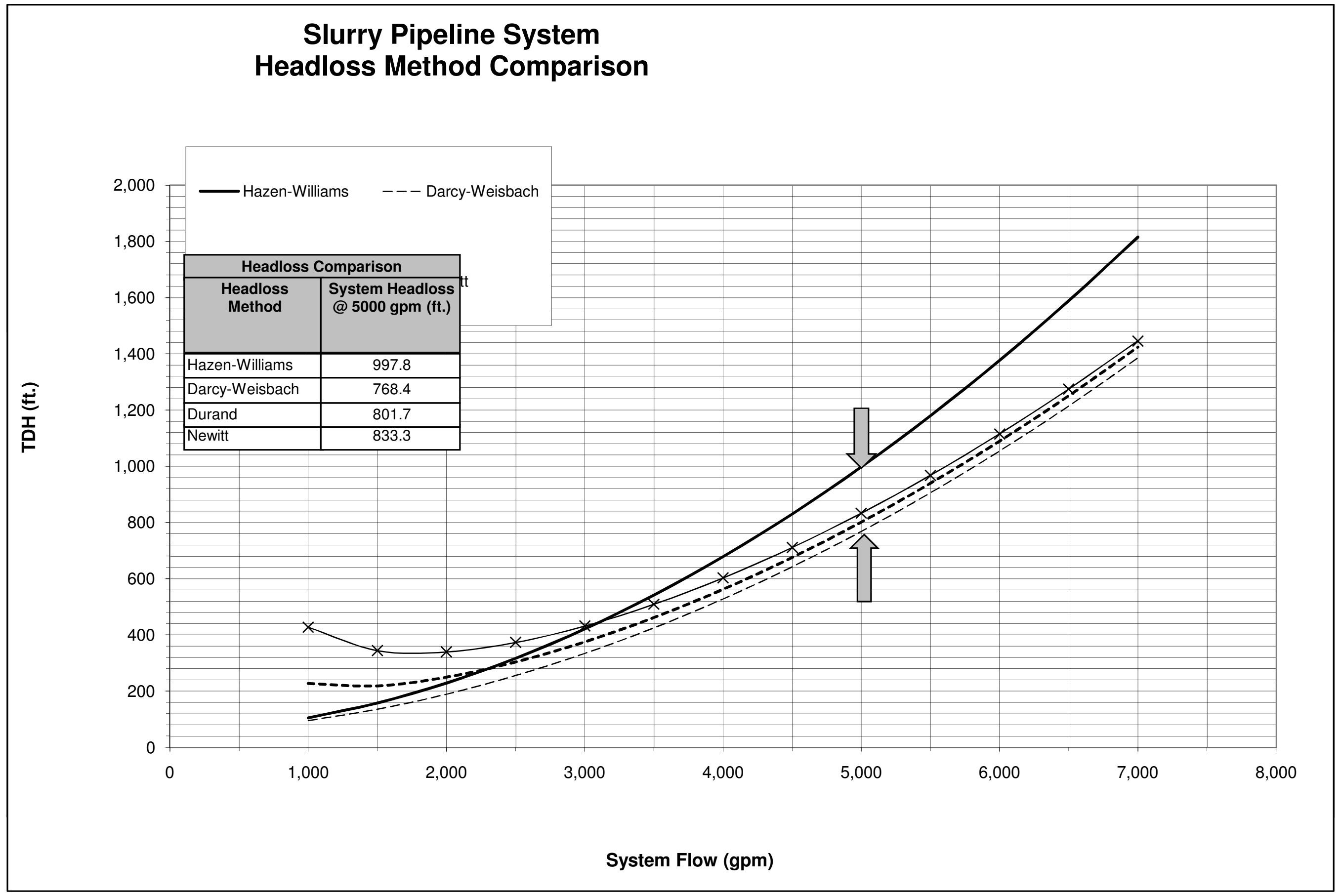
Project:	**Honeywell Onondaga Lake Dredging Project**						
Number:	**444853**	A	Preliminary Internal Draft	ADM	AN	JDF	1/8/2010

System Curve (16-in. DR 9 Pipe)

Flow (gpm)	Headloss (ft.)			
	Hazen-Williams	Darcy-Weisbach	Durand	Newitt
0	--	--	--	--
100	--	--	--	--
500	--	--	--	--
1,000	105.6	95.2	227.3	427.7
1,500	158.6	135.6	218.6	344.4
2,000	229.4	189.2	249.5	340.0
2,500	317.3	255.6	303.6	373.6
3,000	421.8	334.3	375.1	431.9
3,500	542.3	425.2	461.8	509.3
4,000	678.7	527.9	562.2	603.0
4,500	830.6	642.4	675.7	711.4
5,000	997.8	768.4	801.7	833.3
5,500	1,180.0	905.8	939.8	968.1
6,000	1,377.0	1,054.6	1,089.8	1,115.4
6,500	1,588.6	1,214.5	1,251.3	1,274.7
7,000	1,814.8	1,385.6	1,424.4	1,445.8


Slurry Pipeline System
Headloss Method Comparison

Headloss Comparison

Headloss Method	System Headloss @ 5000 gpm (ft.)
Hazen-Williams	997.8
Darcy-Weisbach	768.4
Durand	801.7
Newitt	833.3

Constants

Parameter	Value	Units
Qpump	5,000	gpm
v_f	1.09E-05	ft2/sec
Re	1.27E+06	
ε	5.00E-06	ft.
ε/D	4.88E-06	
f	0.0111	
g	32.2	ft/sec2
SG_m	1.07	
SG_s	2.65	
$C_{HDPE, m}$	129	
$C_{HDPE, w}$	150	
C_v	4%	
d_p	0.2	mm
d_p	6.56E-04	ft.
v_o	89.0	mm/sec
v_o	0.29	ft/sec
v_t	0.08	ft/sec
Re_p	0.55	
C_D	43.9	

Minor Losses

Type	k_l
Wide-Radius Bend	0.20
Plug Valve	1.10
Check Valve	4.0

Type	Nos.
Wide-Radius Bend	17
Plug Valve	9
Check Valve	1

Equations

Equations	
Hazen-Williams	$h_f = \frac{4.73L}{C^{1.852} \cdot D^{4.87}} Q^{1.852}$
Friction factor (Swamee and Jain)	$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7D}\right) + \frac{5.74}{\mathrm{Re}^{0.9}}\right]^2}$
Darcy-Weisbach	$h_f = SG_m \cdot f\left(\frac{L}{D}\right)\frac{v^2}{2g}$
Hazen-Williams	$h_f = \frac{4.73L}{C^{1.852} \cdot D^{4.87}} Q^{1.852}$
Durand Equation	$h_{f,slurry} = 81\left[\frac{v^2\sqrt{C_D}}{(SG_s - 1)gD}\right]^{-3/2} C_v h_f$
Newitt Equation	$h_{f,slurry} = 1100 C_v \cdot h_f (SG_s - 1)\frac{gD}{V^2}\frac{v_t}{V}$
Minor Losses	$h_l = k_l \frac{Q^2}{2g \cdot A^2}$

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Project: **Honeywell Onondaga Lake Dredging Project**
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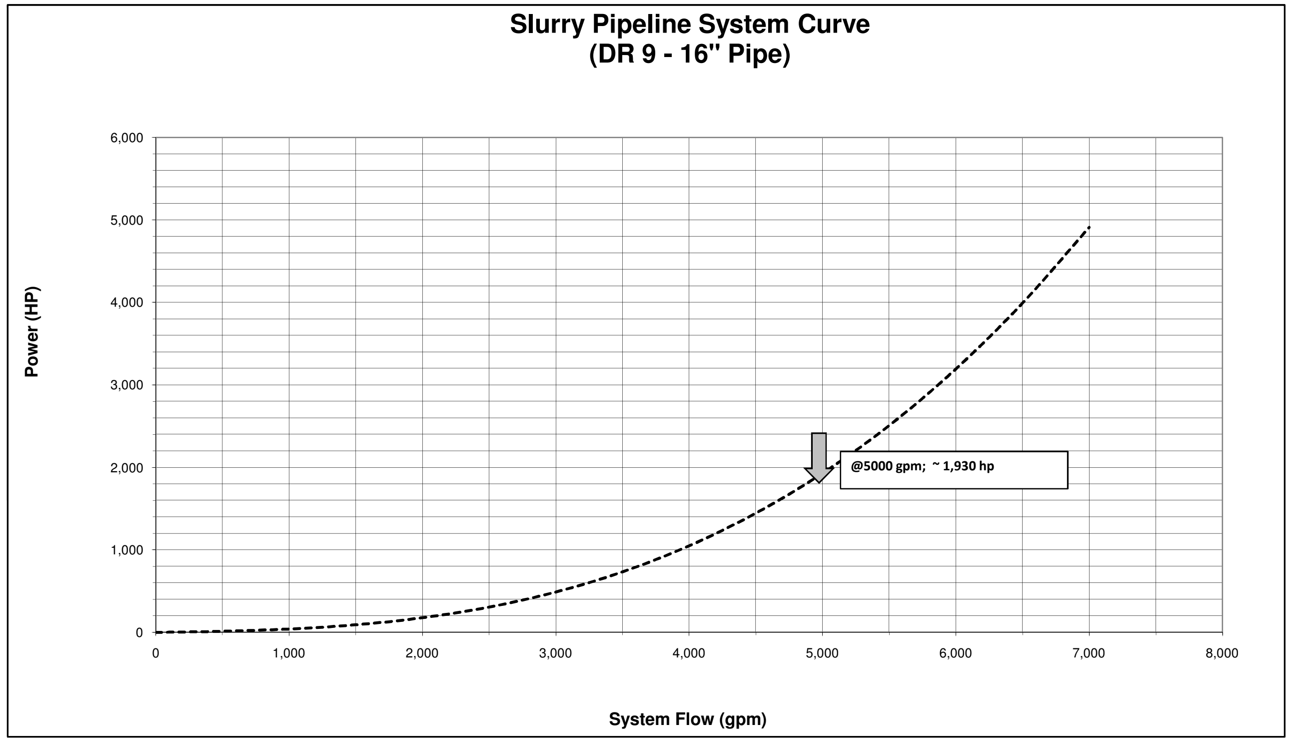
Constants		
Parameter	**Value**	**Units**
Q_{pump}	5,000	gpm
C_{HDPE}	129	
g	32.2	ft/sec^2
SG_m	1.07	
γ	66.8	lb/ft3
ε	70%	

Minor Losses	
Type	**k_l**
Wide-Radius	0.20
Plug Valve	1.10
Check Valve	4.0

Type	Nos.
Wide-Radius Bend	17
Plug Valve	9
Check Valve	1

1	2	3	4	5	6	7	8	9	10	11	12	13
Q (gpm)	**Q (cfs)**	**v (ft/sec)**	**L (ft.)**	**C**	**D_{nom} (in.)**	**ID (in.)**	**A (ft^2)**	**k_l**	**h_f (ft.)**	**h_l (ft.)**	**h_s (ft.)**	**H_L (ft.)**
5,000	11.1	13.5	19,826	129	16	12.302	0.825	17.30	890.4	48.9	58.4	997.8

System Curve (DR 9-16" Pipe)		
Flow (gpm)	**TDH (ft)**	**(Power) HP**
0	58.4	0
100	59.1	2
500	71.4	14
1,000	105.6	41
1,500	158.6	92
2,000	229.4	177
2,500	317.3	307
3,000	421.8	489
3,500	542.3	733
4,000	678.7	1,049
4,500	830.6	1,444
5,000	997.8	1,928
5,500	1,180.0	2,508
6,000	1,377.0	3,193
6,500	1,588.6	3,990
7,000	1,814.8	4,909


Slurry Pipeline System Curve
(DR 9 - 16" Pipe)

@5000 gpm; ~ 1,930 hp

Equations	
Hazen-Williams	$h_f = \frac{4.73L}{C^{1.852} \cdot D^{4.87}} Q^{1.852}$
Minor Losses	$h_l = k_l \frac{Q^2}{2g \cdot A^2}$
Total Headloss	$H_L = h_f + h_l + h_s$

Column	Description
1	Flowrate in gallons per minute
2	Flowrate in cubic feet per second
3	Pipeline velocity in feet per second
4	Reach length in feet
5	Hazen-Williams roughness factor
6	Nominal diameter of pipe in inches
7	Actual inside diameter of pipe in inches
8	Cross-sectional area of flow in square feet
9	Total minor loss coefficient for reach (sum of individual minor loss coefficients)
10	Frictional headlosses through reach using Hazen-Williams Equation in feet
11	Minor losses through reach in feet
12	Elevation change (static head) through reach in feet
13	Total headlosses through reach (sum of friction, minor, and static losses) in feet

TABLE 1: 2.2M cy Dredging Volume (Base+Contingency)

Remediation Area	Dry Weights						
	Gravel-Sized (4.75 - 75mm) (tons)	Sand-Sized (.075 - 4.75mm) (tons)	Silt-Sized (0.005 - .075mm) (tons)	Clay-Sized (< .005 mm) (tons)	Total Coarse Grains (Gravel- and Sand-Sized) (tons)	Total Fine Grains (Silt and Clay-sized) (tons)	Total Dry Weight (tons)
D (ILWD)	7,557	77,733	346,560	107,963	85,291	454,523	539,814
C	4,266	14,733	16,708	3,792	18,999	20,500	39,500
A & B	3,242	37,341	66,758	12,727	40,583	79,485	120,069
E	132,616	253,403	186,161	50,431	386,019	236,592	622,611
TOTAL	147,681	383,210	616,187	174,913	530,892	791,101	1,321,992

Table 2 : Particle Size Distribution

Remediation Area	Average Specific Gravity	Average Percent Gravel-Sized	Average Percent Sand-Sized	Average Percent Silt-Sized	Average Percent Clay-Sized
		(%)	(%)	(%)	(%)
D (ILWD)	2.54	1.4	14.4	64.2	20.0
C	2.77	10.8	37.3	42.3	9.6
A & B	2.68	2.7	31.1	55.6	10.6
E	2.63	21.3	40.7	29.9	8.1

Table 3 : Fine Sand Content

Remediation Area	Average Percent Sand-Sized (.075 - 4.75mm)	Average Fine Sand-Sized (0.075 - 0.425mm)	Total Dry Weight	Total Coarse Grains (Gravel- and Sand-Sized)	Sand-Sized (.075 - 4.75 mm)	Fine Sand-Sized (.075 - 0.425 mm)
	(%)	(%)	(tons)	(tons)	(tons)	(tons)
D (ILWD)	14.4	7.8	539,814	85,291	77733	42105
C	37.3	18.8	39,500	18,999	14733	7426
A & B	31.1	21	120,069	40,583	37341	25214
E	40.7	34.5	622,611	386,019	253403	214801
TOTAL			1,321,992	530,892	383,210	289,546

HANDBOOK OF DREDGING ENGINEERING

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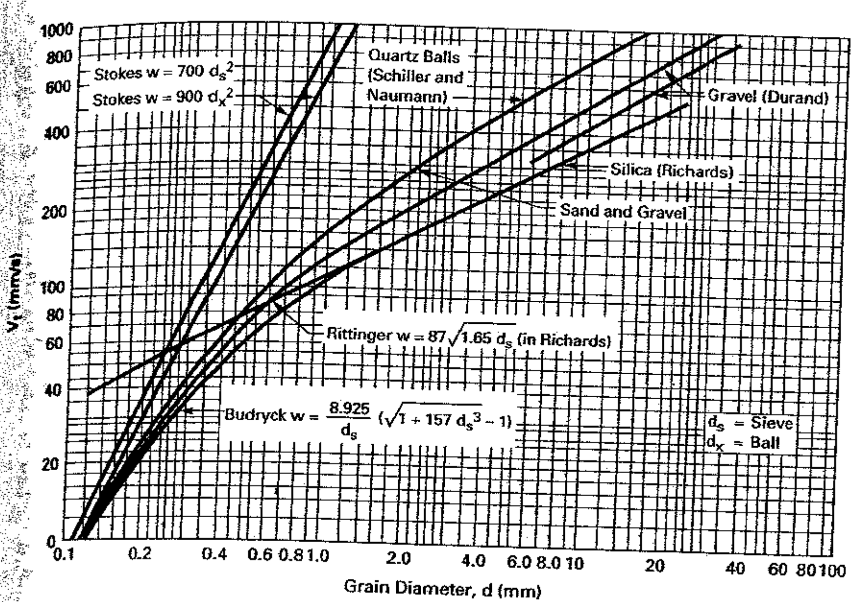

FIGURE 7.22 Terminal velocity experimental data and empirical equations. (*Herbich, 1992*)

Nominal Diameter. The *nominal diameter* (d_n) is defined as the diameter of a sphere with the same volume as the sediment particle and is expressed as

$$d_n = \left(\frac{6V}{\pi}\right)^{1/3} \tag{7.51}$$

where V is the volume.

Geometric Average Diameter. The *geometric average diameter* d_{ave} is defined as

$$d_{\text{ave}} = (abc)^{1/3} \tag{7.52}$$

where a, b, and c are the length, width, and thickness of the particle.

Sediment Particle Shape Factor

The shape of the particle also has an effect of the fall velocity. Several shape factors have been used, including the volumetric shape factor (K) proposed by Heywood (1962), the particle sphericity (Ψ) proposed by Wadell (1934), the Krumbein shape factor (Ω) proposed by Krumbein (1963), and the Corey shape factor (ß). The volumetric shape factor proposed by Heywood (1938) is

$$K = \frac{V}{d_a^3} \tag{7.53}$$

where d_a is the diameter of a sphere that has the same projected area (A_p) as the particle

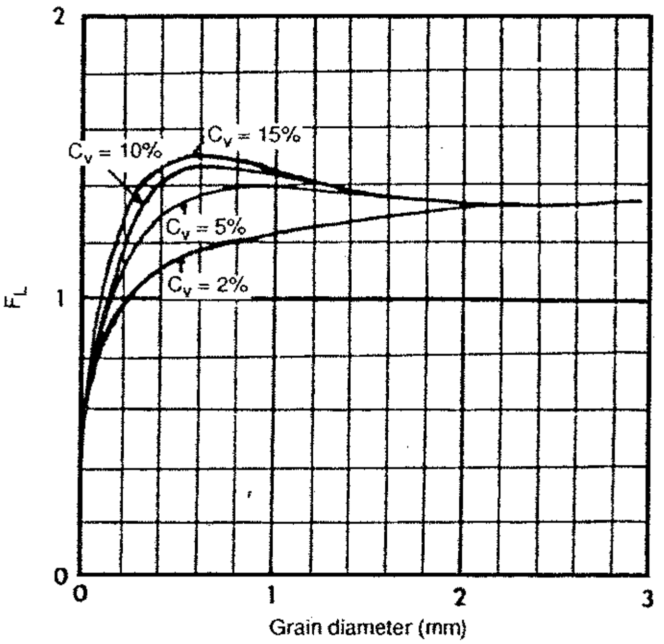

FIGURE 7.27 Variation of parameter F_L with grain diameter d. *(Durand, 1953)*

the inside pipe diameter, in meters (Matousek, 1997). The mechanical friction coefficient of 0.44 agrees better with the results obtained from Fig. 7.28.

The effect of pipe inclination on deposit limit or critical velocity is illustrated in Fig. 7.29. These results show the critical velocity increases as the angle between the pipe and the horizontal increase up to an angle of approximately 35°. The increase in the critical velocity is determined using Eq. (7.81). Thus, slurry pipe systems with inclined pipes must allow for the increased critical velocity or else deposits may occur in the inclined sections and the pipe may plug. It also may suggest that vertical sections may be preferable over short inclines to prevent deposit in the pipe. Thus

$$V_c\,(\text{inclined}) = V_c\,(\text{horizontal}) + \Delta_D\left[\sqrt{2g\,(S_s - 1)\,D}\right] \tag{7.81}$$

Heterogeneous to Homogeneous Flow

Wilson, et al. (1992) proposed that the ratio d/D could be used as an indicator of transition from heterogeneous to homogeneous flow. When $d/D > 0.018$, the flow is fully stratified (homogeneous), and when $d/D < 0.015$, the flow is partially stratified (heterogeneous). Both types of slurry flow can occur for the region $0.015 < d/D > 0.018$. The transition velocity (V_{th}) between homogeneous and heterogeneous regimes is also approximated by

$$V_{th} = (1800\,gdv_t)^{1/3} \tag{7.82}$$

where g is the acceleration of gravity, d is the median grain diameter, and v_t is the terminal velocity.

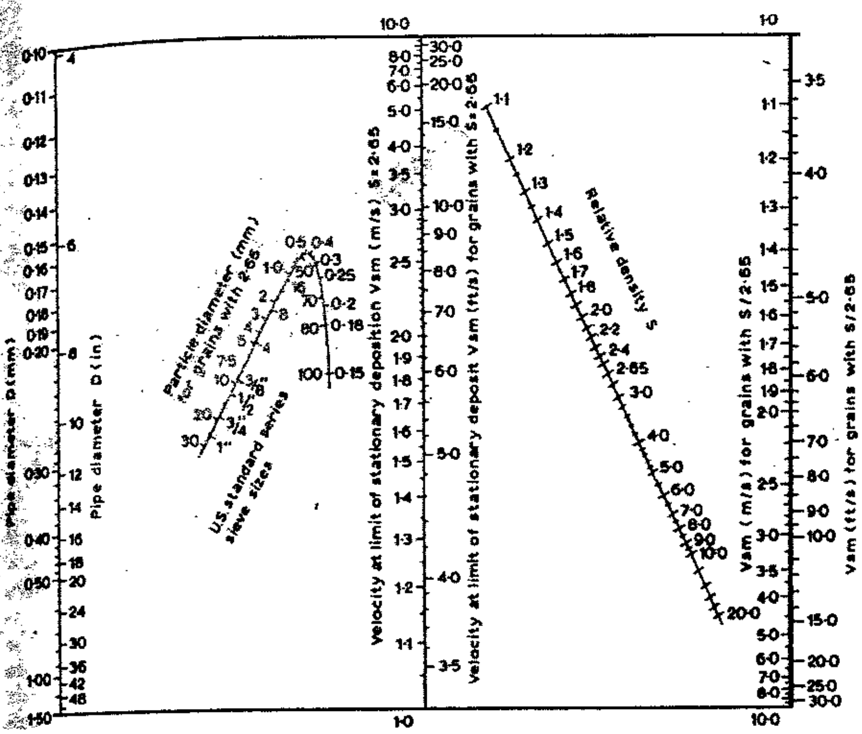

FIGURE 7.28 Nomograph for maximum velocity at limit of stationary deposition (V_{sm}) which is the same as the critical velocity (V_c). (*Wilson, et al., 1997*)

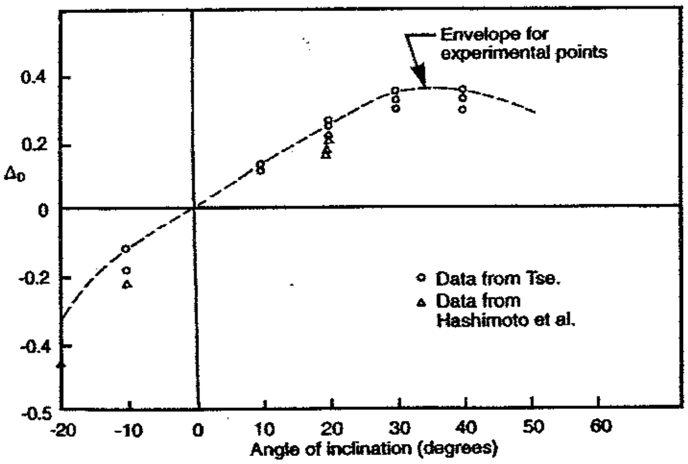

FIGURE 7.29 Effect of angle of inclination on Durand deposition parameter. (*Wilson and Tse, 1984*)

Hazen and Williams Equation

Another equation that is often used in the dredging industry is the Hazen-Williams equation:

$$H = 0.2083\left(\frac{100}{C}\right)^{1.85}\left(\frac{Q^{1.85}}{D^{4.8655}}\right) \tag{7.85}$$

where H is friction head, in feet of freshwater per 100 feet of pipe; D is inside diameter of the pipe, in inches; Q is flow, in gallons per minute; and C is a constant describing pipe roughness determined from Fig. 7.31.

Durand

For saltation flow [$d_{50} > 0.001$ in (0.025 mm)], the head loss per unit length of pipe [feet of water/feet of pipe (meters of water/meters of pipe)] may be expressed as

$$i_m = 66\, C_v i\left(\frac{\rho_s}{\rho_w} - 1\right)\frac{gD}{V^2} + i \tag{7.86}$$

where i_m is the head loss due to mixture per unit pipe length [feet of water/feet of pipe (meters of water/meters of pipe)], i is the head loss due to water per unit length of pipe [feet of water/feet of pipe (meters of water/meters of pipe)], C_v is the sediment concentration by volume, D is the internal pipe diameter, V is the average slurry velocity, ρ_s and ρ_w are the density of slurry and water, respectively; and g is the gravitational acceleration.

The Durand and Condolios (1952) equation for estimating the head loss in a pipe with heterogeneous flow is

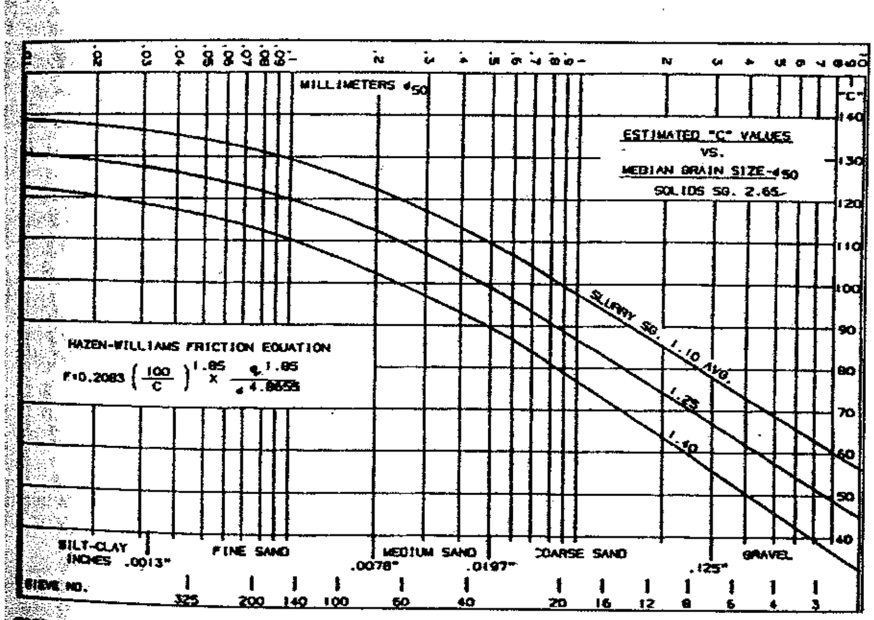

FIGURE 7.31 Constant C for Hazen-Williams equation. *Turner, 1984*)

HAESTAD METHODS

ADVANCED WATER DISTRIBUTION MODELING AND MANAGEMENT

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Table 2.6 Minor loss coefficients

Fitting	K_L	Fitting	K_L
Pipe entrance		90° smooth bend	
Bellmouth	0.03-0.05	Bend radius/D = 4	0.16-0.18
Rounded	0.12-0.25	Bend radius/D = 2	0.19-0.25
Sharp-edged	0.50	Bend radius/D = 1	0.35-0.40
Projecting	0.78	Mitered bend	
Contraction – sudden		$\theta = 15^\circ$	0.05
$D_2/D_1=0.80$	0.18	$\theta = 30^\circ$	0.10
$D_2/D_1=0.50$	0.37	$\theta = 45^\circ$	0.20
$D_2/D_1=0.20$	0.49	$\theta = 60^\circ$	0.35
Contraction – conical		$\theta = 90^\circ$	0.80
$D_2/D_1=0.80$	0.05	Tee	
$D_2/D_1=0.50$	0.07	Line flow	0.30-0.40
$D_2/D_1=0.20$	0.08	Branch flow	0.75-1.80
Expansion – sudden		Tapping T Branch	
$D_2/D_1=0.80$	0.16	d = tapping hole diameter D = main line diameter	$1.97/(d/D)^4$
$D_2/D_1=0.50$	0.57	Cross	
$D_2/D_1=0.20$	0.92	Line flow	0.50
Expansion – conical		Branch flow	0.75
$D_2/D_1=0.80$	0.03	45° Wye	
$D_2/D_1=0.50$	0.08	Line flow	0.30
$D_2/D_1=0.20$	0.13	Branch flow	0.50
Gate valve – open	0.39	Check valve – conventional	4.0
3/4 open	1.10	Check valve – clearway	1.5
1/2 open	4.8	Check valve – ball	4.5
1/4 open	27	Cock – straight through	0.5
Globe valve – open	10	Foot valve – hinged	2.2
Angle valve – open	4.3	Foot valve – poppet	12.5
Butterfly valve – open	1.2		

Walski (1984)

$$K_L = C_f D^4 / C_v^2 \qquad (2.25)$$

where D = diameter (in., m)
C_v = valve coefficient [gpm/(psi)$^{0.5}$, (m^3/s)/(kPa)$^{0.5}$]
C_f = unit conversion factor (880 English, 1.22 SI)