A DREDGING KNOWLEDGE–BASE EXPERT SYSTEM FOR PIPELINE DREDGES WITH COMPARISON TO FIELD DATA

A Dissertation

by

DEREK ALAN WILSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2010

Major Subject: Ocean Engineering

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Approved by:

Chair of Committee, Robert E. Randall
Committee Members, Steven A. Hughes
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ABSTRACT

A Dredging Knowledge–Base Expert System
for Pipeline Dredges with Comparison to Field Data. (December 2010)
Derek Alan Wilson, B.C.E., Auburn University;
M.S., Auburn University
Chair of Advisory Committee: Dr. Robert E. Randall

A Pipeline Analytical Program and Dredging Knowledge–Base Expert–System (DKBES) determines a pipeline dredge's production and resulting cost and schedule. Pipeline dredge engineering presents a complex and dynamic process necessary to maintain navigable waterways. Dredge engineers use pipeline engineering and slurry transport principles to determine the production rate of a pipeline dredge system. Engineers then use cost engineering factors to determine the expense of the dredge project.

Previous work in engineering incorporated an object–oriented expert–system to determine cost and scheduling of mid–rise building construction where data objects represent the fundamental elements of the construction process within the program execution. A previously developed dredge cost estimating spreadsheet program which uses hydraulic engineering and slurry transport principles determines the performance metrics of a dredge pump and pipeline system. This study focuses on combining hydraulic analysis with the functionality of an expert–system to determine the performance metrics of a dredge pump and pipeline system and its resulting schedule.

Field data from the U.S. Army Corps of Engineers pipeline dredge, *Goetz*, and several contract daily dredge reports show how accurately the DKBES can predict pipeline dredge production. Real–time dredge instrumentation data from the *Goetz* compares the accuracy of the Pipeline Analytical Program to actual dredge operation. Comparison of the Pipeline Analytical Program to pipeline daily dredge reports shows how accurately the Pipeline Analytical Program can predict a dredge project's schedule over several months. Both of these comparisons determine the accuracy and validity of the Pipeline Analytical Program and DKBES as they calculate the performance metrics of the pipeline dredge project.

The results of the study determined that the Pipeline Analytical Program compared closely to the *Goetz* field data where only pump and pipeline hydraulics affected the dredge production. Results from the dredge projects determined the Pipeline Analytical Program underestimated actual long–term dredge production. Study results identified key similarities and differences between the DKBES and spreadsheet program in terms of cost and scheduling. The study then draws conclusions based on these findings and offers recommendations for further use.

To Jennifer

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CHAPTER I

INTRODUCTION

A Dredging Knowledge–Base Expert–System (DKBES) formulates an intelligent hydraulic pipeline dredging project by following the decision making process and analysis methodology of a dredge engineer. The DKBES bases the project design parameters on cost and production factors resulting from extensive analysis. Ultimately, the DKBES can apply pipeline dredge engineering principles to a dredging scenario to develop an accurate and cost effective solution with minimal time and expense to DKBES users.

The DKBES uses two distinct software programs to formulate a pipeline dredging solution. A Pipeline Analytical program determines the performance metrics for a dredge and pipeline system. Chapter II describes in detail the fundamental hydraulic engineering principles and slurry dynamics in practice that govern the production capability of a dredge pump and pipeline system as well as its resulting power consumption.

An object–oriented knowledge–base expert–system determines cost factors and scheduling results. The expert–system follows similar efforts in a mid–rise construction scheduling program that uses an object–oriented process to determine construction costs and scheduling. The expert system further incorporates cost rates from the Spreadsheet Program to apply to the functions and methods that determine dredging cost. Chapter III describes the expert–system architecture in terms of its data structure, functions, and program execution.

Validation of the Pipeline Analytical Program involves comparing program pro-

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This dissertation follows the style of *ASCE Journal of Waterway, Port, Coastal, and Ocean Engineering.*

duction results to actual pipeline dredge production. Chapter IV compares program analytical results to dredge instrumentation data on a real–time basis. Chapter V compares the program analytical results to daily dredge production output over the entire length of several pipeline dredge projects. Data comparison analysis will lend credible insight as to how accurately and precisely the Pipeline Analytical Program reflects real world results.

Analysis compares the DKBES to the Spreadsheet Program on two fronts. Chapter VI compares how the Pipeline Analytical Program and Spreadsheet Program agree on pump and pipeline system performance metrics calculations using similar hydraulics and slurry transport principles. Chapter VI compares the cost calculations of each of the programs to determine their similarities and differences in estimating pipeline dredge project cost based on similar cost engineering principles.

Chapter VIII provides conclusions and recommendations based on analysis between the DKBES, Spreadsheet Program and Field Data Results. Conclusions lend insight as to how well analytical results compared to field data as well as plausible reasons why they differ.

A. Pipeline Dredging

Cutterhead pipeline dredging removes sediment from a channel bottom through hydraulic pumping. Figure 1 illustrates a typical cutterhead pipeline dredge. The dredge uses a cutterhead to break the material from the channel bottom. Figure 2 illustrates a dredge cutterhead. The dredge then uses centrifugal pumps to transport the material through a pipeline to a dredged material placement site (DMPS) for storage. Figure 3 illustrates a typical dredge pump. Figure 4 illustrates the pipeline transport process. Pipeline dredging consumes significant amounts of energy and re-

Fig. 1. Cutterhead pipeline dredging channel bottom(*U.S. Army Corps of Engineers*).

quires considerable capitol investment to effectively maintain navigable waterways to operable depth. The importance of this maintenance dredging continues to increase in order to sustain a vibrant economy and environment.

Navigational dredging totalled \$212M for $44.9\mathrm{Mm}^3(57.6\mathrm{Myd}^3)$ in Fiscal Year 2009 for federally controlled U.S. waterways (Department of the Army, Corps of Engineers, 2010). Pipeline dredging accounted for \$110M and $17.1\mathrm{Mm}^3(22.3\mathrm{Myd}^3)$ of the dredging 2009 projects (Department of the Army, Corps of Engineers, 2010). Arguably, pipeline dredging proposes an expensive proposition. Scheduling and resourcing the equipment necessary for a pipeline dredging project requires careful and intelligent planning in order to effectively execute a dredging project within time and budget.

B. Previous Research on the Subject

This dissertation expands upon previous studies in the field of construction engineering and cutterhead pipeline dredging. These previous works in engineering rely on

Fig. 2. Cutterhead on a pipeline dredge(*U.S. Army Corps of Engineers*).

Fig. 3. Pipeline dredge centrifugal pump(*Ellicott Dredges, LLC.*).

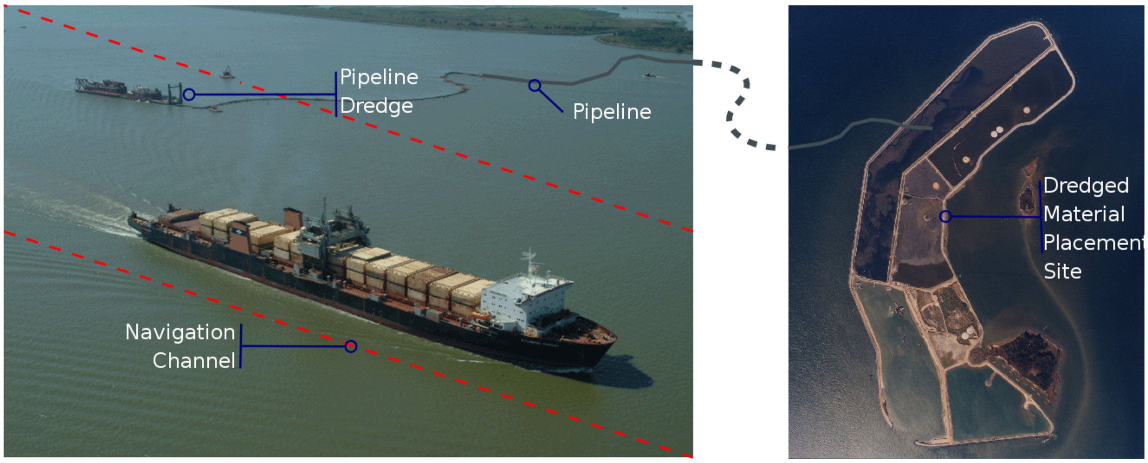


Fig. 4. Pipeline dredged material transport process(*U.S. Army Corps of Engineers*).

several different approaches to solve for cost, production and scheduling. This dissertation integrates the advantages offered by these programs in the effort of developing a versatile knowledge–base expert–system applied to pipeline dredge engineering.

1. Object-Oriented Construction Project Model

The Yau (1992) object-oriented model integrates the scheduling, planning and cost estimation involved in mid-rise construction projects into one object-oriented model. This model classifies the construction elements into ten distinct object classes in an object library. Process modules then apply the various systematic design, planning and evaluation functions, methods and rules to formulate the final building design procedure, scheduling chronology, quantities of material, labor, and equipment and ultimately time and expense. This program allows the user to control the initial input parameters, monitor program progress, and view and export the program results and output.

a. Object Library

The object library represents the physical and functional characteristics of the construction process as data structures. This object library contains the different classes of objects and their attributes as one of ten different classes listed below.

1. Non-Project Specific Classes
    (a) **Task Method**: Class to describe how construction personnel perform the various tasks.
    (b) **Equipment**: Class to describe the construction equipment involved in the task methods.
    (c) **Craft**: Class to describe the specialized profession and trade involved in the task methods.
    (d) **Crew**: Class to describe the level of personnel involved in the task method.
    (e) **Material**: Class to describe the physical elements used to form the construction product.
2. Project Specific Classes
    (a) **Activity**: Class to describe the pre–programmed methods by which construction crews conduct a project.
    (b) **Task**: Class that describes the various elements of project activities.
    (c) **Work Area**: Class that describes the construction platform in terms of the activities.
    (d) **Design Component**: Class that describes the various elements specific to the construction process and part of the final result.

(e) **Cost Code**: Class containing the unit cost of the equipment, materials and activities.

Instances of these objects and their data merge to form the data that interrelate to formulate the construction process in terms of time, resources and logistics into a final delivered product.

b. Process Modules

The Yau (1992) object–oriented program breaks down into several process modules. Each module contains a library of “if–then” rules to process the data objects to formulate a design and construction solution. ASCE (1987) refers to the process of generating these solutions as “Plan–Generate–Test”. Giarratano and Riley (1998) define modules as logical partitions of the knowledge–base by their individual sets of tasks and objectives. Each module contains a unique set of rules to perform distinct functions of the construction scheduling process. The Yau (1992) model contains four different process modules:

1. **Design Initialization**: Module to formulate the basic construction design based on final desired product and initial conditions.

2. **Initial Scheduling**: Module to refine the initial design by associating an estimated time with each component of the construction process.

3. **Detailed Scheduling**: Module to further refine the process by critically analyzing the initial schedule from start to finish along the entire sequence of activities.

4. **Cost Distribution**: Module to aggregate costs associated with each cost activity in the construction process.

Other components in the Yau (1992) model include a blackboard to display relevant instances of the construction model, interactive data editors, project scenario storage files to store data on current projects, historical project files to store data on previous projects, and a system controller to govern the module execution. All of these object–oriented components synchronize to form a functional and versatile scheduling program.

2. Pipeline Dredge Analytical Program

Wilson (2008) developed the Pipeline Dredge Analytical Program to use dredge pump and pipeline hydraulics (Herbich, 2000) and slurry transport principles (Wilson *et al.*, 1997) to determine a dredge pump's production level for a given pipeline system. The Pipeline Dredge Analytical Program (Wilson, 2008) reads data from a digitized pump performance curve for a given dredge pump and calculates where the pipeline system will intersect with the pump curve for given dredge pump and pipeline operating conditions. Figure 5 illustrates this engineering concept of pump curve and pipeline system curve intersection of operation.

The Pipeline Dredge Analytical Program (Wilson, 2008) uses the fundamental attributes of a pipeline dredge system to compute the operating parameters of a pump and pipeline system. These attributes include the pipeline system parameters and sediment and carrier fluid properties as follows in Table 1. The program uses these parameters coupled with dredge pump and pipeline hydraulics (Herbich, 2000) and slurry transport principles (Wilson *et al.*, 1997) to determine the total dynamic head (TDH_s) required of the pump in meters of slurry as:

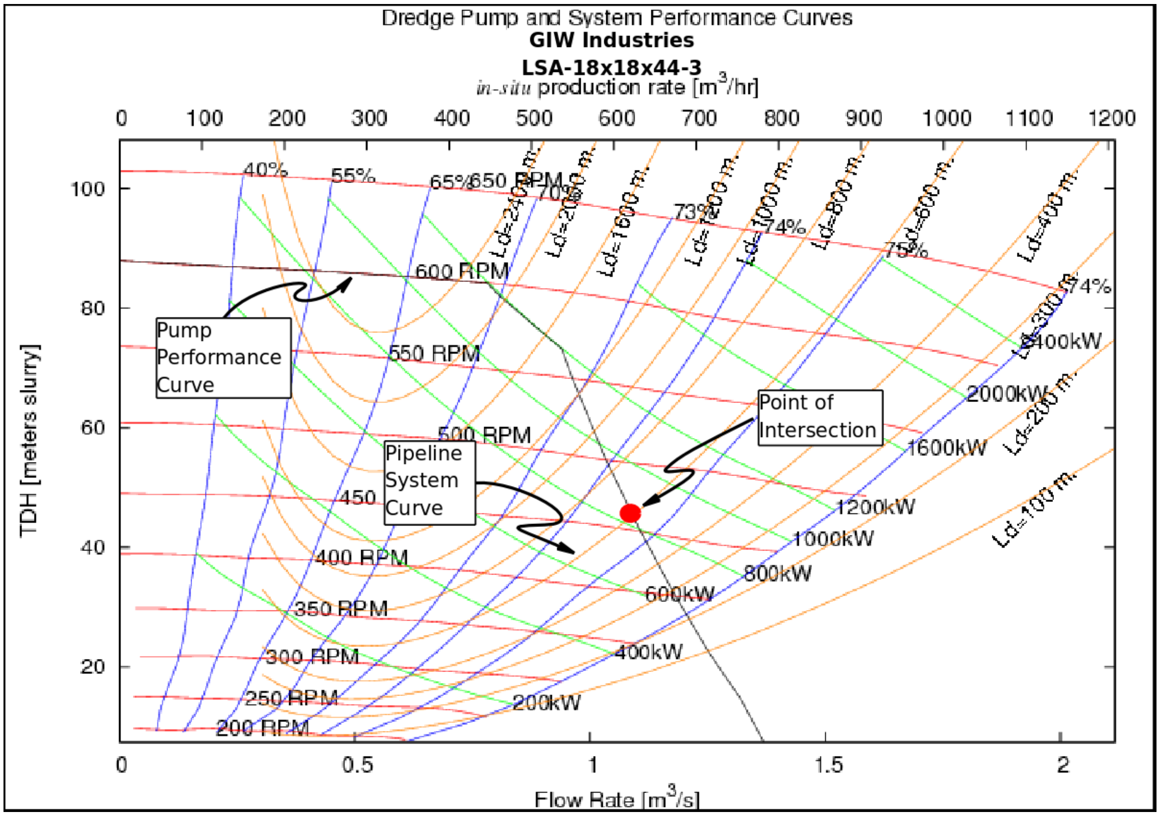


Fig. 5. Typical dredge pump performance curves and pipeline system curves with operating point at their intersection.

$$TDH_s = Z_b + Z_d\frac{S_m - S_f}{S_m} + \frac{V_d^2}{2g}\left(1 + \Sigma k_d\right) + \frac{L_d i_{md}}{S_m} + \Sigma k_s\frac{V_s^2}{2g} + \frac{L_s i_{ms}}{S_m} \qquad (1.1)$$

V_d and V_s represent the discharge and suction velocities, respectively in m/s. k_d and k_s are minor loss coefficients on the discharge and suction pipelines, respectively.

Table 1. Sediment and carrier fluid variables and descriptions

Symbol	**Description**	**Default Value**
D_d	Discharge pipe diameter (m)	
D_s	Suction pipe diameter (m)	
L_s	Suction length (m)	
Z_d	Digging depth (m)	
Z_b	Discharge elevation (m)	
L_d	Pipeline discharge length (m)	
m	Slurry friction gradient exponent	1.7
ϵ_s	Pipe roughness (mm)	0.508mm
μ_s	Pipe sliding friction factor	0.66
ρ_w	Water density (kg/m^3)	1,000kg/m^3
μ_w	Water viscosity (Pa·s)	10^{-3}Pa·s
g	Gravitational acceleration (m/s^2)	9.81(m/s^2)
ρ_s	Solid particle density (kg/m^3)	2,650kg/m^3
d_{50}	Median sediment grain diameter(mm)	
S_m	Specific gravity of sediment slurry	
S_f	Specific gravity of carrier fluid	
S_s	Specific gravity of sediment solid particles	

Figure 6 diagrams the pipeline hydraulic system illustrating the energy grade line (EGL) and hydraulic grade line (HGL) of the pump and pipeline system. i_{md} and i_{ms} are the respective discharge and suction pipeline friction gradients in m/m of water defined as follows:

$$i_{md} = \frac{f_{wd}V_d^2}{2gD_d} + 0.22(S_m - 1)\left(\frac{V_{50d}}{V_d}\right)^m \tag{1.2}$$

$$i_{ms} = \frac{f_{ws}V_s^2}{2gD_s} + 0.22(S_m - 1)\left(\frac{V_{50s}}{V_s}\right)^m \tag{1.3}$$

Friction gradients represent the head loss due to friction over unit length of pipeline. V_{50d} and V_{50s} represent the stratification velocity of the solid material in the discharge and suction pipelines, respectively in m/s as follows:

$$V_{50s} = w\sqrt{\frac{8}{f_{ws}}}\cosh\frac{60d_{50}}{1000D_s} \tag{1.4}$$

$$V_{50d} = w\sqrt{\frac{8}{f_{wd}}}\cosh\frac{60d_{50}}{1000D_d} \tag{1.5}$$

$$w = 0.9v_t + 2.7\left(\frac{(\rho_s - \rho_w)\,g\mu_s}{\rho_w^2}\right)^{\frac{1}{3}} \tag{1.6}$$

$$v_t = \frac{134.14}{1000}\left(d_{50} - 0.039\right)^{0.972} \tag{1.7}$$

$$f_{ws} = \frac{0.25}{log_{10}\left(\frac{\epsilon_s}{3.7\times10^3 D_s} + \frac{5.74}{Re_s^{0.9}}\right)^2} \tag{1.8}$$

$$f_{wd} = \frac{0.25}{log_{10}\left(\frac{\epsilon_s}{3.7\times10^3 D_d} + \frac{5.74}{Re_d^{0.9}}\right)^2} \tag{1.9}$$

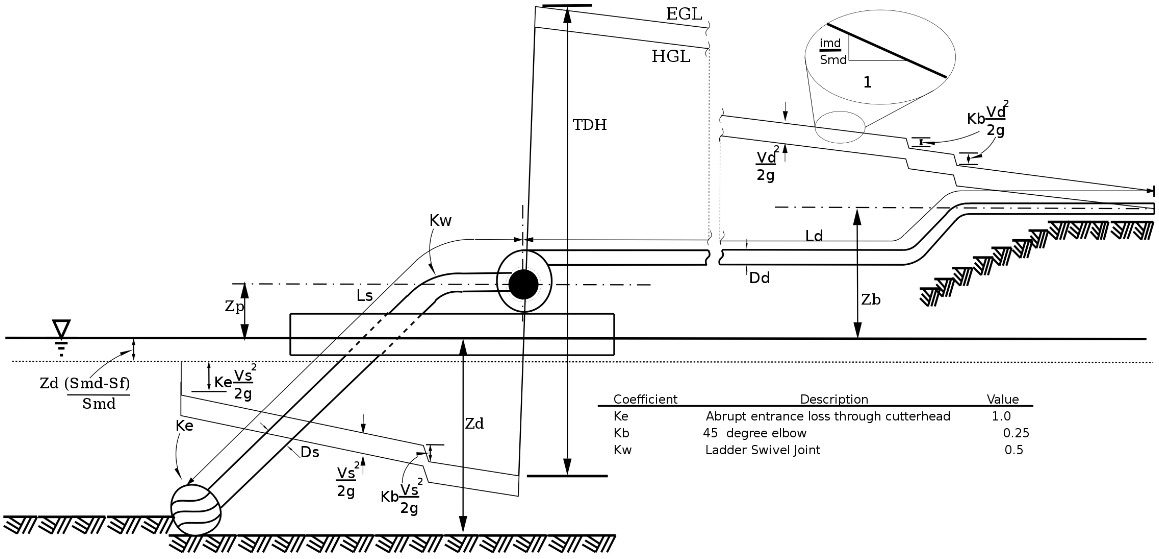


Fig. 6. Pipeline dredge pump and pipeline system illustrating the energy and hydraulic grade lines.

$$R_{es} = \frac{\rho_w S_m V_s D_s}{\mu_s} \tag{1.10}$$

$$R_{ed} = \frac{\rho_w S_m V_d D_d}{\mu_s} \tag{1.11}$$

The Pipeline Dredge Analytical Program computes the production rate and system power requirements for a pipeline dredge system given the pump, pipeline and dredge material characteristics as follows:

$$P = \frac{\rho_w g S_m Q H_p}{\eta} \tag{1.12}$$

$$\dot{M} = Q\frac{S_m - S_f}{S_s - S_f} \times 3600 \tag{1.13}$$

$$Q = V_d \frac{\pi D_d^2}{4} \tag{1.14}$$

where P represents pump power input(W), $\dot{M}$ represents delivered dredged material production rate (m^3/hr), Q represents volumetric flow rate (m^3/s) and η represents pump efficiency.

These output parameters of production and power can determine how much time a dredge operation will take and how much fuel and energy it will consume to determine the projects total aggregate cost and duration.

3. Spreadsheet Cutterhead Dredge Cost Estimation Program

Miertschin and Randall (1998) developed a spreadsheet program to determine the cost of mobilizing, operating and demobilizing a pipeline dredge system. Miertschin and Randall (1998) and Miertschin (1997) both outline this research. The spreadsheet program calculates the cost of the pipeline dredge and its ancillary equipment required alongside the dredge to service the dredge, transport personnel and equipment and maneuver the pipeline. The dredge owner incurs cost of operating, owning and servicing the equipment as well as employing and supporting necessary personnel. The spreadsheet program further incorporates Herbich (2000) and Wilson *et al.* (1997) principles of pump and pipeline hydraulics to determine the operating point of a dredge pump and pipeline system. These cost and production factors produce a total pipeline dredge cost and duration.

a. Personnel Cost

The spreadsheet program calculates the cost of employees by dividing employees into those on hourly or monthly pay scales. Each category contains its own method to determine total operating costs. The spreadsheet program calculates monthly employee cost based on their monthly salary. The spreadsheet program calculates hourly employee cost by including employee benefits, social security and unemployment benefits from cost factors stored in its data tables. The spreadsheet program also contains the methods to determine these cost factors.

b. Equipment Cost

The spreadsheet program categorizes pipeline dredge equipment into working and standby. Depending upon the task, equipment may stand idle or function at full capacity. Equipment functioning at full capacity incurs cost due to depreciation, maintenance, repairs, insurance, financing and fuel consumption. Equipment on standby only incurs a lower cost. The spreadsheet program contains these cost factors within its data tables as well as the methods used to calculate ultimate costs.

4. CUTPRO

The CUTPRO (Cutterhead Production) Program uses pipeline hydraulics as well as the dredge's size and physical properties to compute its dredge production capability. Mears (1997) directly compared CUTPRO's computation results to U.S. Army Corps of Engineers pipeline dredge projects. Scott (1998) explains the details for providing a CUTPRO input file and interpreting the CUTPRO results. CUTPRO uses size and geometry of the dredge to compute dredge productivity, and, more importantly, dredge efficiency. CUTPRO uses such parameters as dredge length, width, dredge ladder length, cutterhead diameter and material grain size to determine the maximum effective pipeline dredge production rate of the dredged material. CUTPRO, therefore, offers a valid method of computing a pipeline dredge's production characteristics based on dredge and dredge material properties.

CHAPTER II

SLURRY TRANSPORT AND PIPELINE HYDRAULIC ANALYSIS

The Pipeline Dredge Analytical Program (Wilson, 2008) uses the fundamental attributes of dredged material and the pipeline dredge system to compute the operating parameters of a pump and pipeline system. These attributes include the pipeline system parameters and sediment and carrier fluid properties Table 2 describes. The program uses these parameters coupled with dredge pump and pipeline hydraulics (Herbich, 2000) and slurry transport principles (Wilson *et al.*, 1997) to determine the TDH required of the pump in meters of slurry as:

$$TDH_s = Z_b + Z_d \frac{(S_{md} - S_f)}{S_{md}} + \frac{V_d^2}{2g}\left(1 + \sum_{n=1}^{M_d} k_{d_m}\right) + L_d \frac{i_{md}}{S_{md}} + \sum_{n=1}^{M_s} k_{s_m} \frac{V_s^2}{2g} + L_s \frac{i_{ms}}{S_{md}} \quad (2.1)$$

V_d and V_s are the discharge and suction velocities, respectively in m/s. Σk_d and Σk_s are the sum of all minor loss coefficients on the discharge and suction pipelines, respectively. Figure 7 diagrams these factors on the pipeline hydraulic system illustrating the energy grade line (EGL) and hydraulic grade line (HGL) of the pump and pipeline system. The terms i_{md} and i_{ms} are the respective discharge and suction pipeline friction gradients in m/m of water defined as follows:

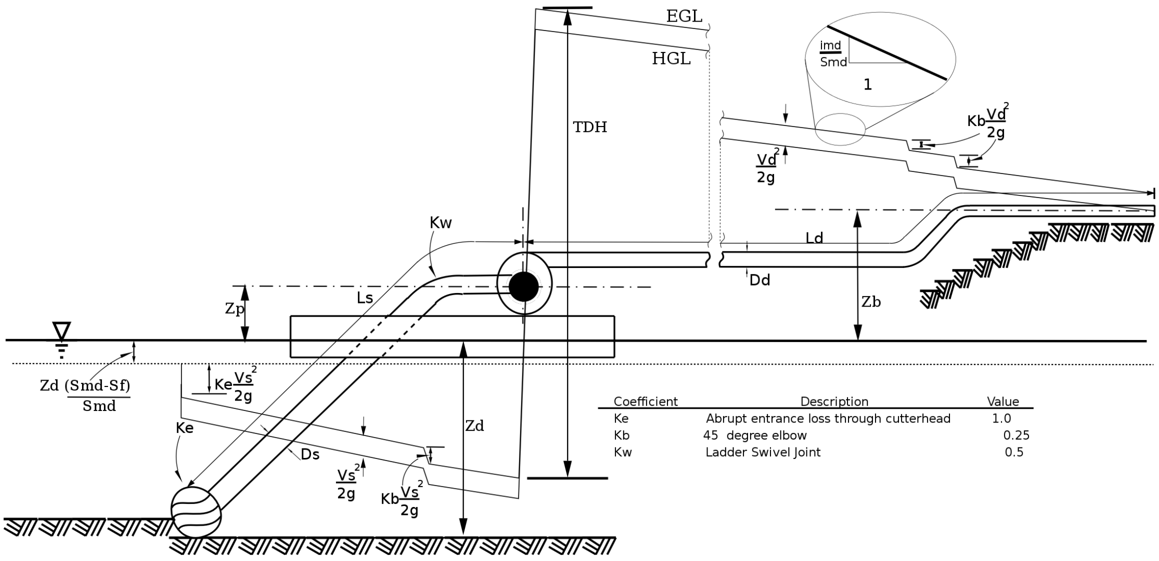
$$i_{md} = \frac{f_{wd} V_d^2}{2gD_d} + 0.22(S_{md} - 1)\left(\frac{V_{50d}}{V_d}\right)^m \quad (2.2)$$

$$i_{ms} = \frac{f_{ws} V_s^2}{2gD_s} + 0.22(S_{md} - 1)\left(\frac{V_{50s}}{V_s}\right)^m \quad (2.3)$$

$$f_{ws} = \frac{0.25}{\log_{10}\left(\frac{\epsilon_s}{3.7\times10^3 D_s} + \frac{5.74}{Re_s^{0.9}}\right)^2} \quad (2.4)$$

Table 2. Pipeline system and dredged material parameters and descriptions

Symbol	**Description**	**Default Value**
D_d	Discharge pipe diameter (m)	
D_s	Suction pipe diameter (m)	
L_s	Suction length (m)	
Z_d	Digging depth (m)	
Z_b	Discharge elevation (m)	
Z_p	Pump elevation (m)	
L_d	Pipeline discharge length (m)	
m	Slurry friction gradient exponent	1.7
ϵ_s	Pipe relative roughness (mm)	0.05mm
μ_s	Pipe mechanical friction factor	0.66
ρ_w	Water density (kg/m^3)	1,000kg/m^3
γ_w	Water unit weight (N/m^3)	9,810N/m^3
μ_w	Water viscosity (Pa·s)	10^{-3}Pa·s
g	Gravitational acceleration (m/s^2)	9.81(m/s^2)
ρ_s	Solid particle density (kg/m^3)	2,650kg/m^3
ρ_f	Carrier fluid density (kg/m^3)	1,015kg/m^3
d_{50}	Median sediment grain diameter(mm)	
S_{md}	Specific gravity of delivered pipeline material	
S_f	Specific gravity of carrier fluid	1.015
S_s	Specific gravity of sediment solid particles	2.65
H_a	Atmospheric Pressure Head (mH$_2$O)	10.4 (mH$_2$O)
H_v	Vapor Pressure Head (mH$_2$O)	0.18(mH$_2$O)



Coefficient	Description	Value
Ke	Abrupt entrance loss through cutterhead	1.0
Kb	45 degree elbow	0.25
Kw	Ladder Swivel Joint	0.5

Fig. 7. Pipeline dredge pump and pipeline system illustrating the energy and hydraulic grade lines.

$$f_{wd} = \frac{0.25}{\log_{10}\left(\frac{\epsilon_s}{3.7\times 10^3 D_d} + \frac{5.74}{Re_d^{0.9}}\right)^2} \tag{2.5}$$

$$R_{es} = \frac{\rho_f V_s D_s}{\mu_w} \tag{2.6}$$

$$R_{ed} = \frac{\rho_f V_d D_d}{\mu_w} \tag{2.7}$$

Friction gradients represent the head loss due to friction over unit length of pipeline. V_{50_d} and V_{50_s} represent the stratification velocity of the solid material in the discharge and suction pipelines, respectively in m/s as follows:

$$V_{50s} = w\sqrt{\frac{8}{f_{ws}}}\cosh\frac{60d_{50}}{1000D_s} \tag{2.8}$$

$$V_{50d} = w\sqrt{\frac{8}{f_{wd}}}\cosh\frac{60d_{50}}{1000D_d} \tag{2.9}$$

$$w = 0.9v_{ts} + 2.7\left(\frac{(\rho_s - \rho_w)\,g\mu}{\rho_w^2}\right)^{\frac{1}{3}} \tag{2.10}$$

v_t represents the particle settling velocity of the d_{50} sediment particles. The Pipeline Analytical Program uses the Wilson *et al.* (1997) regression equations shown in Equations 2.11–2.13 to determine v_t.

$$v_{ts} = v_{ts}^* \left[\frac{\rho_f^2}{\mu(\rho_s - \rho_f)g}\right]^{-1/3} \tag{2.11}$$

$$\begin{aligned}
v_{ts}^* &= (d^*)^2/18 - 3.1234 \times 10^{-4}(d^*)^5 && \\
&\quad +1.6415 \times 10^{-6}(d^*)^8 - 7.278 \times 10^{-10}(d^*)^{11} && (d^* < 3.8) \\
\log_{10} v_{ts}^* &= -1.5446 + 2.9162\log_{10}(d^*) - 1.0432\log_{10}^2(d^*) && (3.8 \le d^* < 7.58) \\
\log_{10} v_{ts}^* &= -1.64758 + 2.94786\log_{10}(d^*) - 1.090703\log_{10}^2(d^*) && \\
&\quad +0.17129\log_{10}^3(d^*) && (7.58 \le d^* < 227) \\
\log_{10} v_{ts}^* &= 5.1837 - 4.51034\log_{10}(d^*) + 1.687\log_{10}^2(d^*) && \\
&\quad -0.189135\log_{10}^3(d^*) && (227 \le d^*)
\end{aligned} \tag{2.12}$$

$$d^* = d\left[\frac{\rho_f(\rho_s - \rho_f)g}{\mu^2}\right]^{1/3} \tag{2.13}$$

The Pipeline Analytical Program uses a fixed value for S_{md} based on the *in-situ* sediment properties. The Pipeline Analytical Program first calculates S_{mi} based on the formula:

$$S_{mi} = 1.05x_f + 1.65(1 - x_f) \tag{2.14}$$

where the linearized formula calculates S_{mi} of 1.05 for pure fine material, 1.65 for pure sandy material, and linearly distributed in between. The Pipeline Analytical

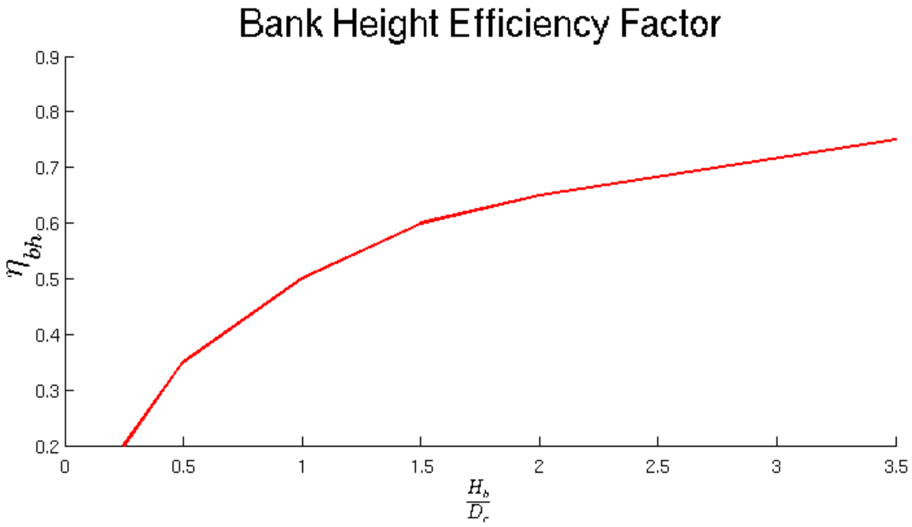


Fig. 8. Scott (1998) empirical relationship between bank height to cutterhead diameter ratio and bank height efficiency.

Program calculates the bulking factor of the dredged material, F_b, based on Herbich (2000) where:

$$F_b = 2.03x_f + 1.90(1 - x_f) \tag{2.15}$$

where F_b represents the bulking factor of the dredged material as it enters the dredge intake. The Pipeline Analytical Program further calculates efficiency reduction factors based on the cutterhead's mechanical ability to pursue the dredged material. Bank height efficiency, η_{bh}, measures the cutterhead's ability to pursue the material in the vertical plane. Scott (1998) calculates η_{bh} based on an empirical relationship between the cutterhead diameter, D_c, and the dredge face thickness, D_f, which measures the height of dredged material on the channel bed that the dredge cuts into. Figure 8 illustrates this empirical relationship.

The dredge efficiency, η_d, measures the cutterhead's ability to pursue the dredged material in the horizontal plane. Scott (1998) uses a dredge efficiency of 0.5 and 0.75 for walking spud and spud carriage cutterhead dredge, respectively. The Pipeline

Analytical Program then calculates the final value for delivered volumetric solids concentration, c_{vd}, and delivered specific gravity, S_{md}, as:

$$c_{vd} = \frac{c_{vi}\eta_{bh}\eta_d}{F_b} \tag{2.16}$$

$$S_{md} = c_{vd}\left(S_s - S_f\right) + S_f \tag{2.17}$$

The Pipeline Dredge Analytical Program computes the production rate for a pipeline dredge system given the pump, pipeline and dredged material characteristics as follows:

$$\dot{M} = Qc_{vd} \times 3600 \tag{2.18}$$

$$Q = V_d\frac{\pi D_d^2}{4} \tag{2.19}$$

where $\dot{M}$ represents production rate (m^3/hr) of dry solids and volumetric flow rate (m^3/s). In addition to these production metrics, the program also calculates the stationary bed velocity of the slurry material in the pipeline. The stationary bed Velocity, V_{sm}, represents the slurry velocity in the pipeline at which the solid material begins to settle out and accumulate along the bottom of the pipeline. V_{sm} represents the minimum velocity dredge pumps must maintain. The Pipeline Analytical Program uses Matusek's formula from Herbich (2000) to calculate V_{sm} for d_{50} outside the range of the nomograph as follows:

$$V_{sm} = 8.8k\left(\frac{\mu_s\left(S_s - S_f\right)}{0.66}\right)^{0.55}\frac{D_d^{0.7}d_{50}^{1.75}}{d_{50}^2 + 0.11D_d^{0.7}} \tag{2.20}$$

The Pipeline Analytical Program also uses a reduction factor to account for the effects of S_{md} as follows:

$$k = \begin{array}{ll} 6.75 c_r^{\alpha}\left(1 - c_r^{\alpha}\right)^2 & (c_{rm} < 0.33) \\ 6.75\left(1 - c_r\right)^{2\beta}\left(1 - \left(1 - c_r\right)^{\beta}\right) & \text{otherwise} \end{array} \tag{2.21}$$

$$c_r = 1.67 c_{vd} \tag{2.22}$$

$$\alpha = -\frac{\log(3)}{\log c_{rm}} \tag{2.23}$$

$$\beta = -\frac{\log(1.5)}{\log(1 - c_{rm})} \tag{2.24}$$

$$c_{rm} = 0.16 D_d^{0.40} d_{50}^{-0.84}\left(\frac{S_s - S_f}{1.65}\right)^{-0.17} \tag{2.25}$$

A. Dredge Pump Hydraulics

A dredge pump will operate at the point where the system TDH_s equals the *TDH* capability of the pump. Each dredge pump will operate according to its dredge pump performance curve. Figure 9 illustrates a typical pump performance curve. The Pipeline Analytical Program plots these pump performance curve data and determines the maximum pump performance curve based on maximum pump speed and maximum pump power. Figure 10 illustrates the maximum performance curve. The pipeline system *TDH* from Equation 2.1 will plot on a pump performance curve as shown in Figure 11.

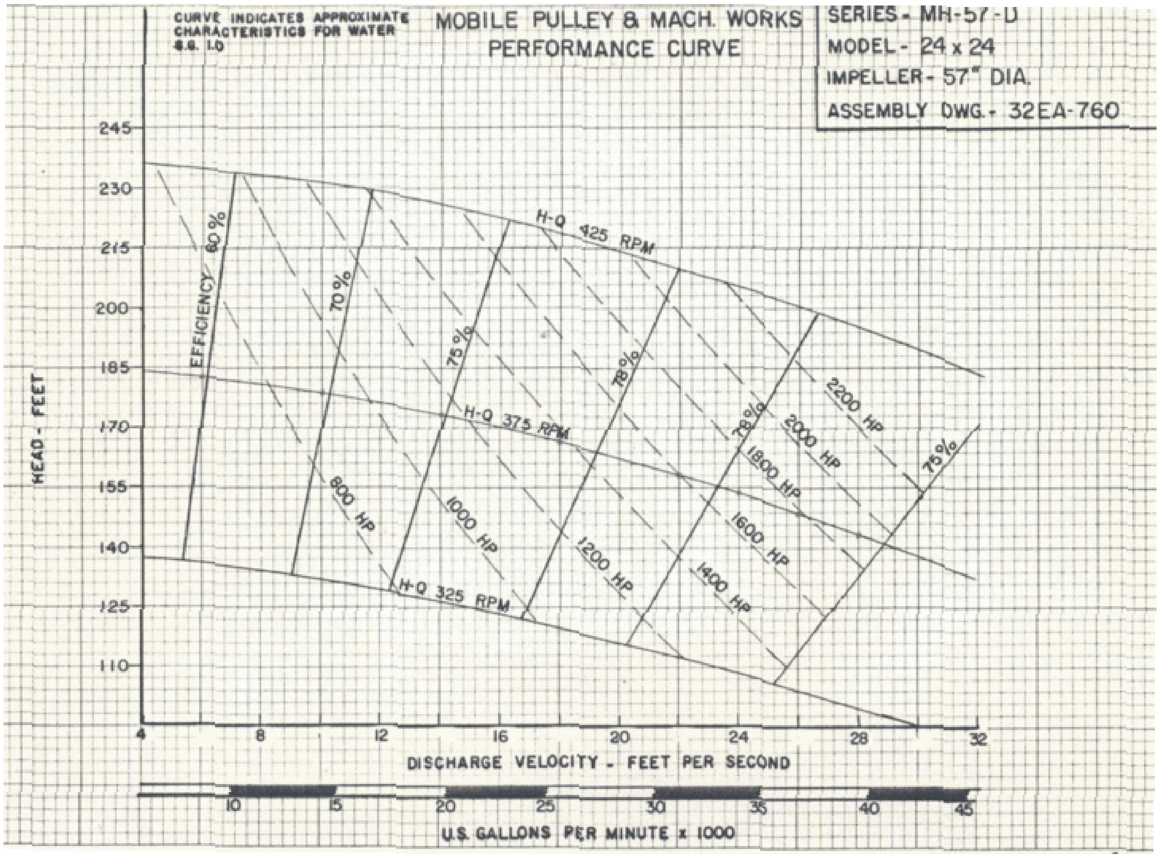


Fig. 9. Dredge pump manufacturer's performance curve (courtesy of Mobile Pump and Pulley Machine Works).

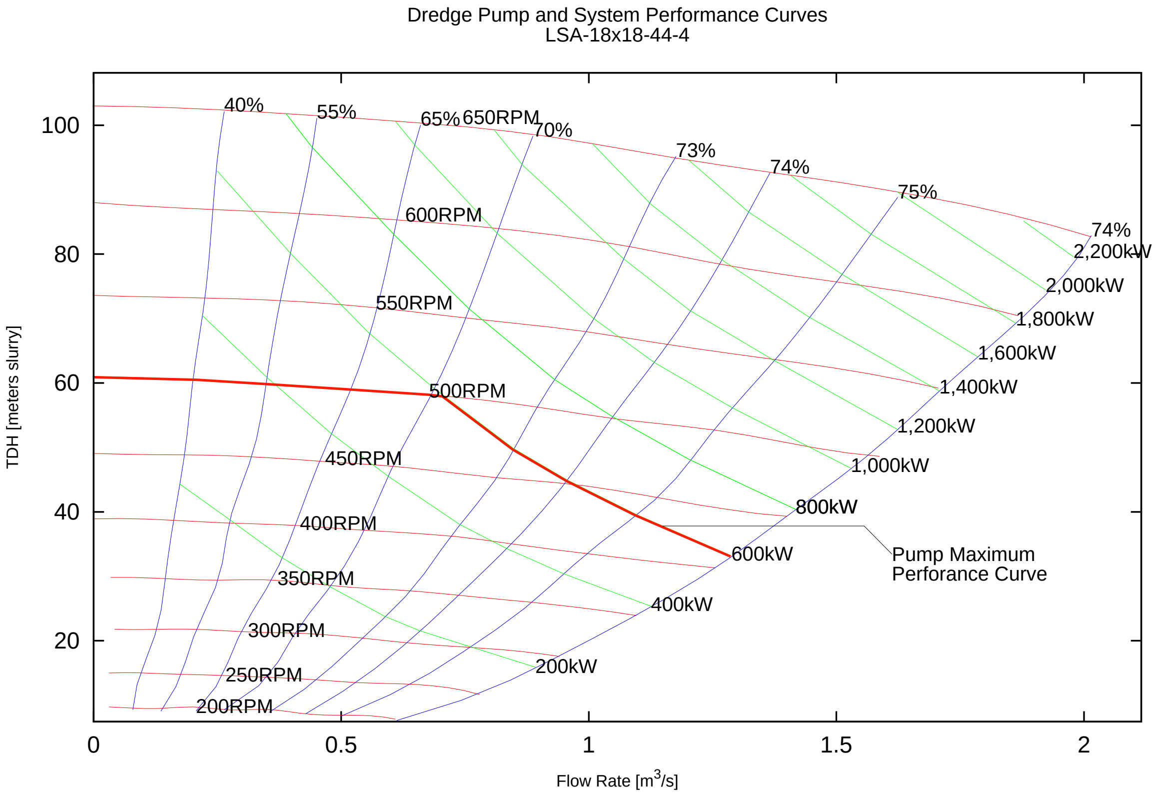


Fig. 10. Dredge pump maximum performance curve.

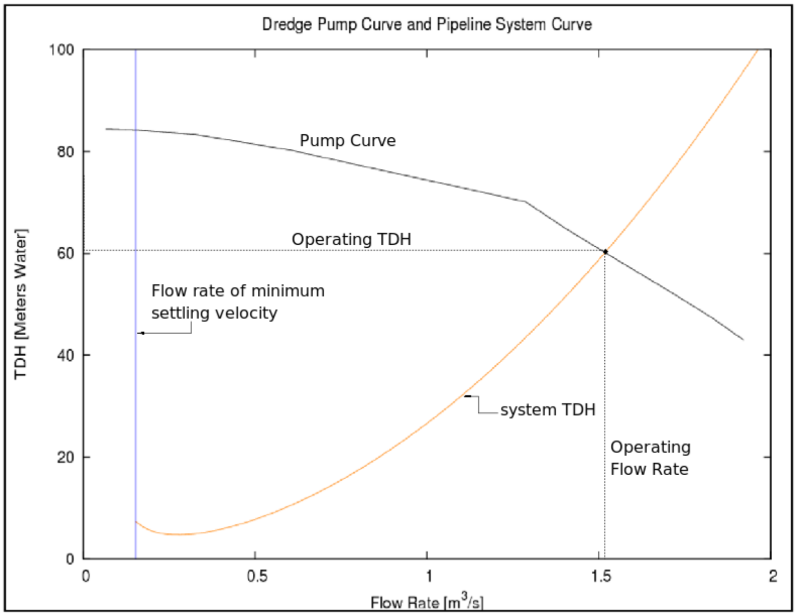


Fig. 11. Dredge pump and system performance curves for single pump.

B. Dredge Pump Cavitation

The Pipeline Analytical Program accounts for cavitation for the pump and pipeline system by comparing the net positive suction head available ($NPSHA$) in the pump to the pump's net positive suction head required ($NPSHR$). A pump system must maintain enough $NPSHA$ to meet the minimum requirement of $NPSHR$ for the pump. A typical pump curve provides the $NPSHR$ data as Figure 9 illustrates. The Pipeline Analytical Program calculates the $NPSHA$ as:

$$NPSHA = \frac{H_a - H_v}{S_{md}} - Z_d \frac{(S_{md} - S_f)}{S_{md}} - Z_p - \left(1 + \sum_{m=1}^{M} k_s\right) \frac{V_s^2}{2g} - L_s \frac{i_{ms}}{S_{md}} \qquad (2.26)$$

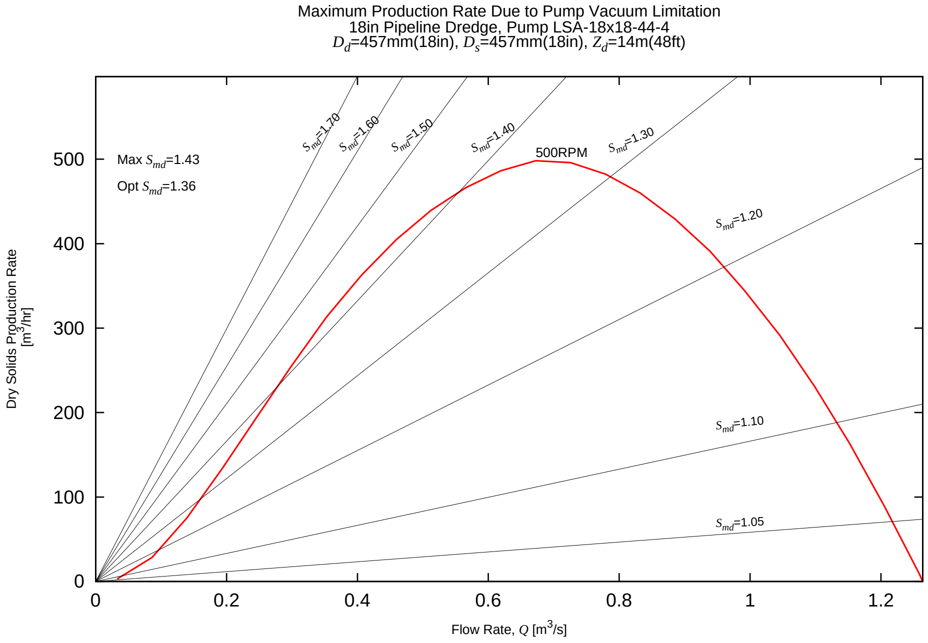


Fig. 12. Dredge pump and pipeline system maximum production curve.

The Pipeline Analytical Program determines the flow rate where a pump will cavitate for each RPM based on Equation 2.26 and the dredge pump affinity law for $NPSHR$ as:

$$NPSHR(RPM_2) = NPSHR(RPM_1)\left(\frac{RPM_2}{RPM_1}\right)^2 \tag{2.27}$$

The Pipeline Analytical Program plots a pumps maximum production by varying Q and S_{md}. Figure 12 plots the maximum production curve where $NPSHA$ equals $NPSHR$.

The Pipeline Analytical Program uses the $NPSHA$ data from the pipeline system and the $NPSHR$ data for each pump RPM to determine the pump's limited performance due to cavitation. For a given flow rate, the Pipeline Analytical Program calculates the system $NPSHA$ from Equation 2.26. The Pipeline Analytical

Program then determines the maximum RPM the pump can run based on Equation 2.27 as:

$$RPM_{max} = RPM_0 \left(\frac{NPSHA}{NPSHR(RPM_0)} \right)^{1/2} \tag{2.28}$$

Figure 13 illustrates the resulting maximum pump performance curve accounting for cavitation.

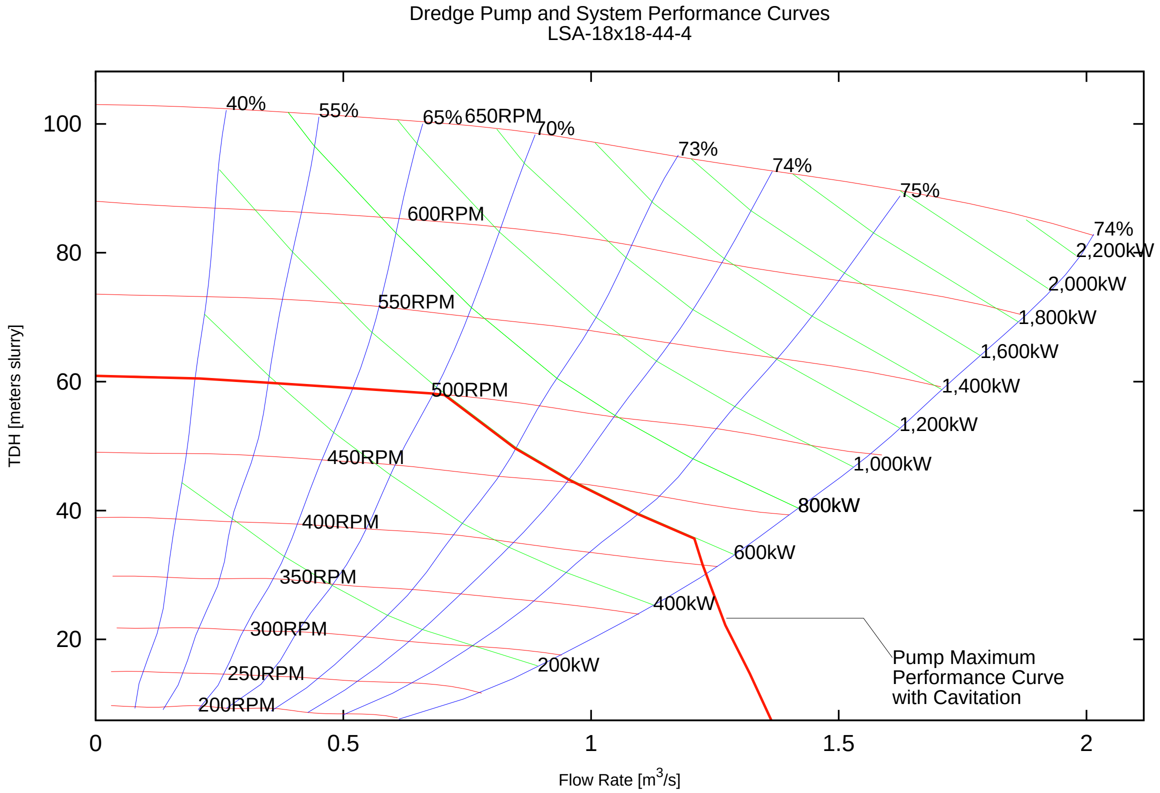


Fig. 13. Dredge pump maximum performance curve accounting for cavitation limitation.

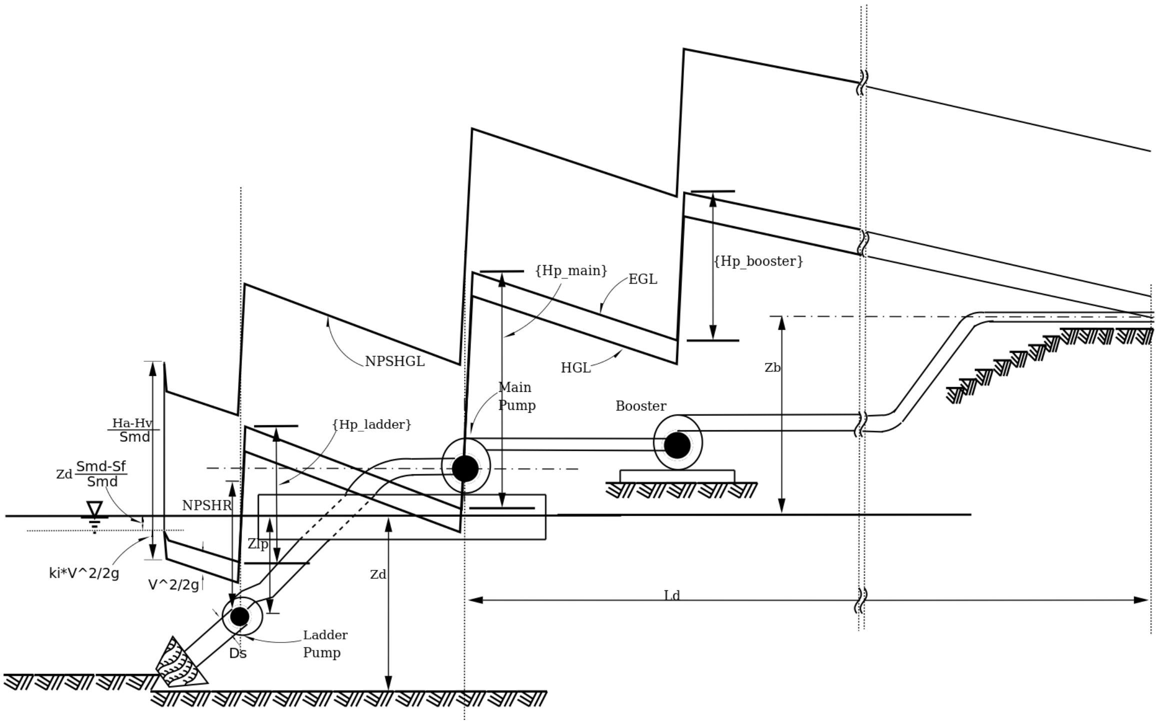


Fig. 14. Dredge pump series with ladder pump.

C. Pumps in Series

For pumps in series, the Pipeline Analytical Program calculates the overall pump system performance by adding the *TDH* of each pump in the series for a given flow rate. Each pump adds hydraulic head to the pipeline system at the same flow rate in the pipe. The pumps in series add TDH to the EGL and HGL. Figure 14 illustrates pumps in series and a ladder pump with HGL, EGL and NPSHGL.

The pump and pipeline system will interact at the intersection between the system curves for the pipeline and a composite pump curve that sums the *TDH* of each pump in the series for any given flow rate. Figure 15 illustrates this concept.

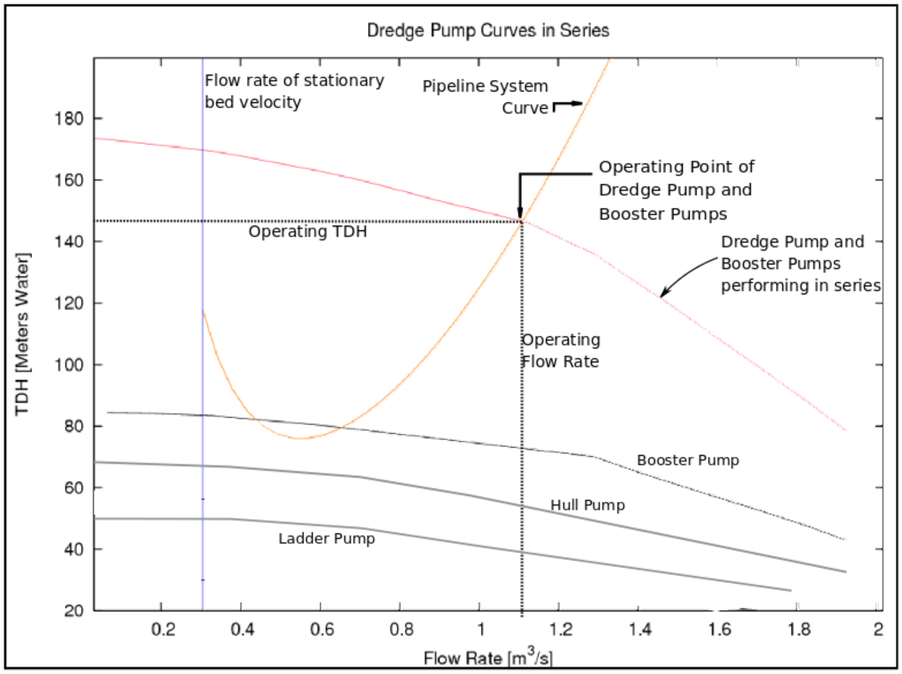


Fig. 15. Dredge pump curves and system performance curve for pumps in series.

D. Pump Performance Metrics

The Pipeline Analytical Program determines the resulting pump performance metrics for a given pump series and a range of L_d. The Pipeline Analytical Program determines the intersection of the system head curves for each L_d as Figure 16 illustrates. The Pipeline Analytical Program determines the performance metrics of the pump series by calculating the intersection of the composite pump curve and system curve for each L_d. The Pipeline Analytical Program determines the production rate, $\dot{M}$, and pump aggregate power, P, for each L_d producing a pump performance metrics graph as Figure 17 illustrates.

Pump Series Composite Pump and System Curves
for 0.5m(20.0in) Dredge
MPMW-18x18x34, LSA-18x18-44-4, LSA-18x18-44-4
D_d=508mm(20in), D_s=457mm(18in), Z_d=14m(48ft)

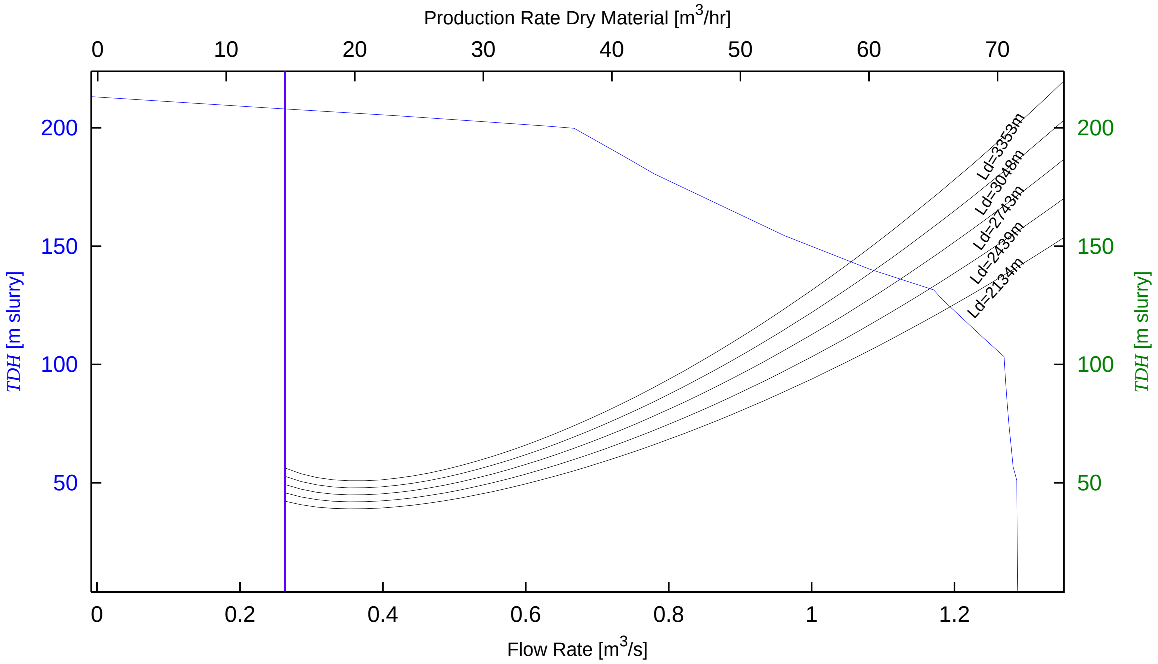


Fig. 16. Composite dredge pump curve and system performance curves for broad range of L_d.

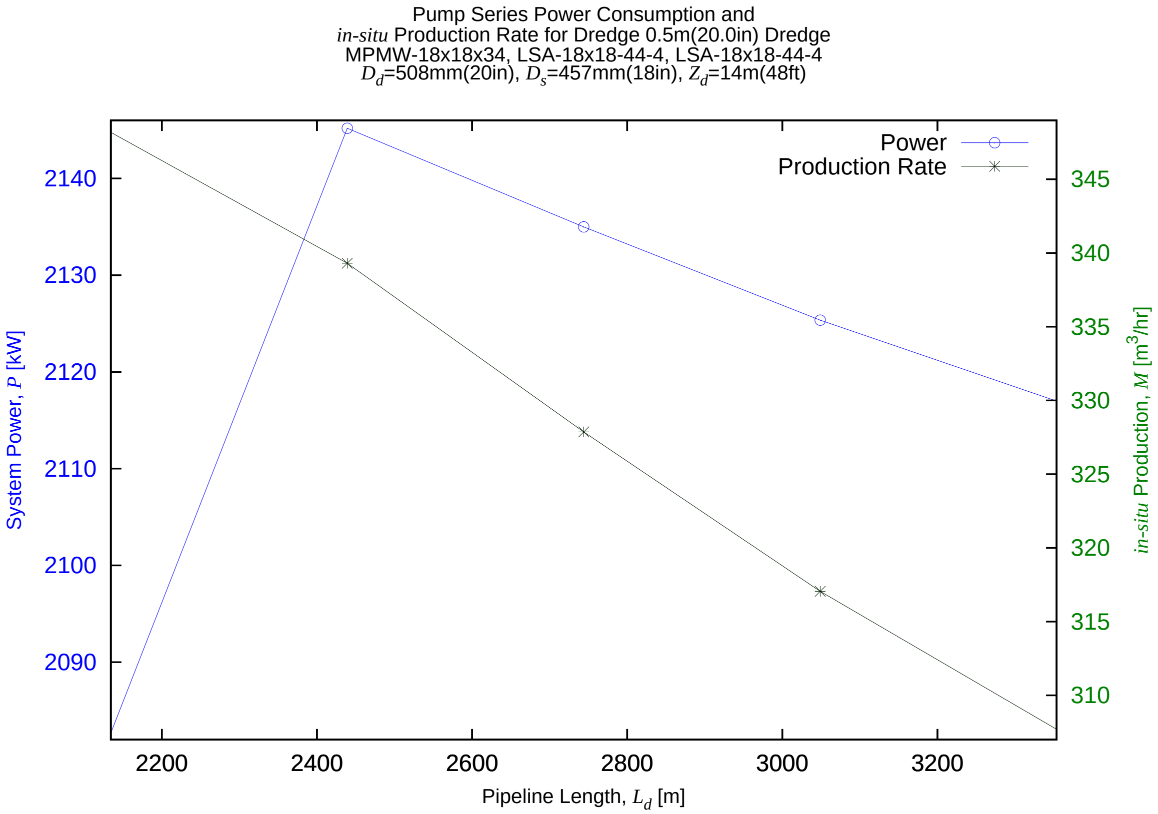


Fig. 17. Composite dredge pump and system performance metrics for production rate and power consumption.

E. Pipeline Hydraulics Summary

The Pipeline Analytical Program uses a methodical and analytical approach to computing the resulting pump system production and power consumption. This approach uses widely adopted empirical formula and soundly proven engineering principles that apply universally to dredge pump and pipeline systems based on basic pump and pipeline parameters. The Pipeline Analytical Program, therefore, provides a versatile and precise analytical tool to solve a pipeline dredge system's overall performance for a wide range of project applications.

CHAPTER III

DKBES OBJECT–ORIENTED STRUCTURE

The Dredging Knowledge–Base Expert–System (DKBES) uses an object–oriented architecture to store, process and retrieve pipeline dredging data. Object classes represent object types through attributes. Attributes contain common data parameters for each class. Message handlers perform functions on objects to change their attribute values or create new objects based on these attributes. A rules–base controls the operation of the pipeline dredge project design based on object parameters. The DKBES uses these object–oriented principles to formulate a pipeline dredging project based on the equipment and personnel available, the dredging design components, and the areas where the dredging takes place. This architecture efficiently solves the hydraulic engineering and economic principles in the complex and dynamic work environment of pipeline dredging.

A. Object Classes

The DKBES divides the object classes into non–project specific classes and project specific classes. Non–project specific classes use a common repository of data to form objects of equipment and personnel. Non–project classes base their data on user input or values calculated from the non–project specific classes. Some of these classes contain subclasses. Subclasses apply inheritance principles where the subclasses contain all of the attributes of its parent class. All of these classes form the fundamental design components of a pipeline dredge project.

1. Non-Project-Specific Classes

Non-Project Specific Classes represent the persistent data that do not change between dredge projects. The DKBES stores these data objects within the Knowledge–Base or calls them from an accessible database when needed.

a. Equipment

The equipment class contains the attributes associated with mechanical equipment used for a dredging project. Equipment ranges from the dredge itself to the pipeline used to transport the dredged material to the work boats and barges necessary to support dredge and personnel operations. All dredge equipment share common attributes associated with their operating expense.

The dredge size (measured by the discharge pipeline diameter) determines the quantity and size of the ancillary equipment. Larger dredges require more and larger support equipment. Equipment size will determine the capitol cost and installed power which will determine the overall operating cost of the equipment. Objects of equipment will reflect these factors in their attributes. Table 3 describes the equipment attributes.

Table 4 lists some of the equipment types the DKBES uses for pipeline dredge projects. These equipment types function as subclasses of equipment which, by definition, inherit the attributes of the equipment class. The pipeline subclass requires an additional attribute of section length. The pipeline subclass maintains the installed power attribute although not necessary.

Table 3. Equipment class attributes

Class attribute	**Description**
Name	Name of equipment
Dredge-Size	Size of dredge measured by pipeline diameter [m(in)]
Capitol-Cost	Acquisition cost of dredge [$]
Useful-Life	Average useful life of equipment [years]
Installed Power	Power plant capacity [kW (hp)]
Standby-Rate	Expense of letting equipment sit idle [$/hr]
Quantity	Quantity required for dredge project

b. Personnel

The personnel class contains the attributes associated with the personnel required to transport and operate the dredge and equipment. Personnel share common attributes of salary and minimum number required for the dredge project. Some personnel operate on an hourly pay rate while others operate on a monthly pay basis. Similarly to the equipment class, the size of the dredge determines the minimum number of personnel required and their associated salary. Table 5 describes the personnel attributes. Table 6 lists the types of personnel that function as subclasses of the personnel class.

Table 4. Equipment subclasses

Equipment subclass	**Description**
Work-Tug	Tug used for transporting the pipeline dredge, pipeline and other equipment.
Crew-Survey-Tug	Tug used for transporting personnel and conducting surveys.
Derrick	Barge with crane used to lift pipeline and other equipment into place.
Fuel-Water-Barge	Barge used to transport and store fuel and water.
Work-Barge	Barge used to carry and store equipment.
Pipeline-Dredge	Dredge plant with installed cutterhead, pumps and pipeline to dredge the material from the channel bottom.
Dredge-Pumps	Pumps installed on the dredge to pump the dredged material
Pipeline	Actual sections of pipe used to transport dredged material.
Joints	Mechanical connectors used to hold pipeline sections together.
Pontoons	Floating caissons used on floating sections of pipeline.
Booster-Pumps	Additional dredge pumps used in series along the pipeline.

Table 5. Personnel class attributes

Class attribute	**Description**
Name	Name of personnel
Dredge-Size	Size of dredge measured by pipeline diameter [m(in)]
Pay-Period	Hourly or monthly pay period
Pay-Rate	Employee salary per pay period [$]
Min-number	Number of these personnel required for dredge project of the given dredge size

Table 6. Personnel subclasses

Equipment subclass	**Description**
Monthly Employees	
Captain	Dredge project principal
Officer	Dredge project principal assistants
Chief-Engineer	Primary equipment manager
Office-Help	On or offsite administrative assistant
Hourly Workers	
Leverman	Dredge operator
Dredge-Mate	Dredge operator's assistant
Tug-Crew	Tug operator
Equipment-Operator	Ancillary equipment operator
Welder	Skilled welding specialist
Deckhand	General workers who assemble dredge pipeline
Electrician	Skilled electrical specialist
Discharge-Foreman	Foreman in charge of dredged material discharge
Shore-Crew	Crew members handling land–based operations of pipeline dredge project
Oiler	Diesel engine technician

Table 7. Task–method class attributes.

Class attribute	**Description**
Name	Name of task method
Equipment Used	List of equipment used in the task.
Personnel Used	List of personnel used. in the task.

c. Task-Method

The DKBES uses task methods to determine the time, cost and sequencing of a pipeline dredge project's integral operations. Each task method contains a method used to calculate the resulting time and cost parameters. These methods use the dredge project's attributes such as dredge size, pipeline length, and towing distance to determine the time, cost and number of crew required to perform the task. The methods use a list of equipment required for each task as well as additional associated costs to determine the total aggregate cost associated with the task method for the particular dredge project. Table 7 describes the task-method class.

Dredge operators must mobilize both dredge and pipeline for a dredge project, perform the necessary channel dredging and demobilize dredge and pipeline. The size and complexity of the dredge plant and pipeline requires significant mobilization and demobilization for safe and efficient transport. Table 8 lists the subclasses of Task–Method that account for these mobilization and demobilization tasks.

Table 8. Task method subclasses and their description.

Task–Method subclass	**Description**
Mobilization	
Prepare-dredge-for-transfer	Prepare dredge for barging from storage site to dredge site.
Prepare-pipeline-for-transfer	Prepare pipeline for barging from storage site to dredge site.
Transfer-pipeline	Transport pipeline sections by barge from storage site to dredge site.
Transfer-dredge	Transport dredge by barge from storage site to dredge site.
Setup-pipeline	Setup pipeline sections from dredge site to placement site.
Setup-dredge	Setup dredge at dredge site.
Dredge–Navigation–Channel	Perform dredging on navigation channel
Demobilization	
Prepare-dredge-for-transfer	Prepare dredge for barging from dredge site to storage site.
Prepare-pipeline-for-transfer	Prepare pipeline for barging from dredge site to storage site.
Transfer-pipeline	Transport pipeline sections by barge from dredge site to storage site.

Continued on next page

Table 8. Continued.

Task–Method subclass	**Description**
Transfer-dredge	Transport dredge by barge from dredge site to storage site.
Store-pipeline	Store pipeline sections from barge to storage site.
Store-dredge	Store dredge at storage site.

2. Project-Specific Classes

Project Specific Classes represent the data the DKBES produces for a particular dredge project. The DKBES creates these data objects from the data stored in the Non-Project Specific Classes and functions associated with the Task Methods. These objects then form the specific project components used to schedule and compute costs for the dredge project.

a. Cost-Code

The cost-code class contains the cost factors for equipment and personnel involved in a particular pipeline dredge project. The DKBES constructs cost-code objects from equipment and personnel objects based on cost calculation functions within the process modules. Cost-code objects contain the daily cost rates for equipment and personnel, hourly standby rates for equipment and the quantity of equipment or personnel required for a pipeline dredge project. Table 9 describes the cost-code class.

Table 9. Cost-code class attributes

Class attribute	**Description**
Dredge-Size	Size of dredge measured by pipeline diameter [m(in)]
Parent	Parent object of equipment or personnel that the cost code object calculates the cost factors for
Daily-Working-Rate	Daily cost factor for equipment or personnel object[$/day]
Hourly-Standby-Rate	Hourly cost factor equipment in standby mode[$/hr]
Quantity	Number of equipment or personnel required for the dredge project

b. Tasks

The Tasks class represents elements of the construction process. Tasks apply task-methods to the design components and work areas to determine task duration and aggregate cost. Table 10 describes the task class structure. Each element of the dredging project uses a task object to represent when it occurs in the dredging project, how long it takes to complete, how much it costs, and what resources it consumes in terms of equipment, personnel and fuel. Task objects list what other tasks must finish before they can begin with the preceded-by attribute. Likewise, task objects list what other tasks must wait to begin by the succeeded-by attribute.

Table 10. Task class attributes

Class attribute	**Description**
Name	Name of task
Task-Method Object	Link to the task method object
Design-Component	Link to the design-component object the task belongs to
Work-Area	Link to the design-component work-area object the task belongs to
Start-Date	Start date and time of task
Duration	Length in hours and days of the task.
Cost	Aggregate cost of task[$].
Preceded-By	Tasks that must complete before this task can initiate.
Succeeded-By	Tasks that immediately follow this task

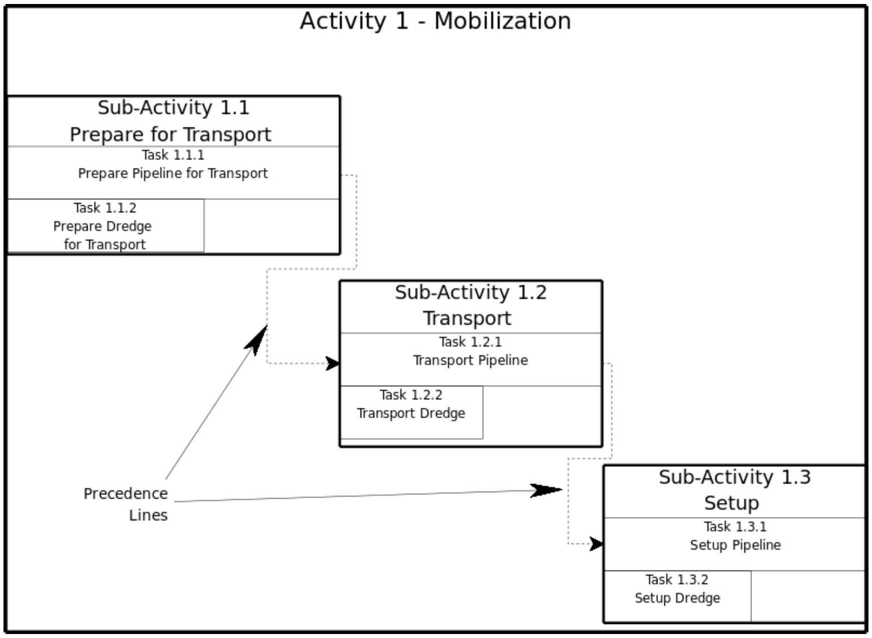


Fig. 18. Activity class precedence example.

c. Activity

The Activity class groups the elements of the dredge project containing several task objects or activity objects as sub-activities. Table 11 describes the activity class structure. Activities structure the dredge project through order of precedence or succession of tasks and sub-activities. Activities must wait for all predecessors to complete before they may begin. An activity calculates its start time as the latest finish time of all of its predecessors and its finish time as the latest finish time of all of its sub-activities and tasks. Figure 18 describes this process where the outer boxes represent activities, the inner boxes represent embedded sub-activities and tasks, and the dashed lines represent precedence where the one task or activity must finish before the successor may begin.

Table 11. Activity class attributes

Class attribute	**Description**
Name	Name of task
Sub-Activities	Link to other activity objects included in within the activity
Sub-Tasks	Link to task objects included in within the activity
Design-Component	Link to the design-component object the activity belongs to
Work-Area	Link to the design-component work-area object the activity belongs to
Start-Date	Start date and time of activity
Duration	Length in hours and days of the activity
Cost	Aggregate cost of activity[$].
Preceded-By	Tasks and activities that must complete before this task can initiate.
Succeeded-By	Tasks and activities that immediately follow this activity.

Table 12. Work area class attributes

Class attribute	**Description**
Name	Name of work area
Material-Type	Description of the dredged material
d_{50}	Mean grain size diameter [mm]
x_f	Fraction of fine material
S_{mi}	*in–situ* specific gravity of dredged material
Material-Volume	*in–situ* Volume of dredged material [m^3]
Channel Width	Width of navigation channel [m(ft)]
Channel Depth	Depth of navigation channel [m(ft)]

3. Work Areas

The work-area class describes the navigation channel for the dredge project. Work areas contain the attributes for the navigation channel relevant to the pipeline dredge process such as volume of material, material type and dredging depth. Table 12 describes the attributes for the work area.

a. Design–Component

The design–component class describes the dredge project in terms of the pipeline dredge, the work area(s), pipeline routes and dredged material placement site (DMPS). The design component attributes include links to the objects of these classes. Table 13 describes the attributes for the work area.

Table 13. Design–component class attributes

Class attribute	**Description**
Name	Name of design component
Pipeline Dredge	Object of pipeline dredge used for project
Work Areas	Objects of work areas in design component
Pipeline Routes	Objects of pipeline routes in design component
DMPS	Placement site objects in design component

B. Message Handlers

Message handlers perform functions on the DKBES objects based on their object class. Different object classes use different procedures and methods for determining their parameters although the Object–Oriented system calls the same function name for each object class. The Object–Oriented system will always assign the correct method to each object according to its class.

Message handlers serve several functions in the DKBES. Message handlers determine a task's duration and cost and generate cost code objects from equipment and personnel objects. Furthermore, message handlers handle ancillary functions such as sending the dredging schedule to a graphics output format for user viewing.

1. Cost–Code Generation

A message handler generates cost–code objects for equipment and personnel objects. Cost–Code objects relate the cost of personnel and equipment to the pipeline dredge project. Every crew member, craftsman and piece of dredging equipment has a base cost, salary for personnel and capital cost for equipment. However, geographic areas of operation as well as fluctuation in the price of commodities and interest rates will affect the overall cost of operating equipment and employing personnel. Therefore, the DKBES calculates operating cost of personnel and equipment based on the Miertschin and Randall (1998) spreadsheet program and stores these parameters in Cost–Code objects. These objects, in turn, provide the figures for the resulting cost of a pipeline dredging project. One message handler generates cost–code objects for equipment objects while another generates cost–code objects for personnel objects since these two classes contain different class attributes.

a. Equipment Cost–Codes

The equipment Cost–Code message handler generates a Cost–Code object for all equipment objects in the object library. The message handler uses the equipment object parameters of capital cost C_c, Standby–Rate R_{sb}, and quantity q. The message handler first calculates equipment depreciation cost factor, F_d, based on the capital cost of the equipment based on Miertschin and Randall (1998) as:

$$F_d = q\left(F_m + F_r + F_i\right) \tag{3.1}$$

Table 14 describes the depreciation parameters and their default values. The message handler then calculates the daily cost of depreciation from Miertschin and Randall (1998) as:

$$C_d = \frac{C_c F_d}{100 N_d} \tag{3.2}$$

where N_d represents the number of dredge days per year the dredge can operate. The message handler calculates the cost of fuel and lubricating oil for equipment from Miertschin and Randall (1998) as:

$$C_{fl} = 24\left(1 + f_l\right) P_{ins} f_c t_{100} q f_f \tag{3.3}$$

Table 14. Equipment depreciation cost factors from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
F_m	Percentage of capital cost necessary for annual maintenance of equipment	4.2%
F_r	Percentage of capital cost necessary for annual major repairs	9.0%
F_i	Percentage of capital cost necessary for insurance	2.5%

Table 15 describes the fuel and oil parameters and their default values. The message handler determines the cost of financing from Miertschin and Randall (1998) as:

$$C_f = \frac{C_c q}{T_{ul} N_d} \tag{3.4}$$

The message handler then generates a Cost–Code object with the preceding daily cost factors as attributes and the equipment objects as the value for its parent object as Figure 19 illustrates.

b. Pipeline Cost–Codes

The rules–base generates cost codes for the pipeline equipment differently from the remaining dredging equipment. Different material types affect the depreciation rate of the pipeline. The coarser the material, the more accelerated the wear in the pipeline. Therefore, the message handler calculates depreciation differently then from other equipment. The message handler uses the design component parameters for lengths of floating pipeline, submerged pipeline and shore pipeline as L_d. The work area object

Table 15. Equipment fuel and oil cost factors from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
P_{ins}	Installed power of equipment	
f_l	Lubricating oil factor	0.1
f_c	Fuel consumption gradient for diesel engines	0.253L/(kW.hr)
t_{100}	percentage of time dredge operates at 100% capacity	75.0%
f_f	Diesel cost rate	\$1.00/L

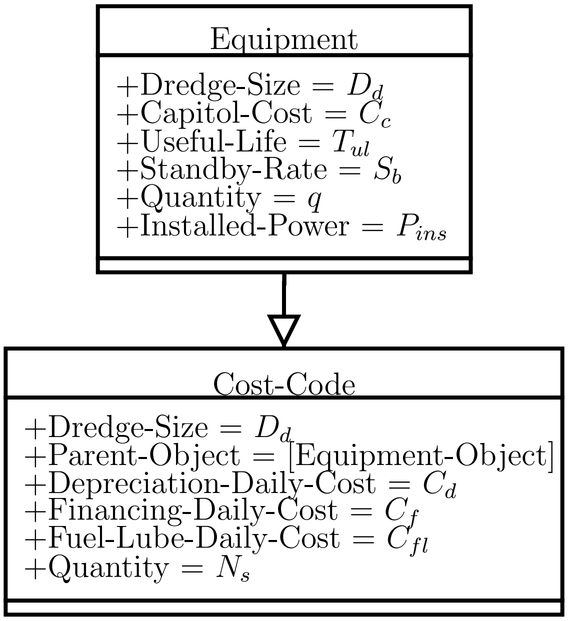


Fig. 19. Equipment cost–code object generation.

contains the value for material type expressed as the d_{50}. The pipeline equipment objects contain the values for the section lengths of the floating, submerged and shore pipeline as l_d. The message handler calculates the quantity of pipeline sections from Miertschin and Randall (1998) as:

$$N_s = \frac{L_d}{l_d} \tag{3.5}$$

The message handler calculates the cost factors for depreciation and financing similarly to that for the previous equipment with the exception of omitting the fuel and lubrication costs. The message handler calculates depreciation cost factor from Miertschin and Randall (1998) as:

$$F_d = N_s \left(F_m + F_r + F_i\right) \tag{3.6}$$

Table 16 describes the pipeline depreciation parameters and their default values. The message handler then calculates the daily cost of depreciation from Miertschin and Randall (1998) as:

$$C_d = \frac{C_c F_d}{100 N_d} \tag{3.7}$$

The message handler determines the cost of financing from Miertschin and Randall (1998) as:

$$F_c = \frac{C_c N_s}{\alpha_s T_{ul} N_d} \tag{3.8}$$

where α_s accounts for a serviceable life reduction factor. Table 17 lists the α_s values U.S. Army Corps of Engineers (2007) provides. The message handler then generates a Cost–Code object for each of the floating, submerged and shoreline pipeline segments based on these parameters as Figure 20 illustrates. In addition to the pipeline sections,

Table 16. Pipeline equipment depreciation cost factors from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
F_m	Percentage of capital cost necessary for annual maintenance of equipment	5.1%
F_r	Percentage of capital cost necessary for annual major repairs	11.0%
F_i	Percentage of capital cost necessary for insurance	2.5%

Table 17. Dredged material reduction factors.

Dredged Material	d_{50} **range**	**Default** α_s **Value**
Silt & Clay	$d_{50} \leq 75\mu\text{m}$	1.0
Sand	$75\mu\text{m} < d_{50} \leq 2\text{mm}$	0.5
Gravel	$2\text{mm} < d_{50}$	0.167

the message handler generates Cost–Code objects for pipeline joints for floating and submerged pipeline and pontoons for floating pipeline.

c. Personnel Cost–Codes

The personnel cost message handler generate a cost code for personnel similarly to the equipment cost message handlers. Monthly salaried employee cost–codes receive the employee base pay rate while hourly employees receive adjustment factors for employee benefits. The message handler imports the employee objects parameters

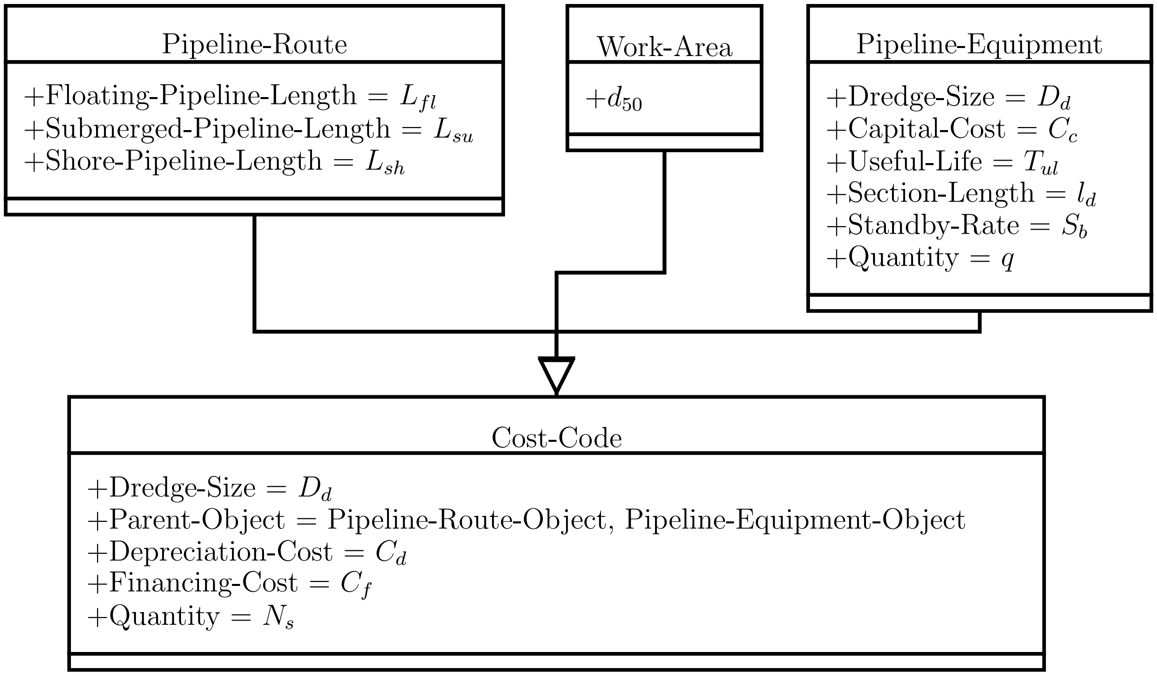


Fig. 20. Pipeline route cost–code object generation.

of pay–period (P_p), salary (S_e), and minimum number (N_m). The message handler then calculates the daily cost rate for monthly salaried employees from Miertschin and Randall (1998) as:

$$C_e = S_e \frac{12}{365} \tag{3.9}$$

For hourly employees, the message handler determines the daily cost rate from Miertschin and Randall (1998) as:

$$C_e = S_e N_{hs} N_{sd} \left(1 + \beta_{ot} + \frac{N_h}{365} + \frac{N_v}{365}\right) \left(1 + \beta_{ss} + \beta_{wc} + \beta_{su} + \beta_{fu}\right) \left(1 + \beta_{fr}\right) \tag{3.10}$$

Table 18 describes the cost parameters The message handler then generates a Cost–Code object with the daily cost, minimum number, and the employee object name as Figure 21 illustrates.

Table 18. Employee cost factors from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
N_{hs}	Number of hours per shift	12.0
N_{sd}	Number of shifts per day	1
β_{ot}	Overtime factor	14.3%
N_h	Holidays per year	13
N_v	Vacation days per year	10
β_{ss}	Social Security factor	2%
β_{wc}	Worker Compensation factor	45%
β_{su}	State unemployment factor	3.5%
β_{fu}	Federal unemployment factor	1.0%
β_{fr}	Fringe benefits factor	1.0%

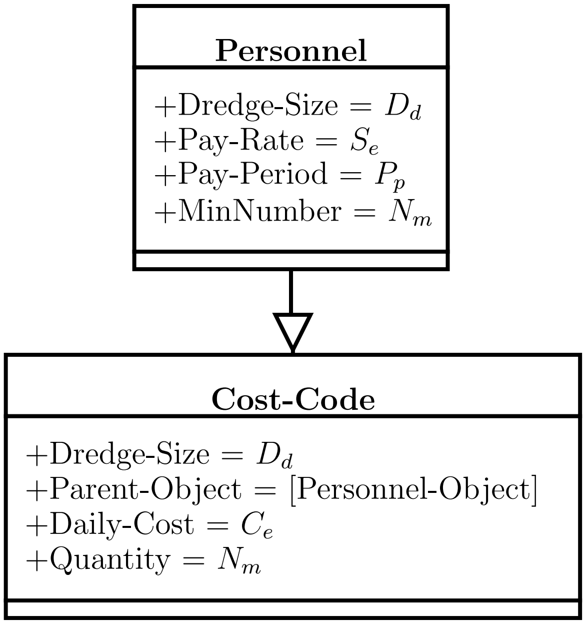


Fig. 21. Personnel cost–code object generation.

2. Determine Task Duration

The DKBES uses message handlers to determine a task's total duration from start to finish. Each Task object contains a pointer to its associated Task–Method. Message handlers associated with these task methods then calculate the duration based upon the Task objects parameters.

a. Dredge Channel Task Determine Duration

The message handler that determines the duration of a Dredge–Channel Task uses the results from the Pipeline Analytical Program and the properties of the Design–Component objects. The Pipeline Analytical Program calculates the performance metrics for the pump series in terms of *in–situ* production rate. The Design–Component object associated with the task provides the total pipeline length and the work–area object associated with the task provides the volume of *in–situ* material. Figure 22

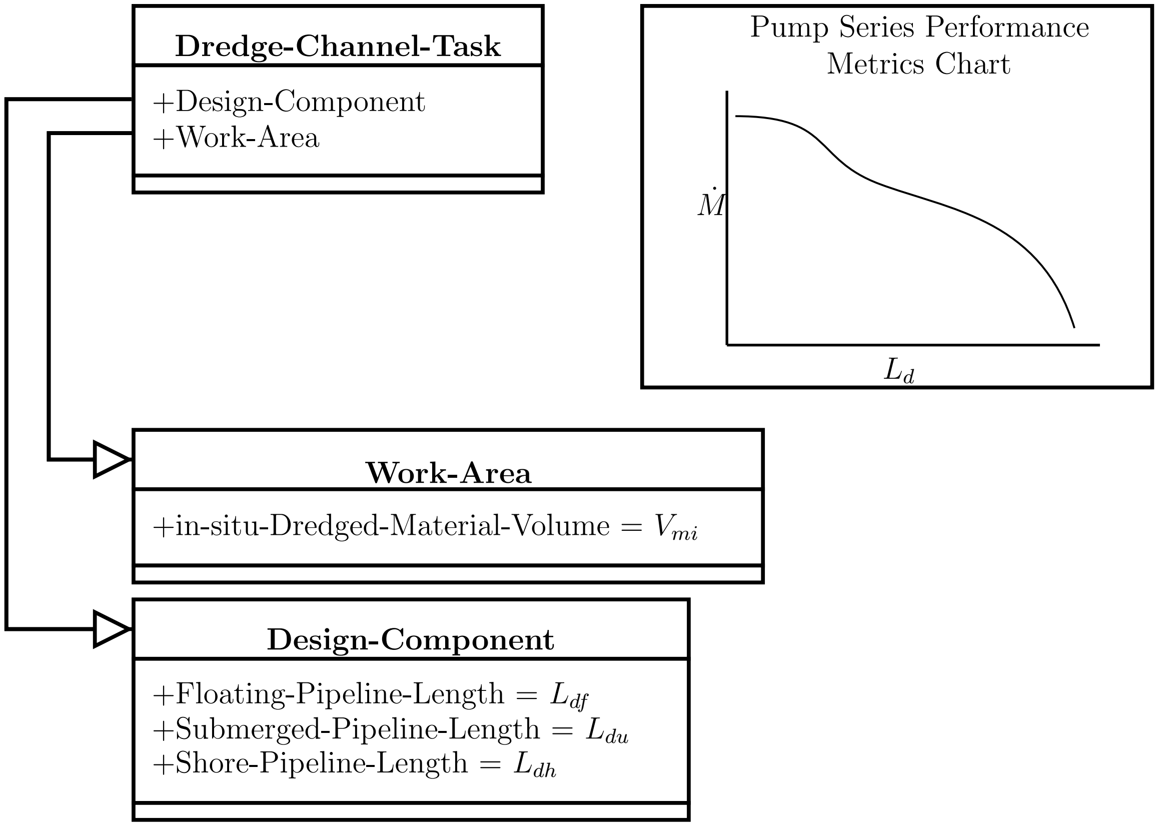


Fig. 22. Objects used to calculate dredge channel duration from Miertschin and Randall (1998).

illustrates these object relations and Table 19 describes the variables. The message handler calculates the duration of the task from Miertschin and Randall (1998) as:

$$T_{dc} = \frac{1}{\bar{T}_{dp}} \frac{V_{mi}}{P_{mi}} \tag{3.11}$$

b. Mobilization and Demobilization

The DKBES determines the times required to mobilize and demobilize the pipeline dredge project. The task methods contain message handlers that determine the time required to transport, setup and store the pipeline and dredge. Tables 20 and 21

Table 19. Variables used to determine dredge–channel task duration from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
T_{dc}	Time to dredge channel section [days]	
$\bar{T}_{dp}$	Average time dredge spends pumping [hrs/day]	16hrs/day
V_{mi}	*in–situ* volume of dredged material [m^3]	
P_{mi}	Production rate of *in–situ* dredged material [m^3/hr]	

lists the formula the message handlers use to calculate each duration. L_t and V_t represent the towing distance and speed, respectively. The DKBES uses default values of 241km(150miles) and 161km/day(100miles/day) for these respective parameters. The message handlers determine L_{df}, L_{du}, L_{dh} from the design–component object parameters similarly to the message handler used to determine the duration for a dredge–channel task.

3. Task–Costs

A dedicated message handler computes a task's cost through its task method. This message handler determines cost factors from the cost–code objects associated with the equipment and personnel the task method requires. The message handler then returns the total cost to assign to the task.

a. Mobilization and Demobilization

Message handlers calculate costs for the mobilization and demobilization tasks from cost–code objects for equipment and personnel. The message handlers for each task–

Table 20. Pipeline mobilization durations from Miertschin and Randall (1998).

Task–Method	**Duration Formula**
Prepare-dredge-for-transfer	$$T_{mpd} = 0.25D_d \qquad (3.12)$$
Prepare-pipeline-for-transfer	$$T_{mpp} = 0.0479\left(L_{df} + L_{du} + L_{dh}\right)^{1/2} \qquad (3.13)$$
Transfer-pipeline	$$T_{mtp} = \frac{L_t}{24V_t} \qquad (3.14)$$
Transfer-dredge	$$T_{mtd} = \frac{L_t}{24V_t} \qquad (3.15)$$
Setup-pipeline	$$T_{msp} = 0.7T_{mpp}\frac{(L_{df} + 1.25L_{du} + L_{dh})}{(L_{df} + L_{du} + L_{dh})} \qquad (3.16)$$
Setup-dredge	$$T_{msd} = 1.0 \qquad (3.17)$$

Table 21. Pipeline demobilization durations from Miertschin and Randall (1998).

Task–Method	**Duration Formula**
Prepare-dredge-for-transfer	$$T_{dpd} = 1.0 \tag{3.18}$$
Prepare-pipeline-for-transfer	$$T_{dpp} = 0.6T_{msp} \tag{3.19}$$
Transfer-pipeline	$$T_{dtp} = \frac{L_t}{24V_t} \tag{3.20}$$
Transfer-dredge	$$T_{dtd} = \frac{L_t}{24V_t} \tag{3.21}$$
Store-pipeline	$$T_{dsp} = 1.0 \tag{3.22}$$
Store-dredge	$$T_{dsd} = 1.0 \tag{3.23}$$

method contain a list of equipment and personnel necessary for the task. Furthermore, the message handler lists which equipment function as working and those that idle on standby. The message handler then aggregates the daily cost of these cost–codes and applies the task's duration to compute a total task cost from Miertschin and Randall (1998) as:

$$C_d = T_{task}\left(24\sum_{k=1}^{N_{sb}} C_{sb}(k) + \sum_{k=1}^{N_{we}} C_{we}(k) + \sum_{k=1}^{N_{pcc}} (C_p(k) + C_{sbs}) + C_{spt}\right) \tag{3.24}$$

$$C_{we} = C_d + C_f + C_{fl} \tag{3.25}$$

Table 22 defines these variables. Table 23 describes the cost–code objects and their function used to calculate cost of the prepare–pipeline-for–transfer–to–site and prepare–pipeline-for–transfer–from–site tasks. Table 24 describes the cost–code objects and their function used to calculate cost of the prepare–dredge–for–transfer–to–site and prepare–dredge–for–transfer–from–site tasks. Table 25 describes the cost–code objects and their function used to calculate cost of the transfer–dredge, setup–dredge, and store–dredge tasks. Table 26 describes the cost–code objects and their function used to calculate cost of the transfer–pipeline, setup–pipeline and store–pipeline tasks.

Table 22. Variables used to calculate task cost from Miertschin and Randall (1998).

Symbol	**Description**	**Default Value**
T_{task}	Task duration [day]	
C_{sb}	Hourly standby rate of equipment [\$/hr]	
N_{sb}	Number of equipment on standby	
C_{we}	Daily rate of working equipment [\$/day]	
N_{we}	Number of working equipment	
C_p	Daily working rate of personnel [\$/day]	
C_{sbs}	Daily subsistence rate for personnel [\$/day]	25[\$/day]
N_{pcc}	Number of personnel	
C_{spt}	Daily cost for supplies and tools [\$/day]	100[\$/day]

Table 23. Cost–code objects used to determine cost to prepare pipeline for transfer to and from dredge sites from Miertschin and Randall (1998).

Object Class	**Function**
Equipment	
Pipeline	Stand–by
Pipeline Joints	Stand–by
Pipeline Pontoons	Stand–by
Work tug	Working
Crew tug	Working
Fuel/water barge	Working
Work barge	Working
Derrick–Barge	Working
Personnel	
Shore–Crew	Working

Table 24. Cost–code objects used to determine cost to prepare dredge for transfer to and from dredge sites from Miertschin and Randall (1998).

Object Class	**Function**
Equipment	
Dredge	Stand–by
Booster–Pumps	Stand–by
Personnel	
Deck–Hand	Working

Table 25. Cost–code objects used to determine cost to transfer the dredge from Miertschin and Randall (1998).

Object Class	**Function**
Equipment	
Dredge	Stand–by
Booster–Pumps	Stand–by
Crew tug	Stand–by
Derrick	Stand–by
Fuel/water barge	Stand–by
Work barge	Working
Personnel	
Captain	Working
Deckhand	Working
Tug-Crew	Working

Table 26. Cost–code objects used to determine cost to transfer, setup and store the pipeline from Miertschin and Randall (1998).

Object Class	**Function**
Equipment	
Pipeline	Stand–by
Pipeline Joints	Stand–by
Pipeline Pontoons	Stand–by
Work barge	Working
Personnel	
Deckhand	Working

b. Dredge Channel Task Determine Cost

The dredge channel task cost for a dredge channel task similarly to other task methods. The message handler calculates the cost of equipment and labor from cost–code objects. However, the message handler determines the daily cost of dredge pump and booster pumps based on the Pipeline Analytical Program performance metric calculation for pump power consumption. Table 27 describes the equipment and personnel cost–code objects as well as their function in determining the dredge channel task's cost. The message handler determines the time to dredge the channel section from the dredge–channel task determine duration message handler. The message handler aggregates the daily costs of the equipment and personnel cost–code objects with the exception of the dredge and pump objects. For these objects the message handler uses the object parameters for depreciation and financing. For fuel and lube cost, the message handler uses the performance metrics for pump power consumption from the Pipeline Analytical Program. Figure 23 illustrates the cost–code objects parameters. Table 28 describes the variables used to calculate the total cost of the dredge–channel. The message handler calculates the total cost of the dredge–channel as:

$$
\begin{aligned}
C_{day} = T_{dc} \Bigg(\sum_{k=1}^{N_{pcc}} C_p(k) + \sum_{k=1}^{N_{nep}} \left(C_d(k) + C_f(k) + C_{fl}(k) \right) + \\
\sum_{k=1}^{N_{ep}} \left(C_d(k) + C_f(k) \right) + \left(1 + f_l\right) P_{pump}(k) f_c t_{100} f_f \Bigg)
\end{aligned}
\tag{3.26}
$$

Table 27. Dredge channel task cost–codes from Miertschin and Randall (1998).

Object Class	**Function**
Equipment	
Pipeline-Dredge	Working
Work-Tug	Working
Crew-Survey-Tug	Working
Derrick	Working
Fuel-Water-Barge	Working
Work-Barge	Working
Pipeline	Working
Joints	Working
Pontoons	Working
Booster-Pumps	Working
Personnel	
Captain	Working
Officer	Working
Chief-Engineer	Working
Office-Help	Working
Leverman	Working
Dredge-Mate	Working
Tug-Crew	Working
Equipment-Operator	Working

Continued on next page

Table 27. Continued.

Object Class	**Function**
Welder	Working
Deckhand	Working
Electrician	Working
Dump-Foreman	Working
Shore-Crew	Working
Oiler	Working

Table 28. Variables used to calculate dredge channel task cost.

Symbol	**Description**
N_{nep}	Number of equipment not pumping related
P_{pump}	Pipeline Analytical Program calculated pumping power [kW]
N_{ep}	Number of pumping related equipment

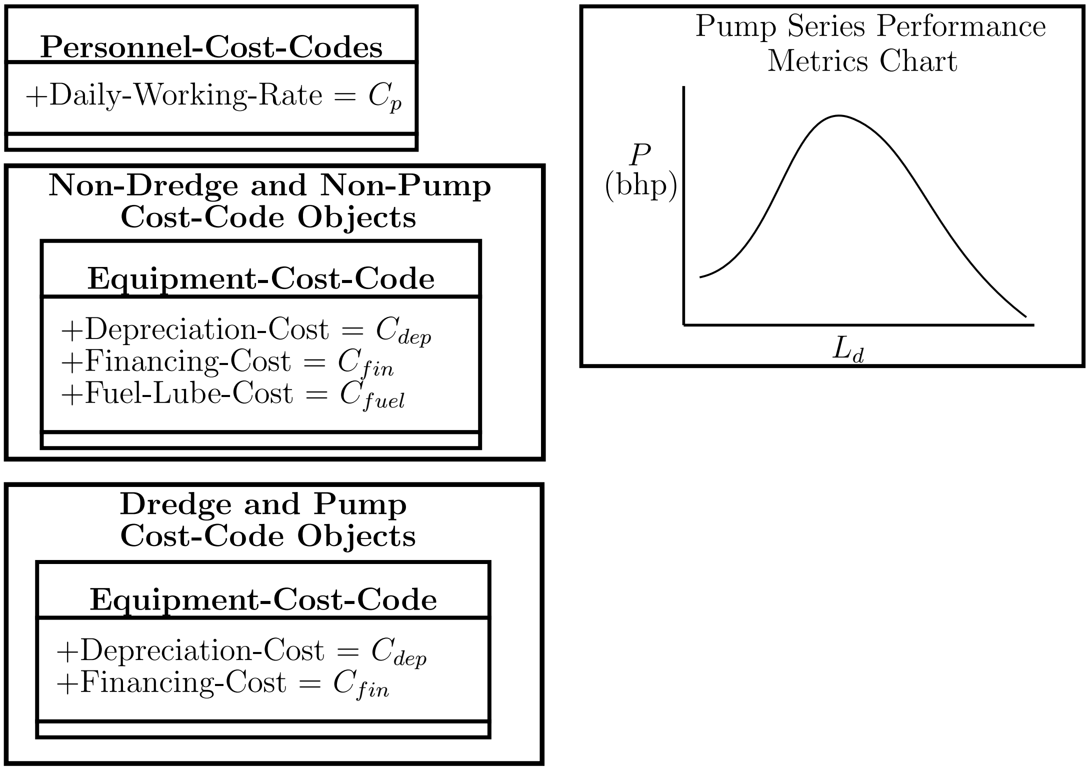
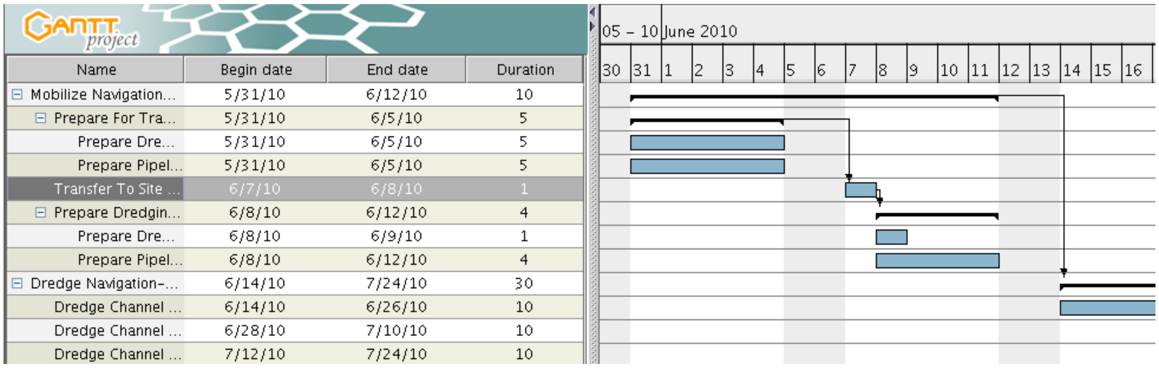


Fig. 23. Objects used to calculate dredge channel cost.



Name	Begin date	End date	Duration
⊟ Mobilize Navigation...	5/31/10	6/12/10	10
⊟ Prepare For Tra...	5/31/10	6/5/10	5
Prepare Dre...	5/31/10	6/5/10	5
Prepare Pipel...	5/31/10	6/5/10	5
Transfer To Site ...	6/7/10	6/8/10	1
⊟ Prepare Dredgin...	6/8/10	6/12/10	4
Prepare Dre...	6/8/10	6/9/10	1
Prepare Pipel...	6/8/10	6/12/10	4
⊟ Dredge Navigation-...	6/14/10	7/24/10	30
Dredge Channel ...	6/14/10	6/26/10	10
Dredge Channel ...	6/28/10	7/10/10	10
Dredge Channel ...	7/12/10	7/24/10	10

Fig. 24. Gantt chart output of the pipeline dredge project.

c. Ancillary Message Handlers

Message handlers format the output for the graphical scheduling output of the resulting pipeline dredge project to a Gantt chart program. The message handler calls the mobilization, dredging and de–mobilization activities and iterates through their sub–activities and tasks exporting their start–date, duration, end–date and precedence parameters to the charting program. Figure 24 illustrates the resulting Gantt chart output.

C. Process Modules

The DKBES uses four process modules to formulate a pipeline dredge project. These modules use the existing knowledge–base of equipment, personnel and task–method objects as well as project specific objects for design–components, work–areas and dredged–material.

1. Design–Initialization

The Design–Initialization Module generates the dredge project activities based on the pipeline dredge, work area and pipeline route specified in the design–component

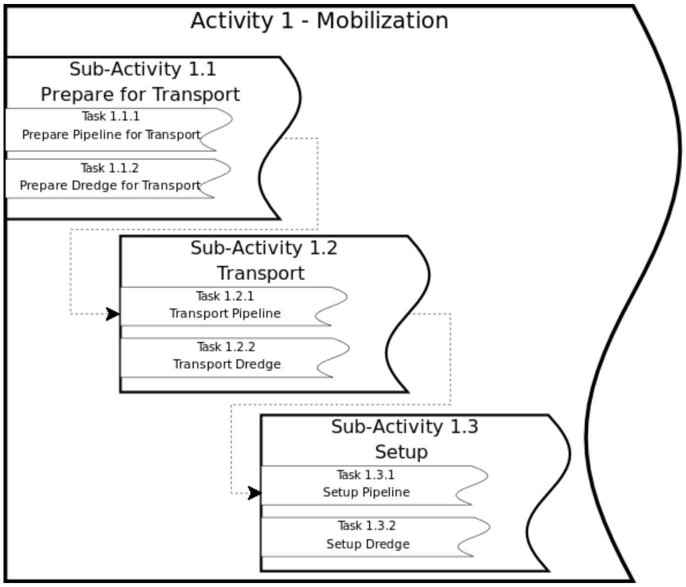


Fig. 25. Initial design of pipeline dredge project.

object. This module uses a rules–base to construct the activities, sub–activities and tasks necessary to execute the dredge project from start to finish. These rules assign tasks to activities and sub–activities and define the precedence relationship between mobilization, demobilization and channel dredging. While the rules construct the order of the pipeline dredge project, they leave out definitive time schedules and start or end times. Figure 25 illustrates the resulting initial design.

a. Build–Mobilization–Demobilization

The Build–Mobilization module rules will generate a mobilization activity for a Design–Component object. Mobilization requires several sub–activities and tasks. Table 29 describes the mobilization activities and their sub–activities and tasks.

Table 29. Precedence factors for mobilization activities and tasks.

Sub–Activities and Tasks	**Preceded-By**
Prep-For-Transfer-To-Site-Activity	None
Prep-Dredge-Task	None
Prep-Pipeline-Task	None
Transfer-To-Site-Activity	Prep-For-Transfer-To-Site-Activity
Transfer-Dredge-To-Site	None
Transfer-Pipeline-To-Site	None
Setup-Dredge-Pipeline-Activity	Transfer-To-Site-Activity
Setup-Dredge-Task	None
Setup-Pipeline-Task	None

b. Dredging–Activity

The DKBES generates the dredging activity and tasks according to the work areas specified in the design–component object. The dredging activity rules-base generates a Dredge–Channel task for each work area in the design component. A Dredge–Channel activity contains each Dredge–Channel tasks for the Design–Component object. Each Dredge–Channel task will contain a Dredge–Channel task method. The rules will order the Dredge–Channel tasks by setting the preceded–by attribute to the Dredge–Channel task of the work area before it in sequence.

c. Build–Demobilization

The Build–Demobilization rules will generate a demobilization activity for a Design–Component object. Table 30 describes the demobilization activities and their sub–activities and tasks.

Table 30. Precedence factors for demobilization activities and tasks.

Sub–Activities and Tasks	**Preceded-By**
Prep-For-Transfer-From-Site-Activity	
Prep-Dredge-Task	
Prep-Pipeline-Task	
Transfer-From-Site-Activity	Prep-For-Transfer-From-Site-Activity
Transfer-Dredge-From-Site	
Transfer-Pipeline-From-Site	
Prepare-For-Storage-Activity	Transfer-From-Site-Activity
Store-Dredge-Task	
Store-Pipeline-Task	

2. Initial–Scheduling

The Initial–Scheduling module contains the rules–base to determine the duration of each task within the initial design. The rules–base applies the message handlers that determine the duration of each task according to its task–method. This module

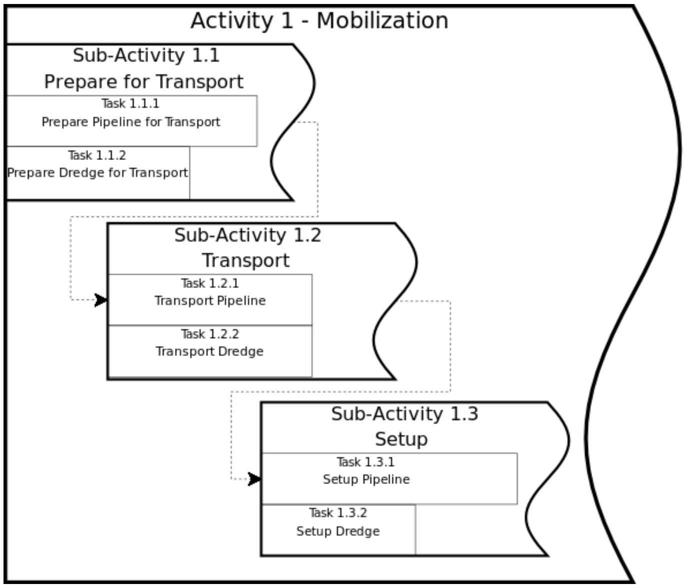


Fig. 26. Initial scheduling of pipeline dredge project.

establishes the time necessary to complete each task within the dredge design will leaving out any calculation to determine the start or end date of the tasks or activities. Figure 26 illustrates the resulting initial scheduling.

3. Detailed–Scheduling

The Detailed–Scheduling module determines the rigid schedule of the dredge project by establishing actual start dates and end dates for each activity and their sub–activities and tasks. The first rule determines tasks and activity start dates by tasks and activities that precede them. A task or activity cannot start before any task or activity that precedes it completes. The second rule evaluates sub–activities and tasks within an activity. Sub–activities and tasks cannot start before their main activity can start. The rules will set the start and end dates of the tasks and activities according to these criteria. Figure 27 illustrates the resulting detailed schedule.

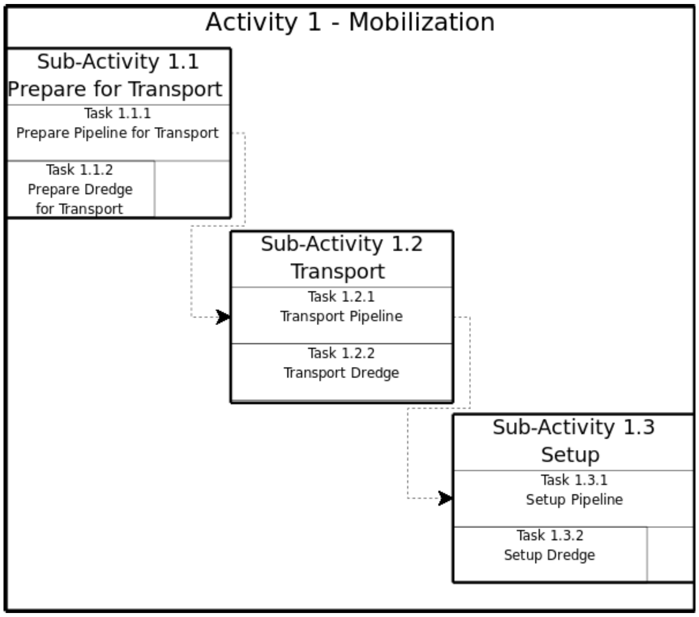


Fig. 27. Detailed scheduling of pipeline dredge project.

4. Cost–Distribution

The Cost–Distribution module determines the aggregate cost of activities, sub–activities and tasks. The rules–base for this module first constructs cost–code objects for all the equipment and personnel objects within the knowledge–base. A rule determines the aggregate cost of each task by applying the message handlers that determine the cost associated with each task. Finally, rules will determine the aggregate cost of activities and sub–activities by the sum of their activity costs.

D. DKBES Architecture Summary

The DKBES object–oriented architecture provides the knowledge–base expert–system the versatility to solve a pipeline dredge projects based on common attributes of the pipeline dredge components. The classes structure the components into objects. Message handlers calculate the object parameters based on class. Rules define the work flow of the pipeline dredge project based on the objects and message handlers that process their attribute values.

CHAPTER IV

GOETZ FIELD DATA COLLECTION

The U.S. Army Corps of Engineers pipeline dredge *Goetz*, a 508mm(20in) cutterhead pipeline dredge with a single onboard dredge pump, collected dredge production data on June 22, 2009 from onboard dredge instrumentation while dredging on the Upper Mississippi River near St. Paul, Minnesota. The dredge production data can provide insight and understanding as to how well the theoretical and empirical equations for pipeline hydraulics and slurry transport compares to actual dredge production. Analysis of the dredge instrumentation data can verify how well the Pipeline Analytical Program can predict production rate on a cutterhead pipeline dredge based on pump and pipeline parameters.

A. *Goetz* Description

Table 31 describes the *Goetz* pipeline dredge parameters involved in the dredging project on the Upper Mississippi River. Figure 28 illustrates the *Goetz* dimensionless pump performance curves. Figure 29 illustrates the dredge pipeline parameters and the dredge pump instrumentation. Table 32 describes the onboard instrumentation data parameters the *Goetz* collects. TDH measurements require further calculation from the instrumentation data where:

$$TDH_s = \frac{P_d - P_s}{S_{md}\gamma_w} + \frac{16\pi^2}{2g}\left(\frac{1}{D_d^4} - \frac{1}{D_s^4}\right)Q^2 \tag{4.1}$$

Table 31. Dredge *Goetz* Pipeline Dredge pump and pipeline system parameters.

Symbol	**Description**	**Value**
D_d	Discharge pipe diameter (m)	0.508m(20in)
D_s	Suction pipe diameter (m)	0.559m(22in)
D_i	Pump impeller diameter (m)	1.370m(54in)
L_s	Suction length (m)	11.0m(36ft)
Z_d	Digging depth (m)	3.7m(12ft)
Z_b	Discharge elevation (m)	24.1m(79ft)
Z_p	pump elevation (m)	0.5m(1.64ft)
L_d	Pipeline discharge length (m)	627.7m(2,059ft)
m	Slurry friction gradient exponent	1.7
ϵ_s	Pipe relative roughness (mm)	0.508mm(0.02in)
ρ_w	Water density (kg/m^3)	1,000kg/m^3
γ_w	Water unit weight (N/m^3)	9,810N/m^3
μ_w	Water viscosity (P·s)	10^{-3}P·s
g	Gravitational acceleration(m/s^2)	9.81m/s^2
ρ_s	Solid particle density(kg/m^3)	2,650kg/m^3
d_{50}	Median sediment grain diameter(mm)	0.1mm
x_f	*in–situ* fine material fraction	0.1
S_{md}	Specific gravity of pipeline slurry	
S_{mi}	Specific gravity of *in–situ* material	
S_f	Specific gravity of carrier fluid	1.0
S_s	Specific gravity of sediment solid particles	2.65
H_a	Atmospheric Pressure Head (mH$_2$O)	10.4 (mH$_2$O)
H_v	Vapor Pressure Head (mH$_2$O)	0.18(mH$_2$O)

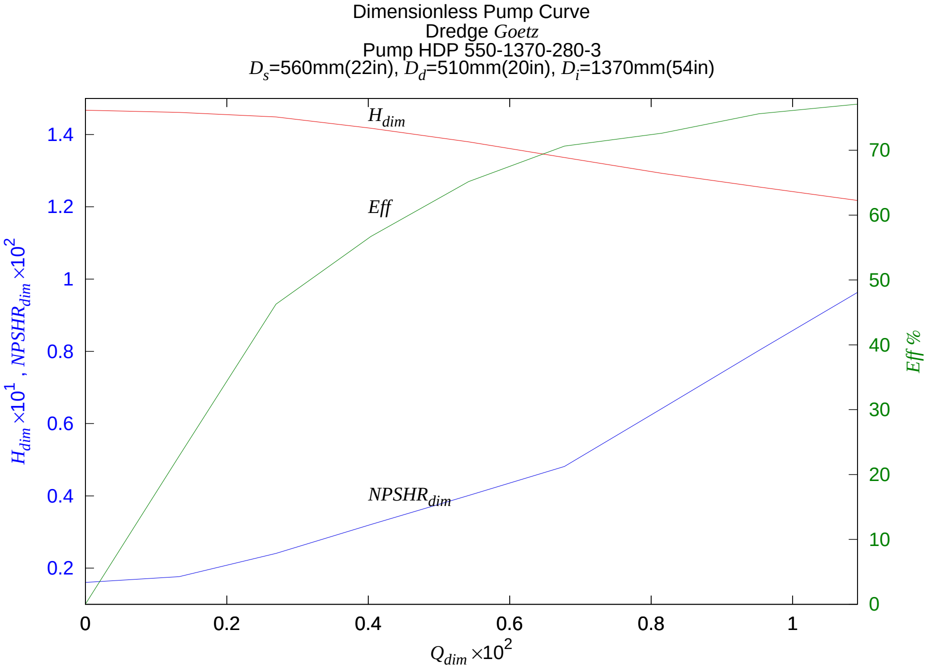


Fig. 28. Dredge *Goetz* dimensionless pump curve.

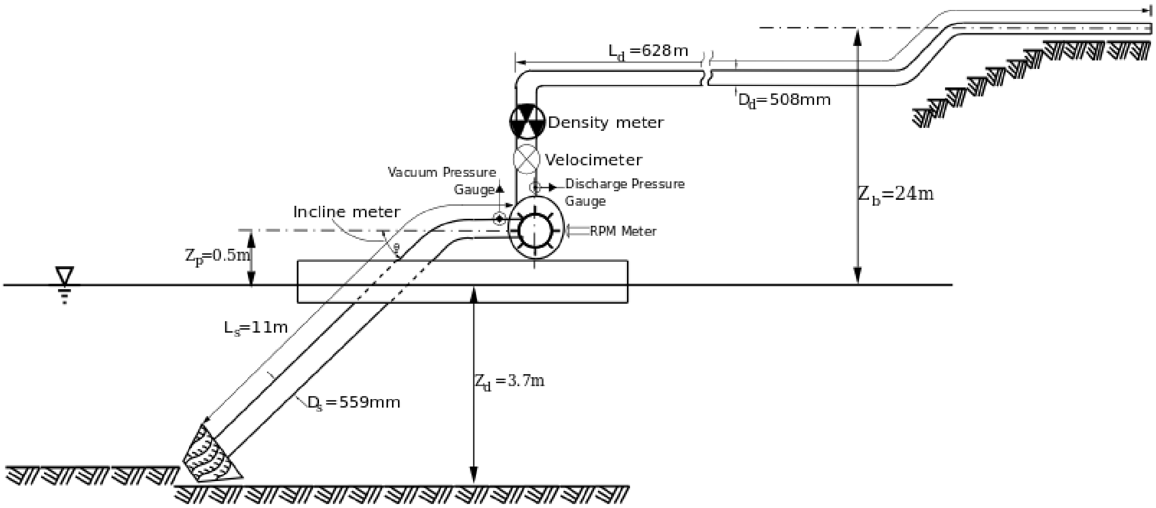


Fig. 29. Dredge *Goetz* pump and pipeline system configuration.

Table 32. Pipeline dredge *Goetz* Silent Inspector parameters.

Pipeline Dredge Parameter	**Pipeline Dredge Instrument**
Z_d	Inclinometer
RPM	Pump RPM meter
P_s	Pump suction pressure gauge
P_d	Pump discharge pressure gauge
V_d	Pump discharge velocity meter
S_{md}	Nuclear density meter

B. Dimensionless Pump Data Analysis

Dimensionless pump parameters indicate how well the dredge instrumentation data coincide to the dredge pump performance curve. Figure 30 illustrates the comparison of the actual dimensionless pump data of dimensionless flow rate, Q_{dim}, and dimensionless head, TDH_{dim}, from the dredge instrumentation data to the pump curve dimensionless data where:

$$Q_{dim} = \frac{Q}{\omega D_i^3} \tag{4.2}$$

$$TDH_{dim} = \frac{TDH_s g}{\omega^2 D_i^2} \tag{4.3}$$

The actual dimensionless head consistently exceeded the theoretical dimensionless curve. Figure 31 illustrates the residuals between the actual dimensionless head and the theoretical dimensionless head according to the pump curve data where:

$$RES_{TDH_{dim}} = TDH_{dim}(\mathsf{actual}) - TDH_{dim}(\mathsf{theoretical}) \tag{4.4}$$

Specific gravity presents the only noticeable pattern of residuals where the residuals decrease steadily when specific gravity increases.

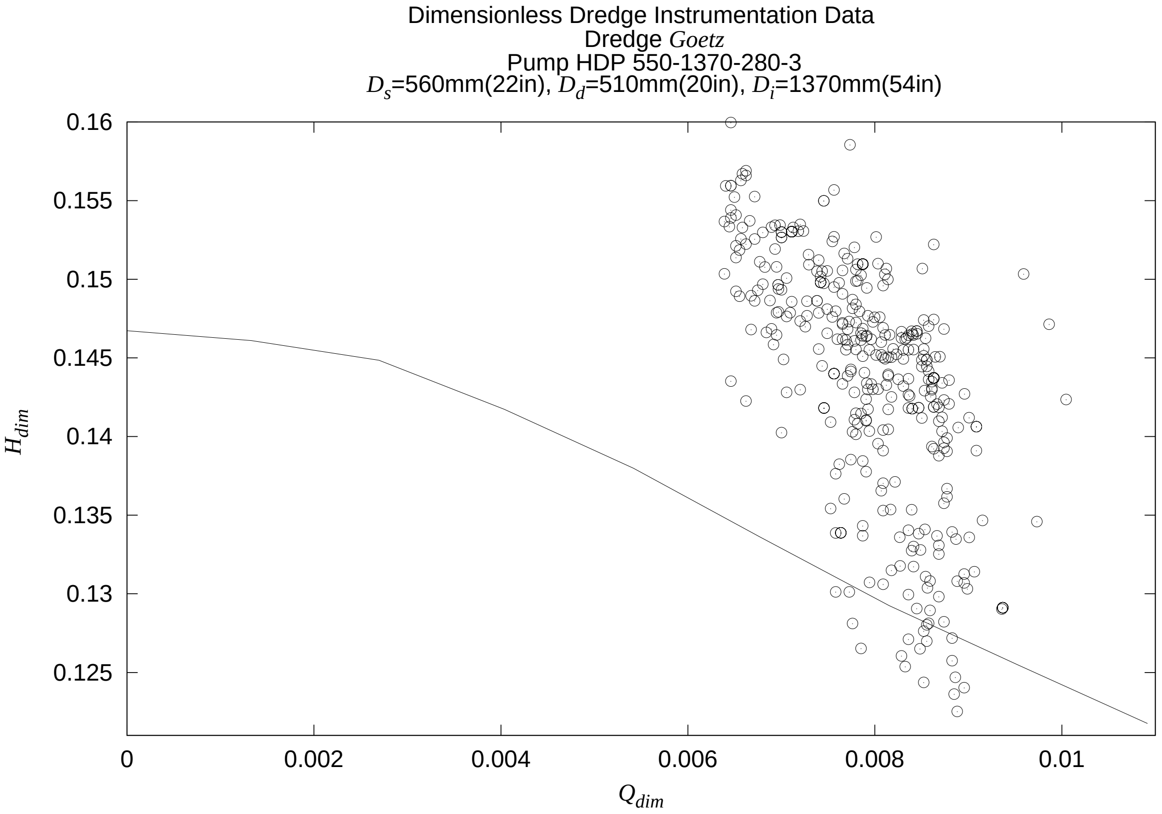


Fig. 30. Dredge *Goetz* dimensionless pump curve as well as Silent Inspector data.

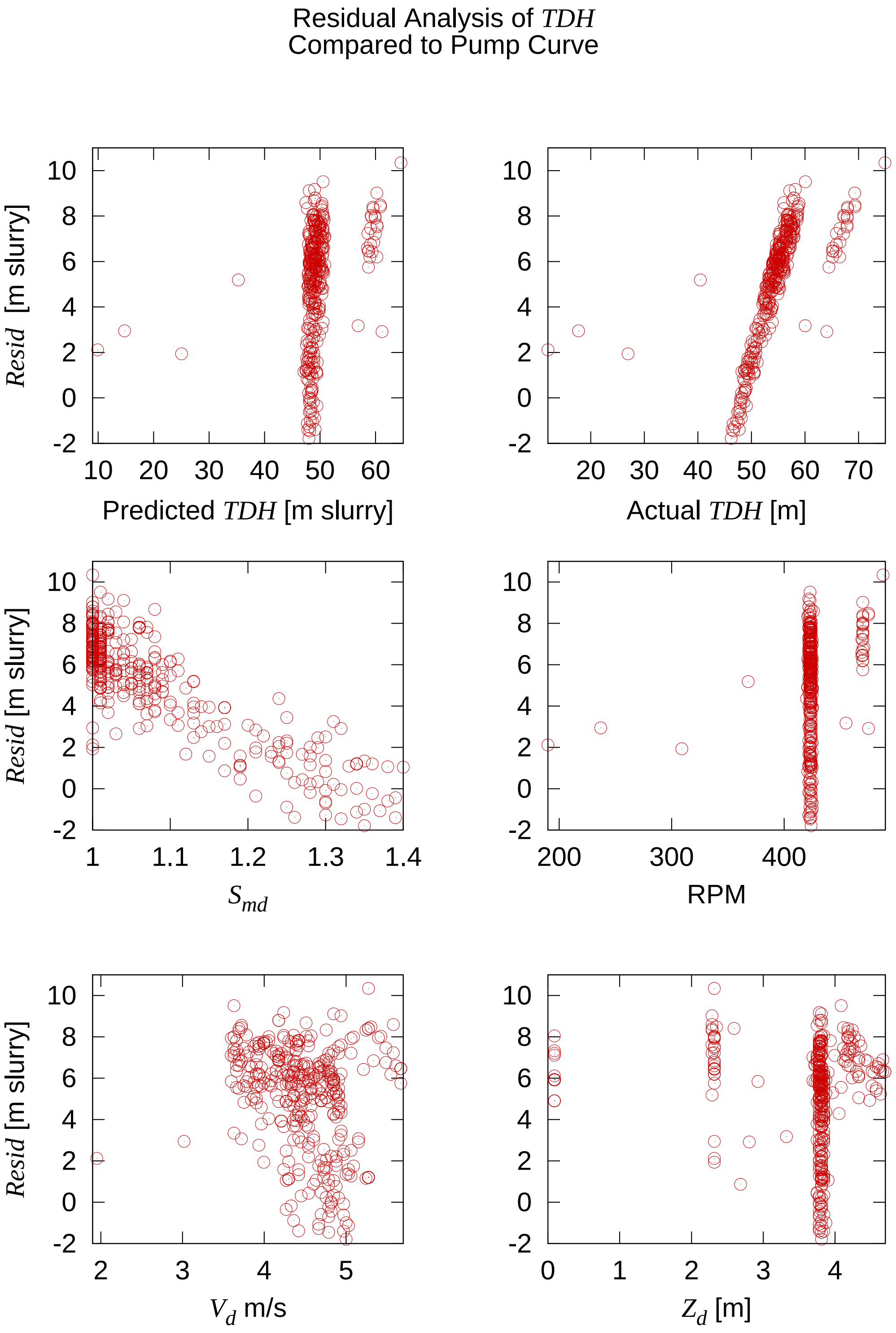


Fig. 31. Residual analysis of Dredge *Goetz* dimensionless pump curve data compared to Silent Inspector data.

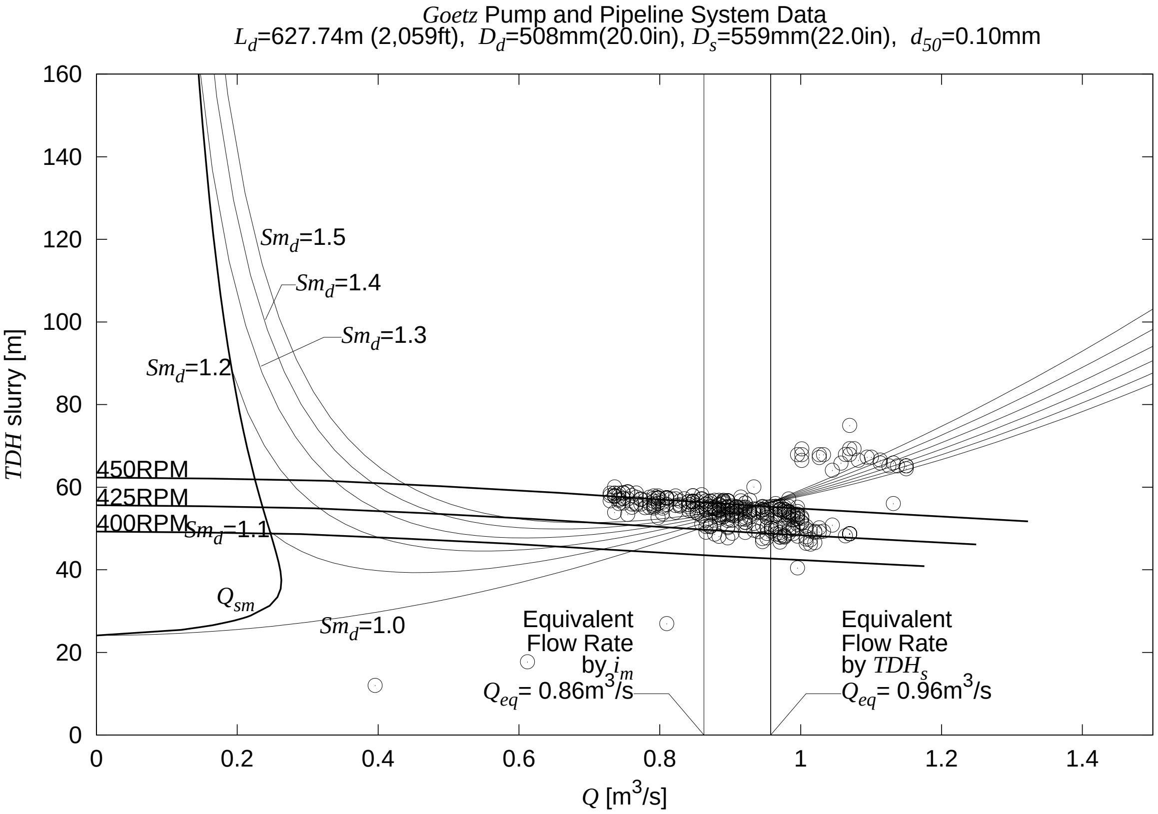


Fig. 32. Dredge *Goetz* pipeline pump and pipeline system curves as well as Silent Inspector data.

C. Pipeline System Data Comparison

The theoretical system head curves based on the Wilson *et al.* (1997) equations showed some interesting comparison to the actual dredge pump data. Figure 32 shows the system head curves for a range of specific gravities and the actual Silent Inspector system data. The theoretical pipeline system curves fall right down the center of the distribution of Silent Inspector data suggesting that the Wilson *et al.* (1997) equations provide a suitable average for the actual data.

Pipeline system curves intersect the pump performance curves corresponding to 450 RPM at the pipeline system flow rate of equivalent fluid, Q_{eq}, where the pipeline system curves act independent of specific gravity. The Wilson *et al.* (1997) equations estimate Q_{eq} as the flow rate where the friction gradient for a slurry equals the friction gradient for the carrier fluid as:

$$\frac{i_{md}}{S_m} = i_{wd} \tag{4.5}$$

$$i_{md} = 0.22\left(S_m - 1\right)\left(\frac{V_{50}}{V_{eq}}\right)^{1.7} \tag{4.6}$$

$$i_{wd} = \frac{f_{wd}V_{eq}^2}{2gD_d} \tag{4.7}$$

$$i_{wd}S_m = i_{wd} + 0.22\left(S_m - 1\right)\left(\frac{V_{50}}{V_{eq}}\right)^{1.7} \tag{4.8}$$

$$i_{wd}\left(S_m - 1\right) = 0.22\left(S_m - 1\right)\left(\frac{V_{50}}{V_{eq}}\right)^{1.7} \tag{4.9}$$

$$i_{wd} = 0.22\left(\frac{V_{50}}{V_{eq}}\right)^{1.7} \tag{4.10}$$

$$V_{eq}^{1.7} = V_{50}^{1.7}\left(\frac{0.22}{i_w}\right) \tag{4.11}$$

$$V_{eq}^{1.7} = 0.22V_{50}^{1.7}\left(\frac{2gD_d}{f_{wd}V_{eq}^2}\right) \tag{4.12}$$

$$V_{eq}^{3.7} = 0.22V_{50}^{1.7}\left(\frac{2gD_d}{f_{wd}}\right) \tag{4.13}$$

$$V_{eq} = V_{50}^{0.460}\left(\frac{0.44gD_d}{f_{wd}}\right)^{0.270} \tag{4.14}$$

$$Q_{eq} = V_{eq}\frac{\pi D_d^2}{4} \tag{4.15}$$

This equation, however, does not account for static lift due to digging depth or friction losses in the suction side of the pump. A more thorough calculation accounts for these factors by determining:

$$TDH_w = TDH_s \tag{4.16}$$

$$\begin{aligned}\cancel{Z_b} + \cancel{\Sigma k_d \frac{V_d^2}{2g}} + \cancel{\Sigma k_s \frac{V_s^2}{2g}} + \cancel{V_d^2} + i_{wd}L_d + i_{ws}L_s = Z_d \frac{S_m - 1}{S_m} + \cancel{Z_b} + \\ \cancel{\Sigma k_d \frac{V_d^2}{2g}} + \cancel{\Sigma k_s \frac{V_s^2}{2g}} + \cancel{V_d^2} + \frac{i_{md}L_d}{S_m} + \frac{i_{ms}L_s}{S_m}\end{aligned} \tag{4.17}$$

Canceling common terms to both sides and expanding i_w and i_m yields:

$$\begin{aligned}\frac{f_{wd}V_d^2}{2gD_d}L_d + \frac{f_{ws}V_s^2}{2gD_s}L_s = Z_d \frac{S_m - 1}{Sm} + \frac{f_{wd}V_d^2}{2gD_dS_m}L_d \\ + \frac{f_{ws}V_s^2}{2gD_sS_m}L_s + 0.22\frac{S_m - 1}{S_m}\frac{V_{50s}^{1.7}}{V_s^{1.7}}L_s + 0.22\frac{S_m - 1}{S_m}\frac{V_{50d}^{1.7}}{V_d^{1.7}}L_d\end{aligned} \tag{4.18}$$

$$V_d = \frac{4Q_{eq}}{\pi D_d^2} \tag{4.19}$$

$$V_s = \frac{4Q_{eq}}{\pi D_s^2} \tag{4.20}$$

$$\frac{16}{2g\pi^2}\left(\frac{f_{wd}L_d}{D_d^5} + \frac{f_{ws}L_s}{D_s^5}\right)Q_{eq}^2 = Z_d + 0.22\left(\frac{\pi}{4}\right)^{1.7}\frac{1}{Q_{eq}^{1.7}}\left(\left(V_{50s}D_s^2\right)^{1.7}L_s + \left(V_{50d}D_d^2\right)^{1.7}L_d\right) \tag{4.21}$$

Since this equation cannot solve for the Q_{eq} explicitly, a computer program must solve for the polynomial root of the equation. At this flow rate, the actual TDH and flow rate of a pipeline system would not depend heavily on the density of the mixture transported in the pipe. The pump and pipeline analytical program could determine the intersection of the pump and pipeline system without significant error caused by inaccurate density assumptions. Figure 32 illustrates the Q_{eq} calculated from both Wilson *et al.* (1997) method and by equating TDH_s for slurry and water. Both methods come reasonably close to the actual intersections of the pipeline system curves. The TDH method provides a more accurate result with some error due to f_w and V_{50} ultimately varying with S_{md}. Figure 33 illustrates the residual analysis of the actual system TDH compared to the theoretical pipeline system curves where:

$$RES_{TDH_s} = TDH_s(\mathsf{actual}) - TDH_s(\mathsf{theoretical}) \tag{4.22}$$

Figure 33 shows high correlation with both specific gravity suggesting that the Wilson *et al.* (1997) equations provide a more precise calculation at higher density slurries rather than water.

D. Maximum Production Data Comparison

The Pipeline Analytical Program compared the *Goetz* production data to the theoretical maximum production based on vacuum limitation of the pump. Analysis calculated $NPSHA$ for the pump based on dredge instrumentation data as:

$$NPSHA = \frac{H_a - H_v}{S_{md}} + \frac{P_s}{\rho_w g S_{md}} + \frac{V_s^2}{2g} \tag{4.23}$$

$$V_s = \frac{D_d^2}{D_s^2} V_d \tag{4.24}$$

For a range of flow rates, the Pipeline Analysis Program calculates S_{md} where $NPSHA$ equal $NPSHR$ from the pump curve data in Figure 28. Figure 34 illustrates the curve of this maximum production relationship. The program further calculated the time–averaged delivered specific gravity, $\bar{S}_{md}$, at 1.067 as Figure 35 illustrates. The Pipeline Analytical Program calculated the optimum S_{md} as 1.60. All dredge

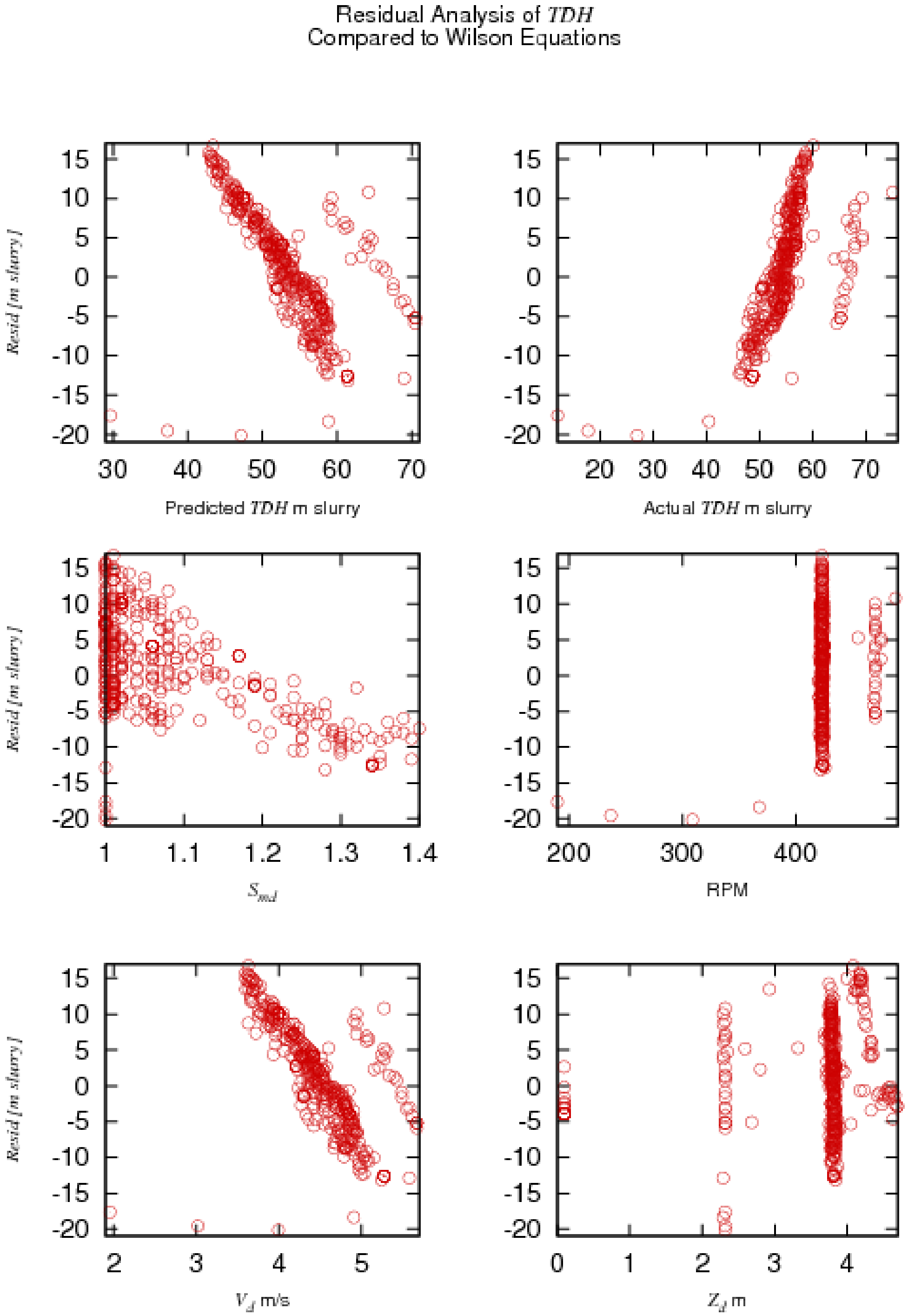


Fig. 33. Residual analysis of Dredge *Goetz* pipeline system curves compared to Silent Inspector data.

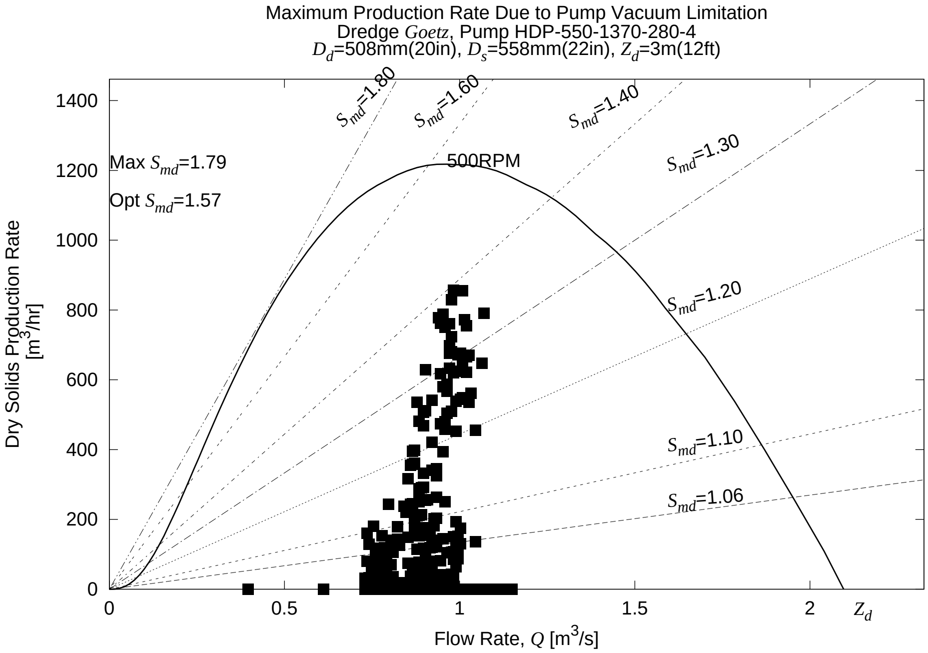


Fig. 34. Dredge *Goetz* maximum production curve.

production data fell well below this mark with the maximum S_{md} at 1.40. This result suggests the *Goetz* can capably dredge denser mixtures than the cutterhead can actually pursue.

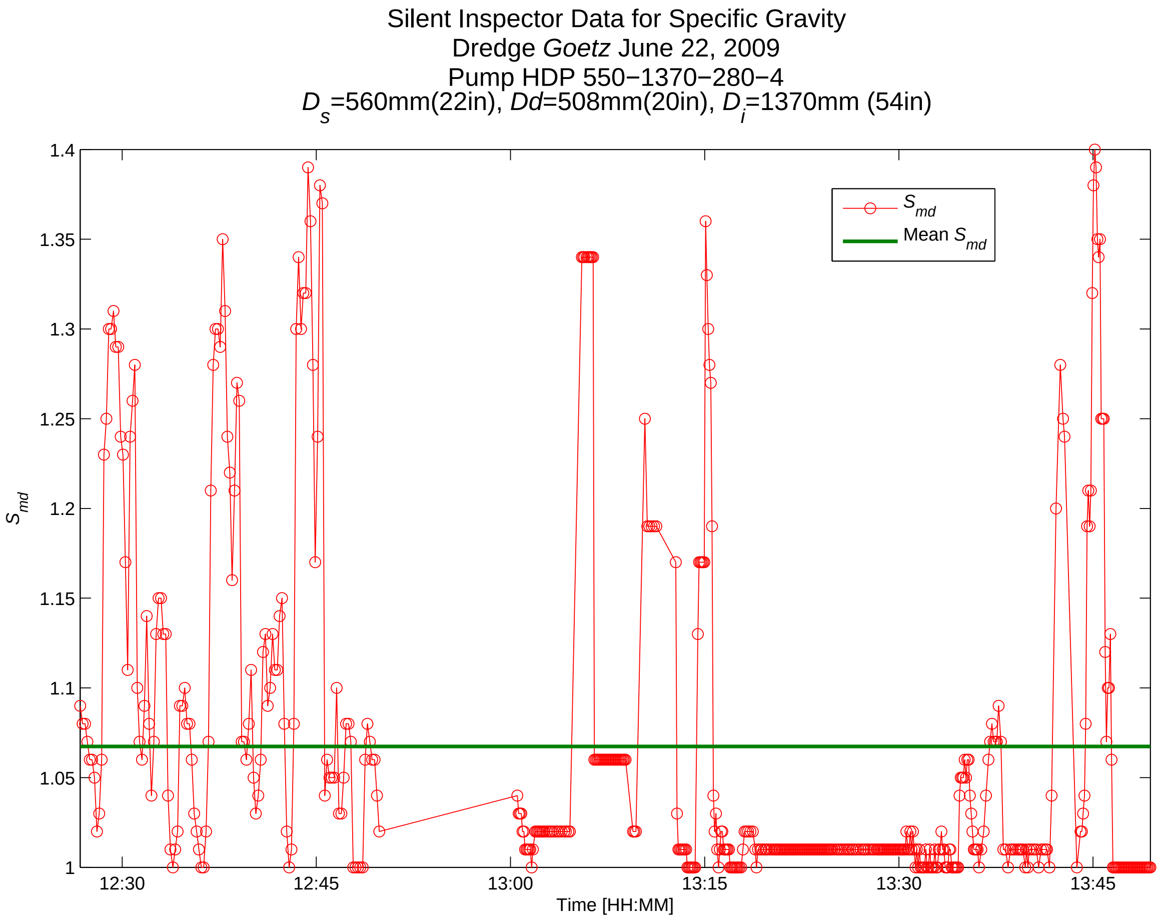


Fig. 35. Dredge *Goetz* time–averaged S_{md}.

E. Dredge Production Analysis

The Pipeline Analytical Program analyzed production of the *Goetz* operation in the Upper Mississippi River on June 22, 2009 based on the dredge pump and pipeline system parameters. The Pipeline Analytical Program used pump data from the dredge pump performance curves and the pipeline system data to compute the operating point based on the interaction between the two. The Pipeline Analytical Program then computed the resulting production rate of the dredged material to compare with the actual results of the *Goetz* dredge instrumentation data.

The Pipeline Analytical Program calculated the operating parameters of the dredge *Goetz* operating under the pipeline system parameters in Table 31 and the pump performance curves in Figure 32. The Pipeline Analytical Program uses maximum operating parameters for pump shaft speed and pump shaft power as 425RPM and 1,192kW(1,600bhp), respectively. Figure 36 illustrates the pump and generated pipeline system curves. Table 33 shows the Pipeline Analytical Program calculated performance metrics. The Pipeline Analytical Program compared these performance metrics to the *Goetz* Silent Inspector data by calculating the actual delivered volume of dry material over a time–span, t_j, as:

$$\mathsf{Volume}_{\mathsf{actual}}(t_j) = \sum_{i=2}^{j} \frac{1}{2}\left(\dot{M}_i + \dot{M}_{i-1}\right)(t_i - t_{i-1}) \tag{4.25}$$

This method uses the trapezoidal rule to numerically integrate production rate. The Pipeline Analytical Program calculates the theoretical volume of dry material from the theoretical production rate as:

$$Volume_{\mathsf{theoretical}}(t_j) = \dot{M}_{\mathsf{theoretical}}\,(t_j - t_1) \tag{4.26}$$

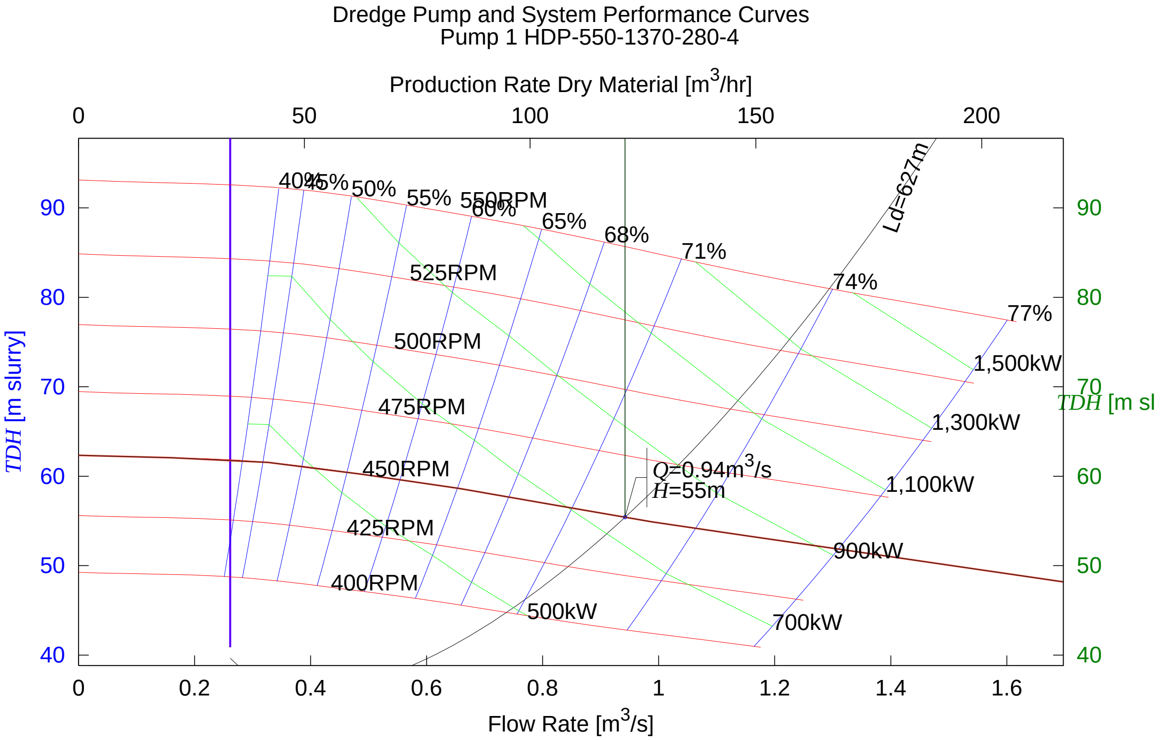


Fig. 36. Pipeline Analytical Program results for Dredge *Goetz* dredging project.

Table 33. Dredge *Goetz* Pipeline Analytical Program performance parameter results.

Performance Parameter	**Value**
S_{mi}	1.62
c_{vi}	0.38
F_b	1.91
η_{bh}	0.35
η_d	0.75
c_{vd}	0.037
S_{md}	1.057
Q	$0.94\text{m}^3/\text{s}(33.24\text{ft}^3/\text{s})$
TDH_s	55m(181.8ft)
$\dot{M}$	$139.1\ \text{m}^3/\text{hr}(181.1\text{yd}^3/\text{hr})$

Figure 37 illustrates the timeline of cumulative volume of dry material based on actual Silent Inspector production measurements and the theoretical pipeline equations as well the percent difference between the actual and theoretical volume as:

$$Volume_{\%\mathsf{difference}} = \frac{Volume_{\mathsf{actual}}(t_j) - Volume_{\mathsf{theoretical}}(t_j)}{Volume_{\mathsf{actual}}(t_j)} \times 100 \tag{4.27}$$

The Pipeline Analytical Program calculated the final actual and theoretical dry material production of 191.6m^3 and 205.2m^3, respectively, making a 6.62% percent difference.

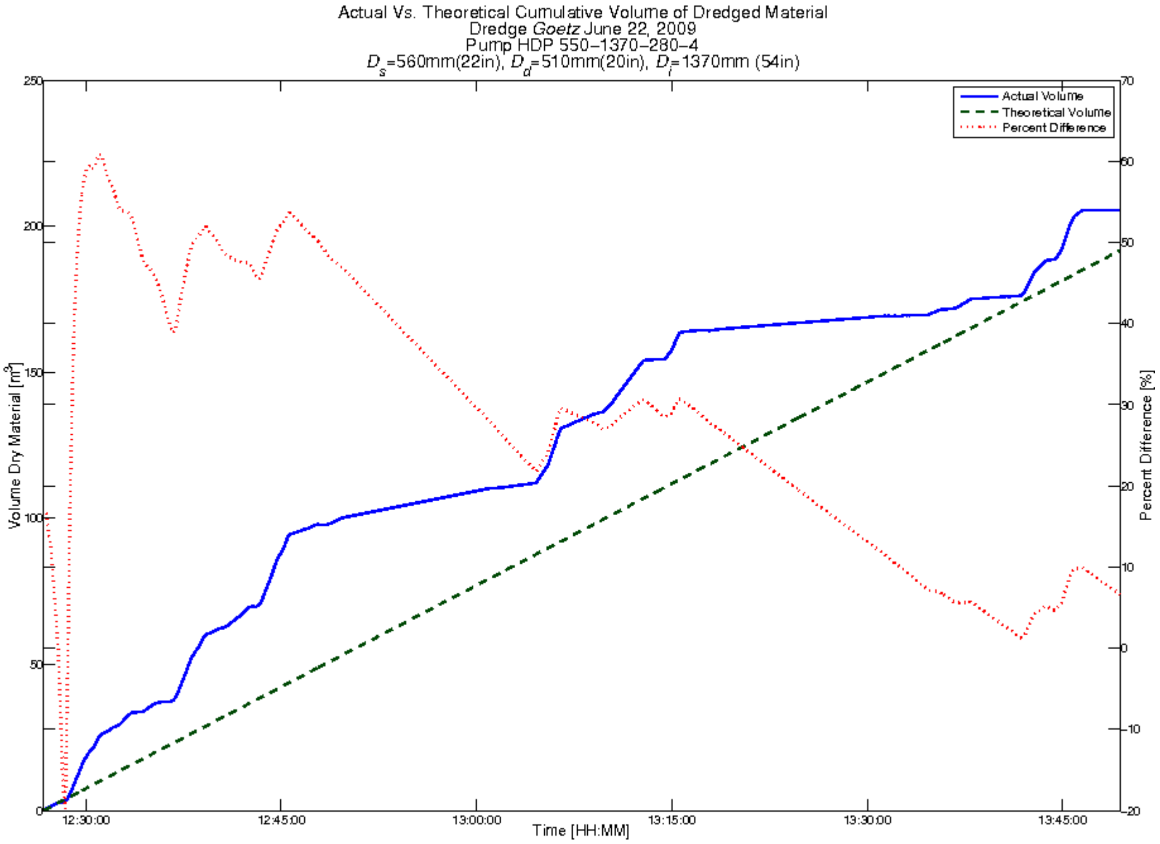


Fig. 37. Production comparison between Pipeline Analytical Program results and Silent Inspector data results.

F. Results and Discussion

The actual Silent Inspector pipeline dredge production data compared well with the Wilson *et al.* (1997) equations for the TDH by illustration of the pipeline system curves in Figure 32. Residual analysis between the actual TDH values and TDH obtained by Wilson *et al.* (1997) equations show the strongest dependence on velocity. Likewise, residual analysis between actual TDH_{dim} and TDH_{dim} obtained from the pump performance curve as shown in Figure 31 showed velocity as the strongest influencing factor and correlation between actual and theoretical values.

The dimensionless head curve in Figure 30 shows that the dredge instrumentation data exceed the manufacturers pump performance curve. This suggests suggests some error in the dredge instrumentation.The Pipeline Analytical Program calculated Q for the dredge pump and pipeline system relatively close to the equivalent fluid flow rate, Q_{eq}. This measurement suggests the *Goetz* operates at a flow rate that stays constant despite change in the S_{md} to simplify dredge operation.

The pipeline analytical program calculated a dry material production rate of 139.1m^3/hr that translates to a final production of final dredged material production of 191.6m^3 compared with 205.2m^3 of actual production with a net difference of 6.62%. The dredge instrumentation measured an average S_{md} of 1.067. The Pipeline Analytical Program calculated S_{md} of 1.057 based on empirical formula for the F_b and S_{mi} based on the fines fraction, x_f. Furthermore, the Pipeline Analytical Program needed to estimate a value for the x_f in lieu of sediment laboratory analysis. Although these values represent reasonable estimates to determine the delivered slurry concentration and ultimate production, actual sediment analysis would help to show that the Pipeline Analytical Program does produce verifiable results for pipeline dredge production.

CHAPTER V

PIPELINE DREDGE PROJECTS

Daily dredge reports from two U.S. Army Corps of Engineers districts provide a comparison between the Pipeline Analytical Program and the actual pipeline dredge production throughout the entire span of a dredge project. Daily dredge reports contain the daily pipeline dredge progress throughout the project lifecycle. Table 34 describes these daily data parameters. The actual names of the dredges and their project numbers have been obfuscated in order to protect potentially proprietary data. These data will lend considerable evidence as to how accurately the Pipeline Analytical Program can calculate the daily production of a pipeline dredge project protracted over many months.

Table 34. Daily dredge report data parameters

Data Parameter	**Description**
Date	Date of dredging activity
Vol	Daily volume of dredged material [m^3]
Z_i	Initial depth of channel [m]
Z_d	Design dredging depth [m]
L_d	Pipeline Length [m]
ADV	Pipeline dredge advance [m]
T_p	Total time dredging [hours]
Pump Series	Pumps used in the pump series

Given these pump and pipeline operating parameters, the Pipeline Analytical Program determines the theoretical daily dredge production. Analysis compares the

% difference between actual production data and theoretical production as:

$$\dot{M}_{\text{\%difference}} = \frac{\dot{M}_{\text{actual}}(t_j) - \dot{M}_{\text{theoretical}}(t_j)}{\dot{M}_{\text{actual}}(t_j)} \times 100 \tag{5.1}$$

Analysis further compares % difference between actual cumulative volume and theoretical cumulative volume as:

$$Volume_{\text{\%difference}} = \frac{Volume_{\text{actual}}(t_j) - Volume_{\text{theoretical}}(t_j)}{Volume_{\text{actual}}(t_j)} \times 100 \tag{5.2}$$

Residual analysis compares the difference between actual and theoretical production rate as:

$$RES_{\text{production}} = \dot{M}_{(\text{actual})} - \dot{M}_{(\text{theoretical})} \tag{5.3}$$

A. Savannah District Project Data

The USACE Savannah District dredges 4.57 million m^3(6 million yd^3) per year from the Savannah River to maintain 15.5m (51ft) navigable depth. Three dredging projects from 2000 and 2003 provide daily dredge report data to compare actual dredge project data to the Pipeline Analytical Program. All three projects used Dredge *A*, an 457mm(18in) cutterhead pipeline dredge. Table 35 describes *A*'s dredge parameters.

1. Dredge *A* Project 1

Table 36 describes the pump system data for Project 1 on the Savannah River using Dredge *A*. Figures 38–40 contain the Pipeline Analytical Program results for the pump and pipeline interaction. Figure 41 illustrates the composite pump series and pipeline performance curves. Figure 42 illustrates the performance metrics of production and power consumption with pipeline length. Figure 43 illustrates the maximum

Table 35. Dredge A parameters

Dredge Parameter	**Value**
D_d	457mm(18in)
D_s	457mm(18in)
L_s	12.2m(40ft)
L_L	26.3m(83ft)
D_c	2.13m(7ft)
Z_{lp}	-6.1m(-20ft)

production capable of the first pump limited by cavitation. as the performance metrics of theoretical production rate with respect to pipeline length. Figure 44 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 45 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

Table 36. Dredge A pump parameters for Project 1.

	Name	D_i	**Power**	**Max RPM**
Ladder	MPMW-18x18x34	863mm(34in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600

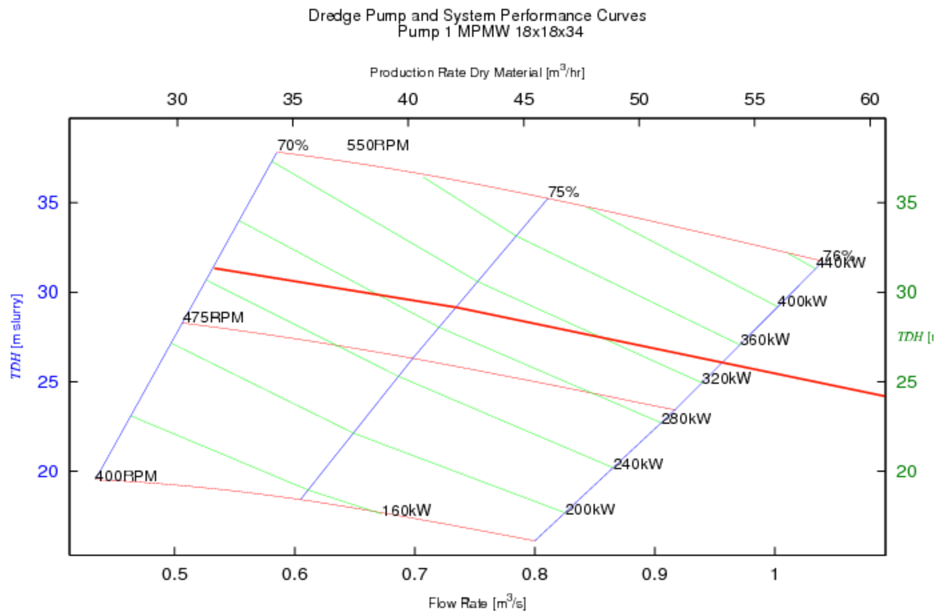


Fig. 38. Pump 1 curves for Dredge *A* on Project 1.

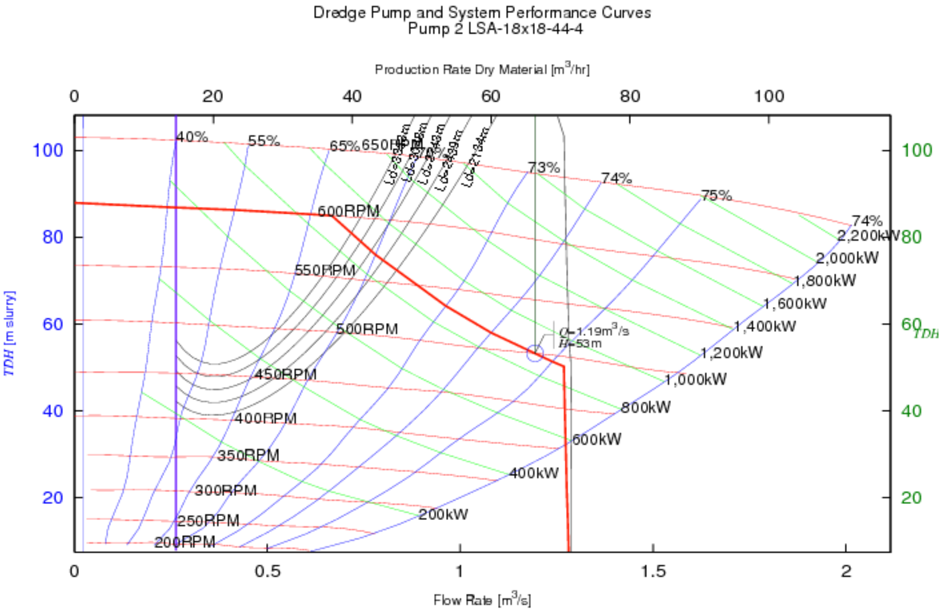


Fig. 39. Pump 2 curves for Dredge *A* on Project 1.

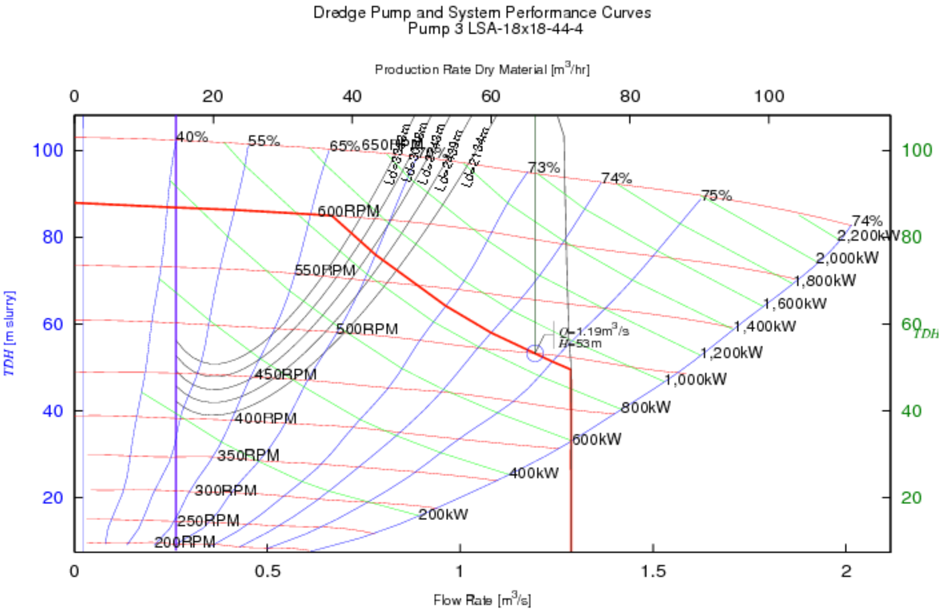


Fig. 40. Pump 3 curves for Dredge A on Project 1.

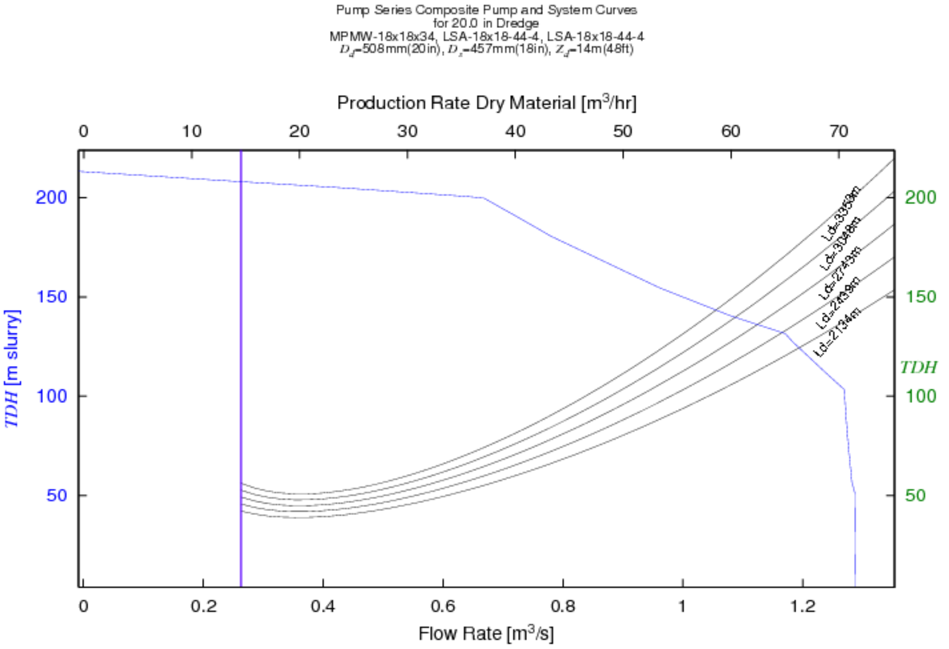


Fig. 41. Pump series composite curve for Dredge A on Project 1.

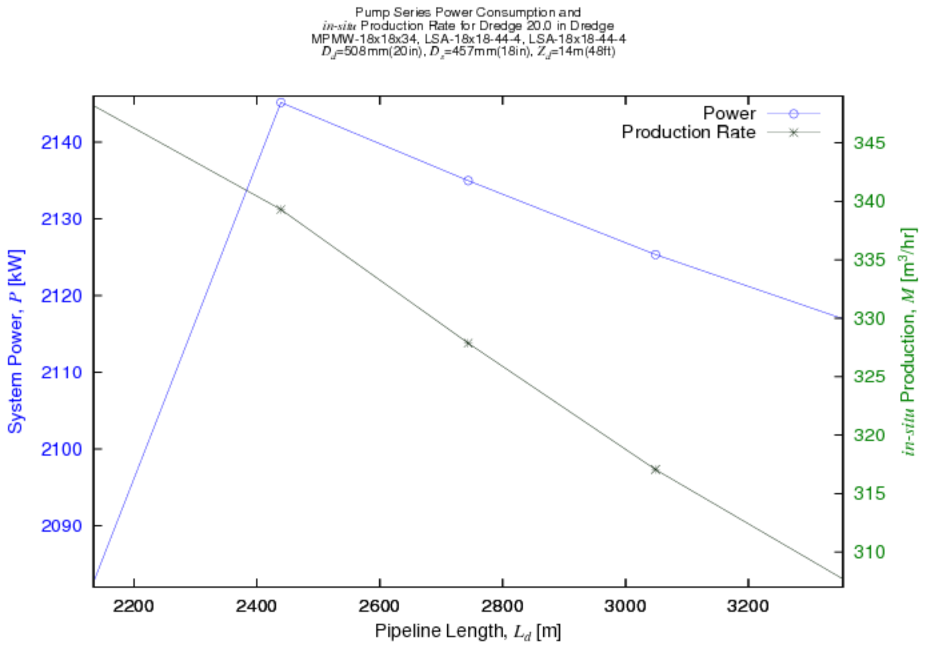


Fig. 42. Pump series performance metrics for Dredge A on Project 1.

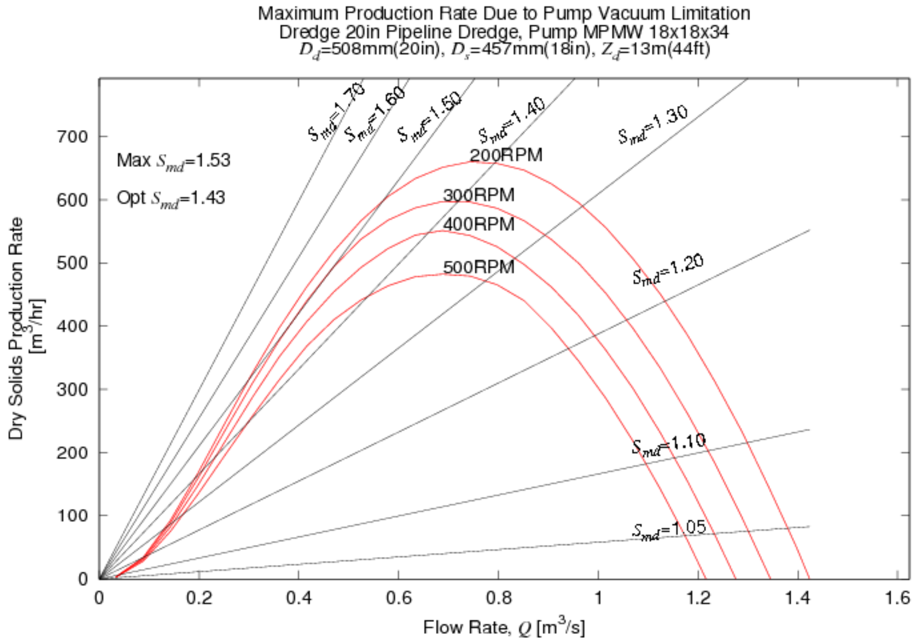


Fig. 43. Ladder pump maximum production curve for Dredge A on Project 1.

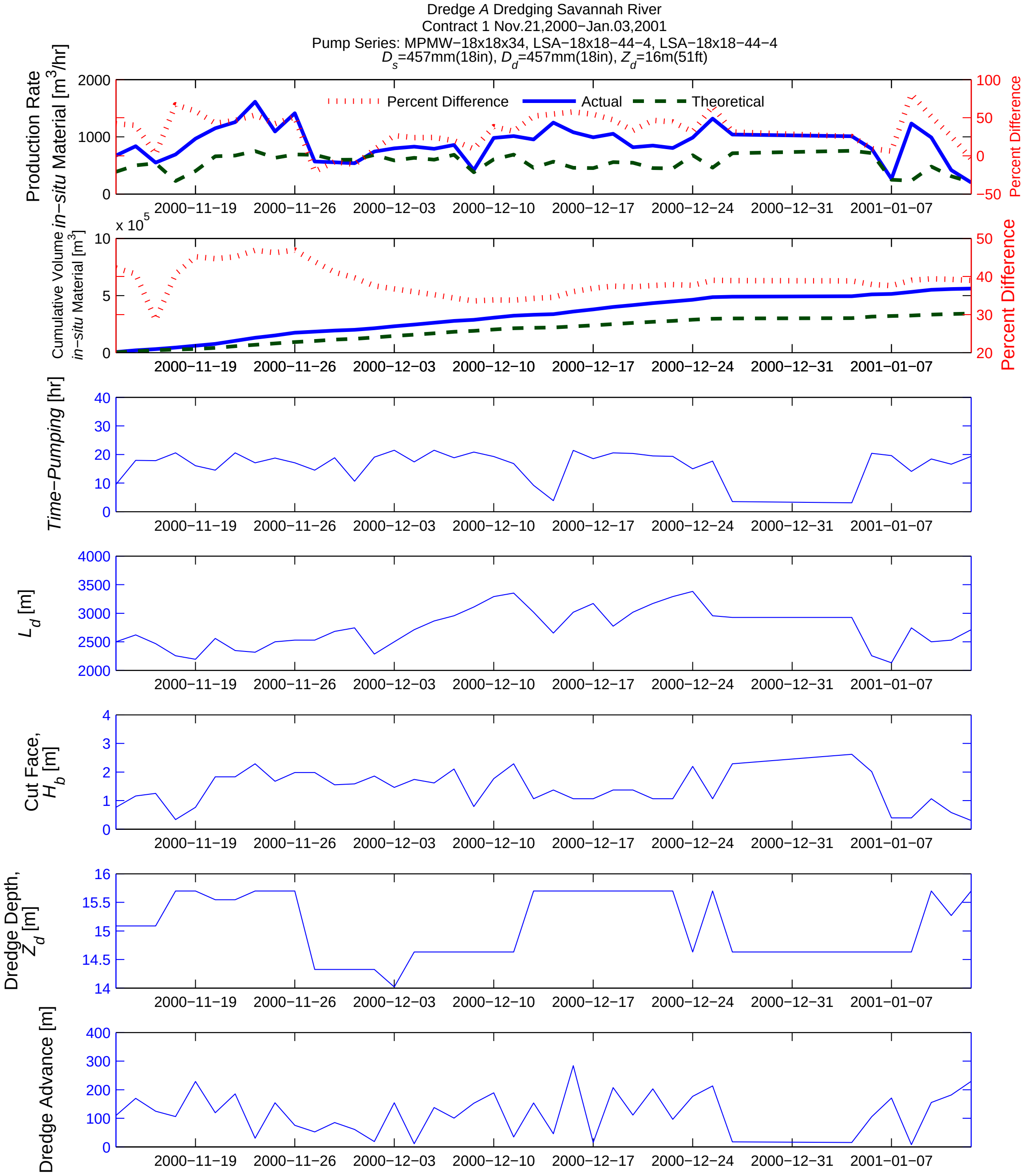


Fig. 44. Comparison between actual dredge production and theoretical dredge production for Dredge *A* on Project 1.

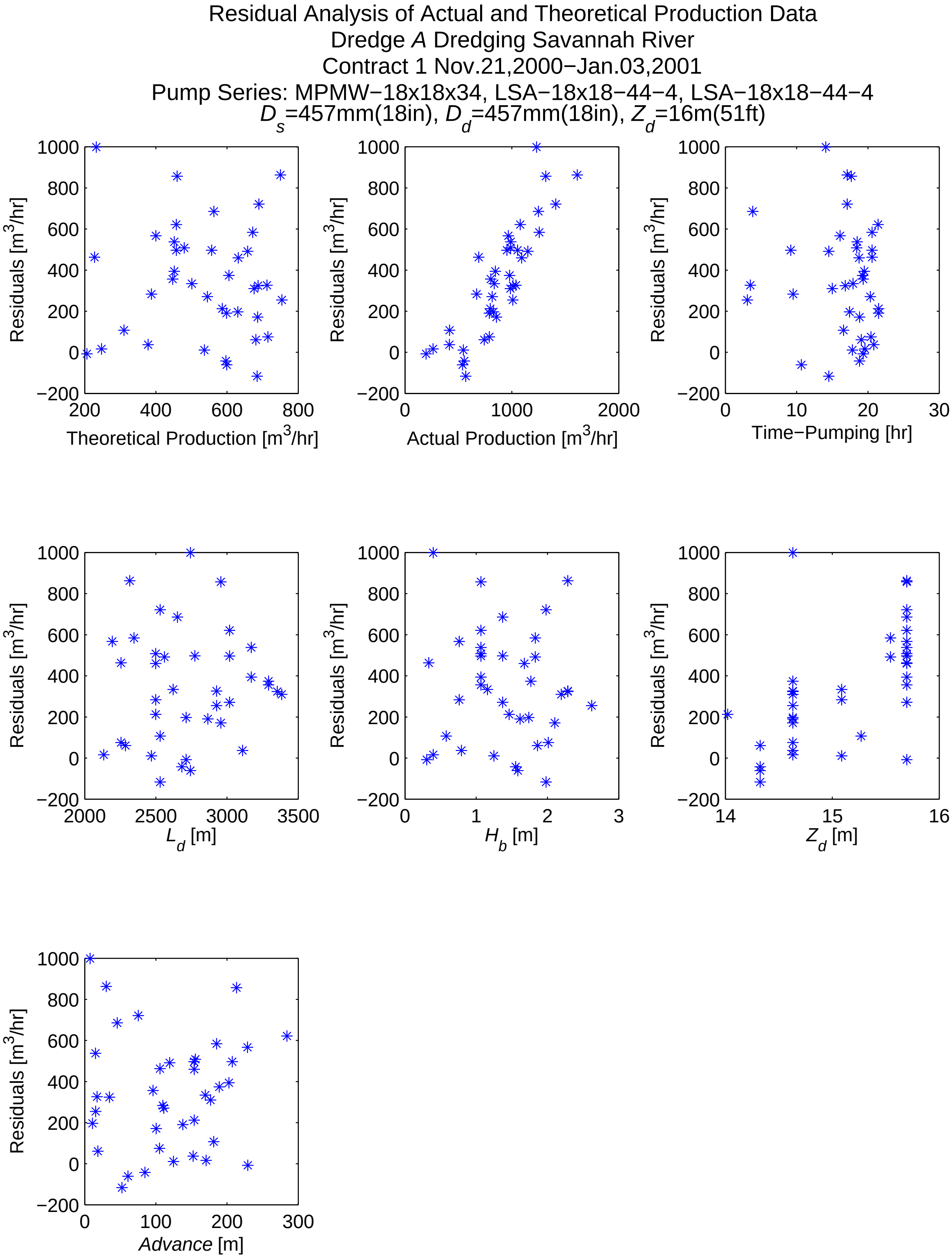


Fig. 45. Residual analysis between actual dredge production and theoretical dredge production for Dredge A on Project 1.

2. Dredge *A* Project 2

In 2003, Dredge *A* dredged Savannah River using two separate dredged material placement sites. The first placement site required at most 3,140m(10,300ft) of pipeline. The second placement site required 12,957m(42,500ft). The pipeline analytical program analyzes the 2003 project as a short–distance and long–distance application. Tables 37 and 38 describe the pump configuration for these two applications.

Figures 46–52 illustrate the pump and pipeline performance curves, the series composite performance curve, the system performance metrics and the maximum ladder pump production rate for the short–distance pipeline application. Figure 53 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 54 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

Table 37. Dredge *A* pump parameters for Project 2.

	Name	D_i	**Power**	**Max RPM**
Ladder	MPMW-18x18x34	863mm(34in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600

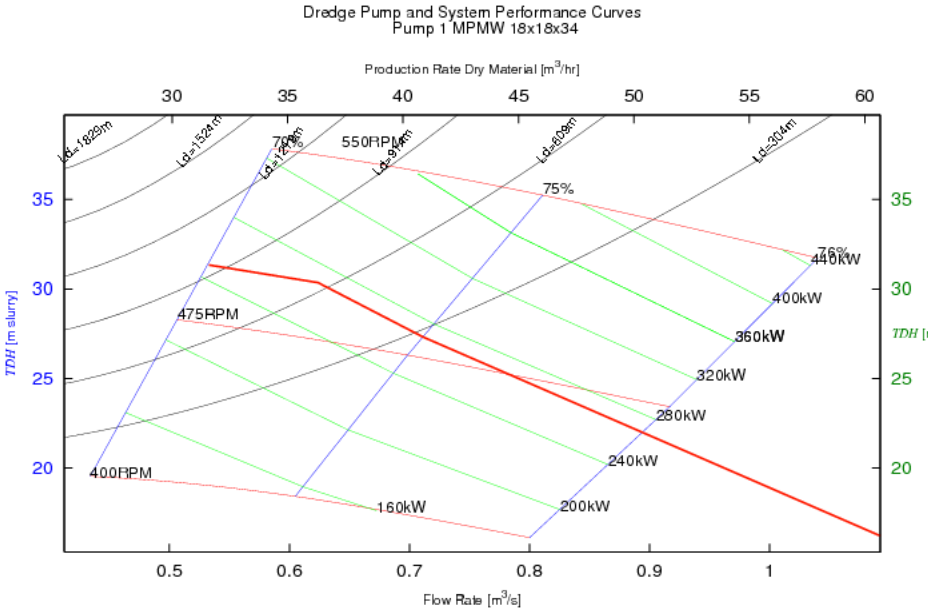


Fig. 46. Pump 1 curves for Dredge *A* in Savannah River on Project 2.

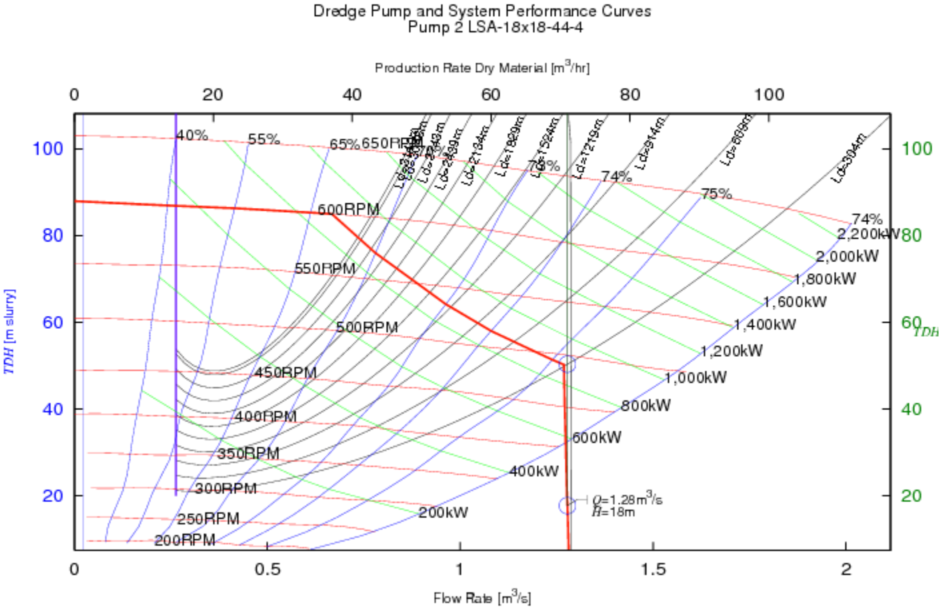


Fig. 47. Pump 2 curves for Dredge *A* in Savannah River on Project 2.

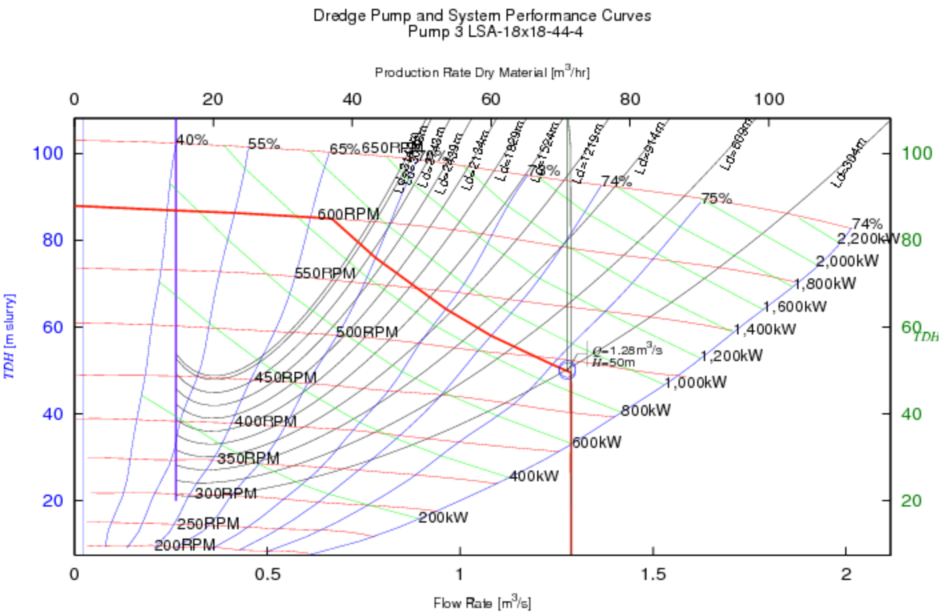


Fig. 48. Pump 3 curves for Dredge *A* in Savannah River on Project 2.

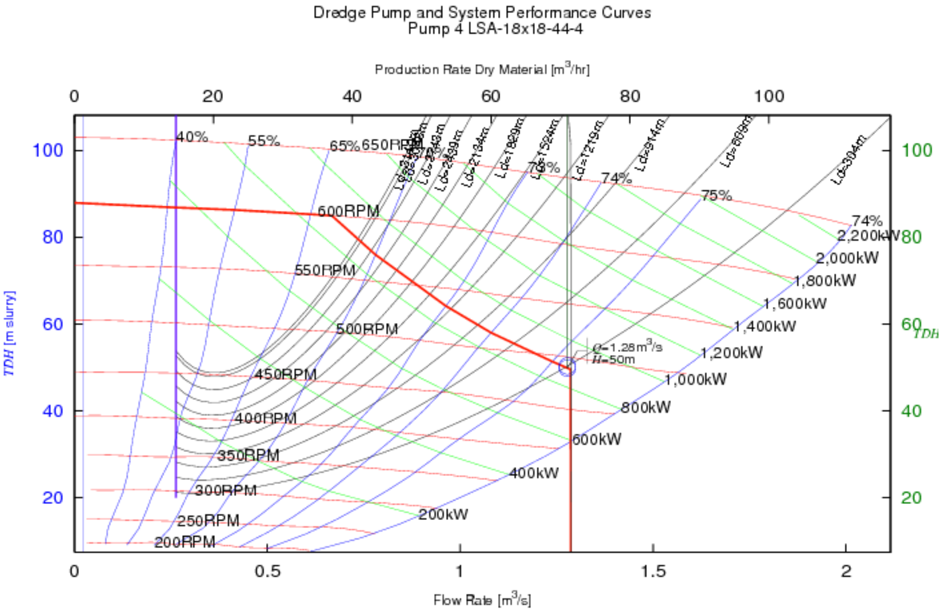


Fig. 49. Pump 4 curves for Dredge *A* in Savannah River on Project 2.

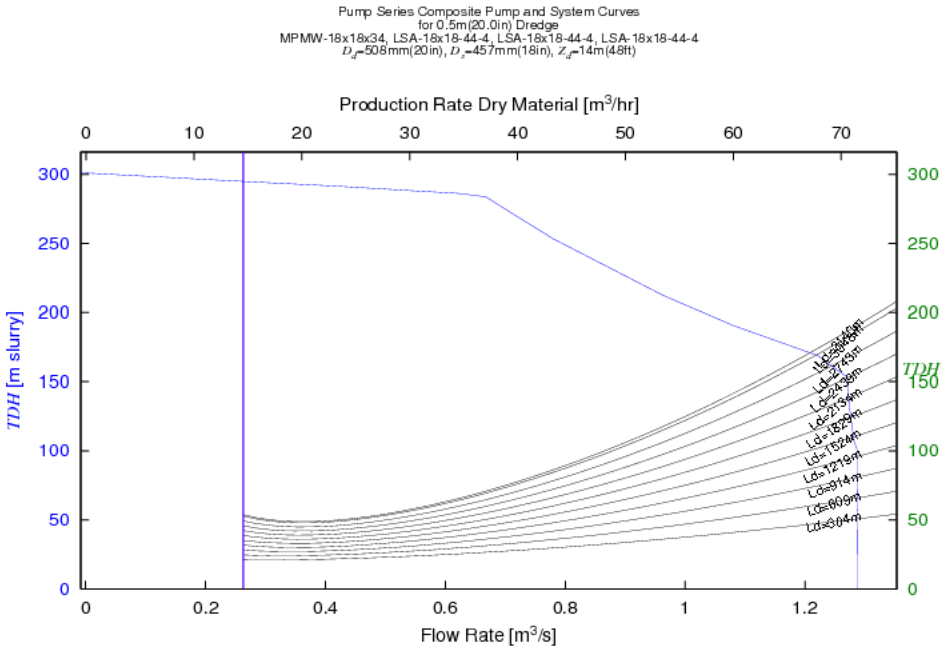


Fig. 50. Pump series composite curve for Dredge A in Savannah River on Project 2.

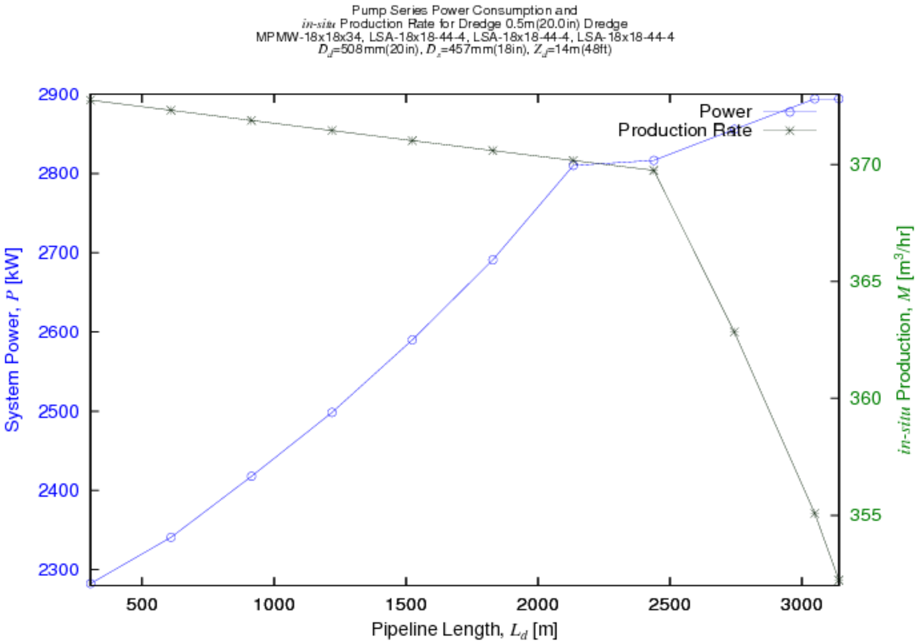


Fig. 51. Pump series performance metrics for Dredge A in Savannah River on Project 2.

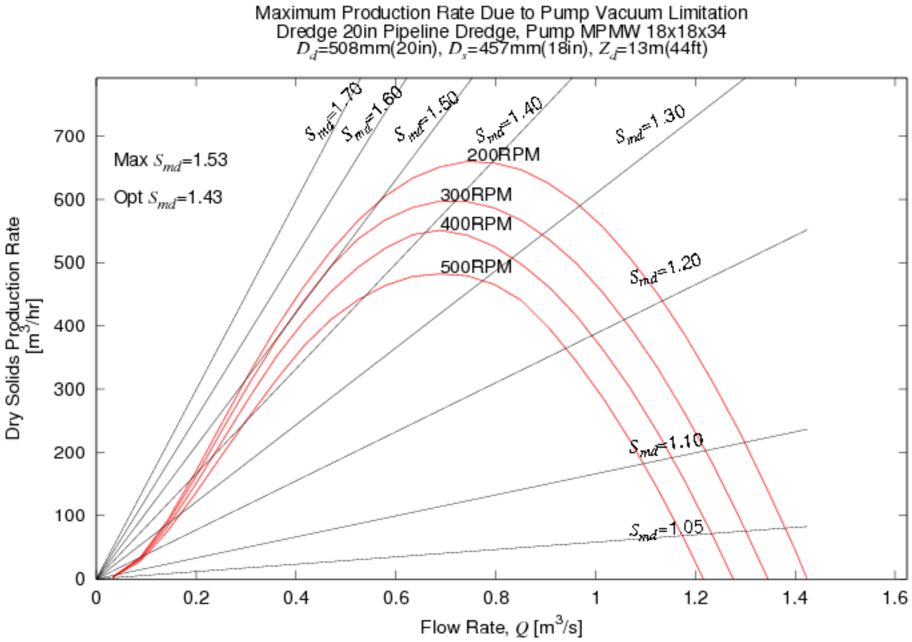


Fig. 52. Ladder pump maximum production curve for Dredge *A* in Savannah River on Project 2.

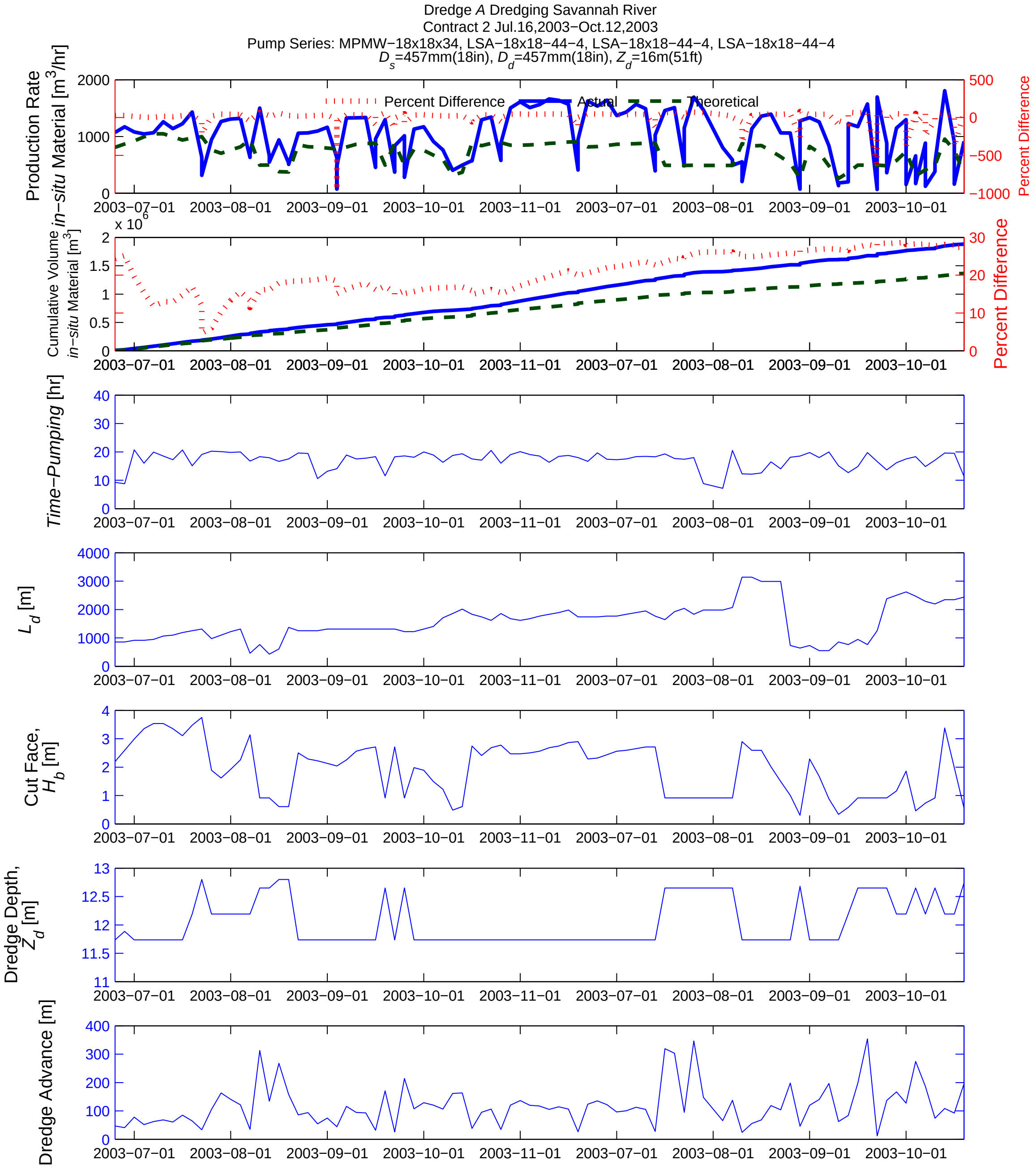


Fig. 53. Comparison between actual dredge production and theoretical dredge production for Dredge *A* in Savannah River on Project 2.

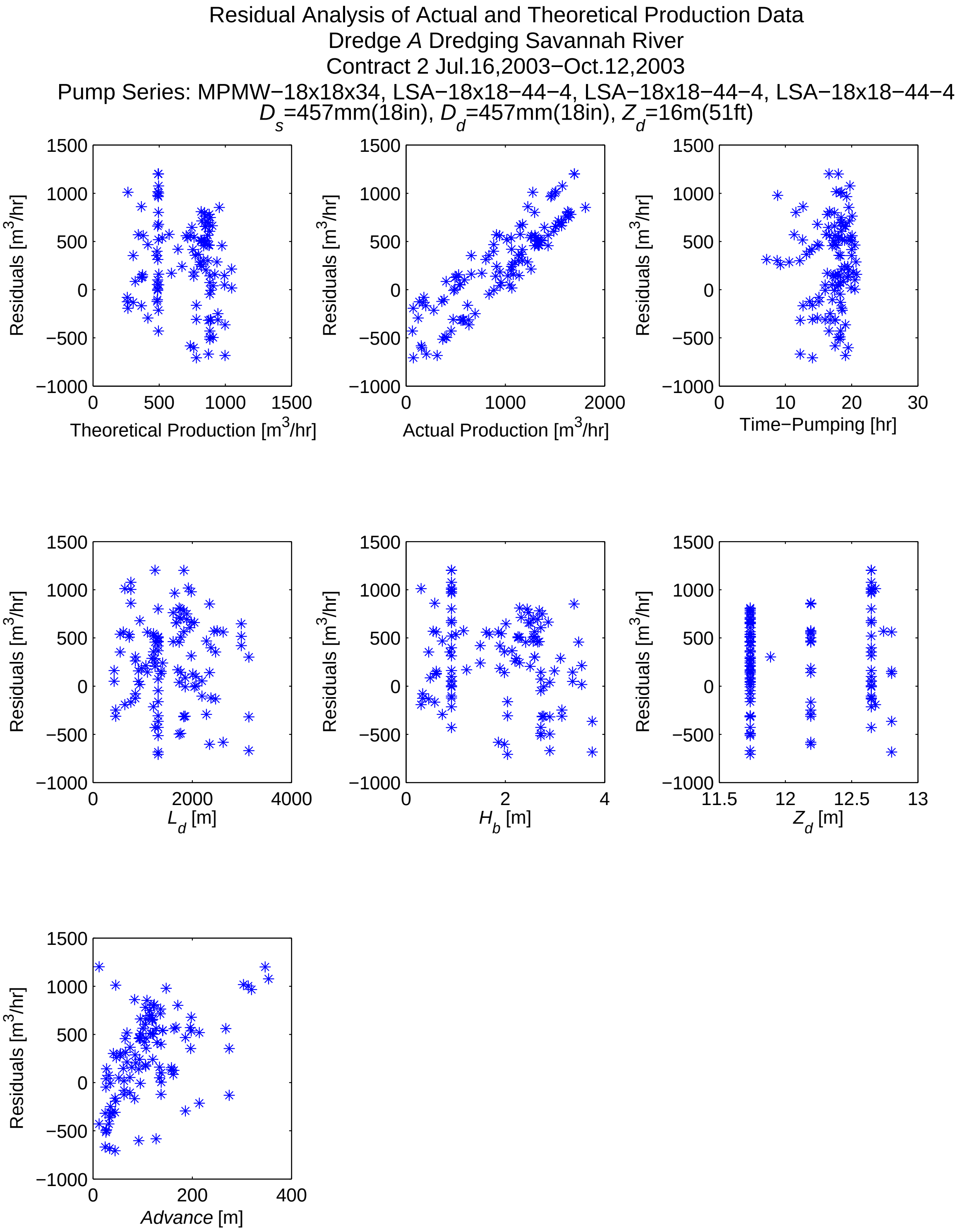


Fig. 54. Residual analysis between actual dredge production and theoretical dredge production for Dredge *A* in Savannah River on Project 2.

3. Dredge *A* Project 3

Figures 55–62 illustrate the pump and pipeline performance curves, the series composite performance curve, the system performance metrics and the maximum ladder pump production rate for the long–distance pipeline application. Figure 63 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 64 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

Table 38. Dredge *A* pump parameters for Project 3.

	Name	D_i	**Power**	**Max RPM**
Ladder	MPMW-18x18x34	863mm(34in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	875kW(1,175bhp)	600
Booster	LSA-18x18-44-4	1,117mm(44in)	2,235kW(3,000bhp)	600

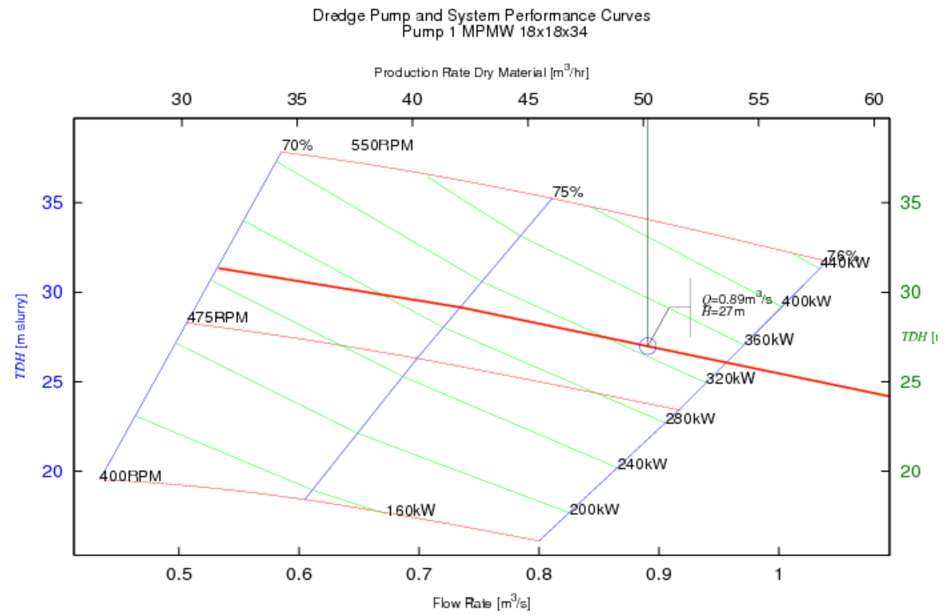


Fig. 55. Pump 1 curves for Dredge *A* in Savannah River on Project 3.

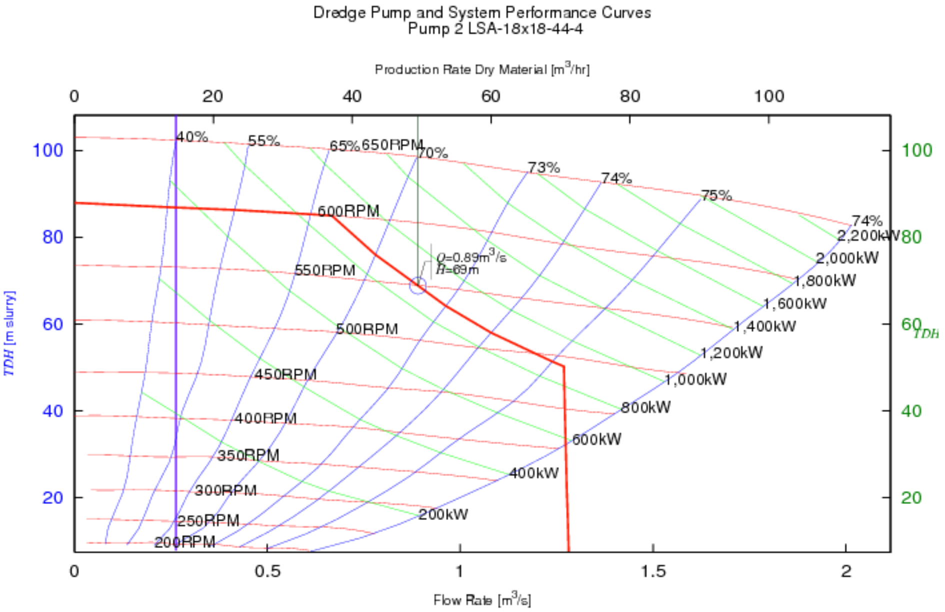


Fig. 56. Pump 2 curves for Dredge *A* in Savannah River on Project 3.

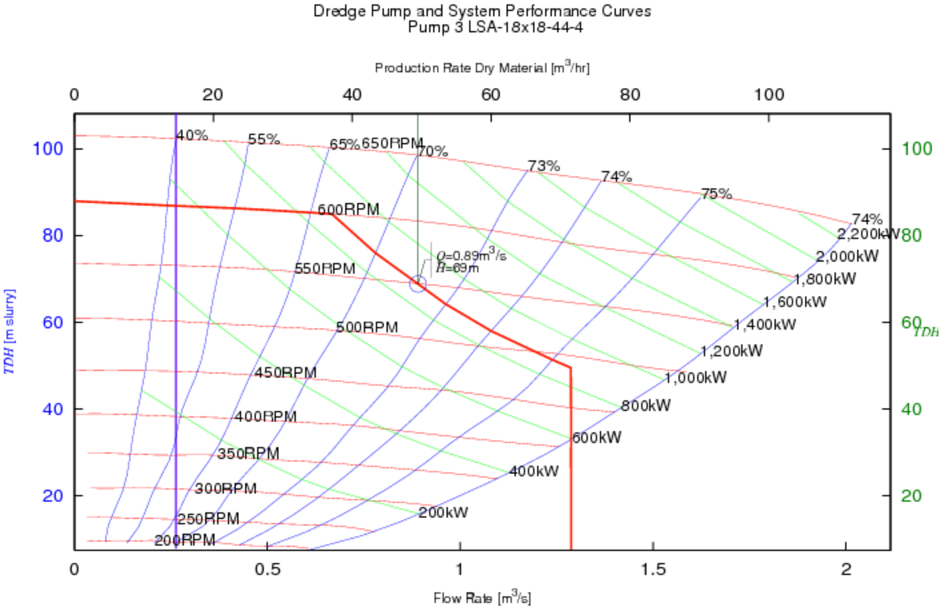


Fig. 57. Pump 3 curves for Dredge A in Savannah River on Project 3.

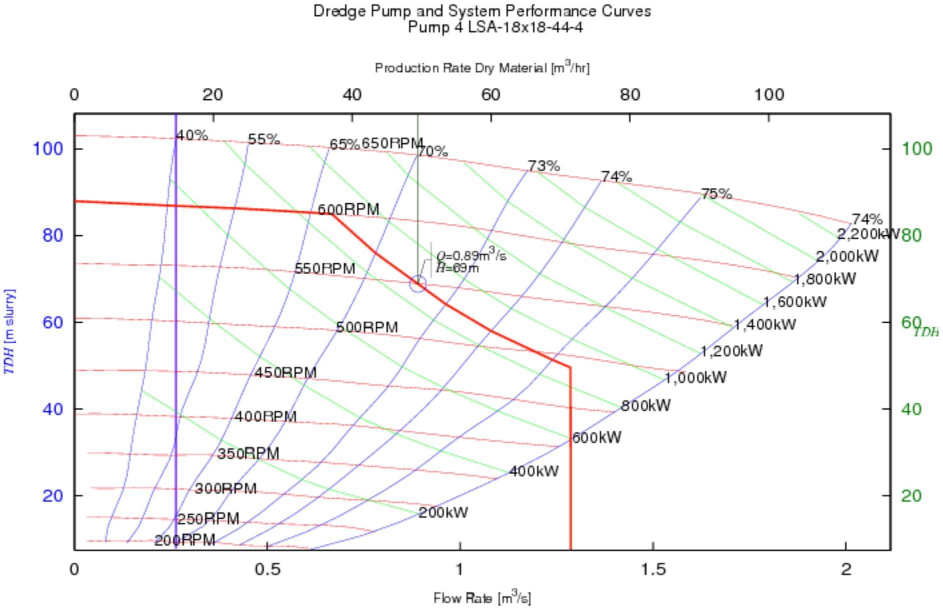


Fig. 58. Pump 4 curves for Dredge A in Savannah River on Project 3.

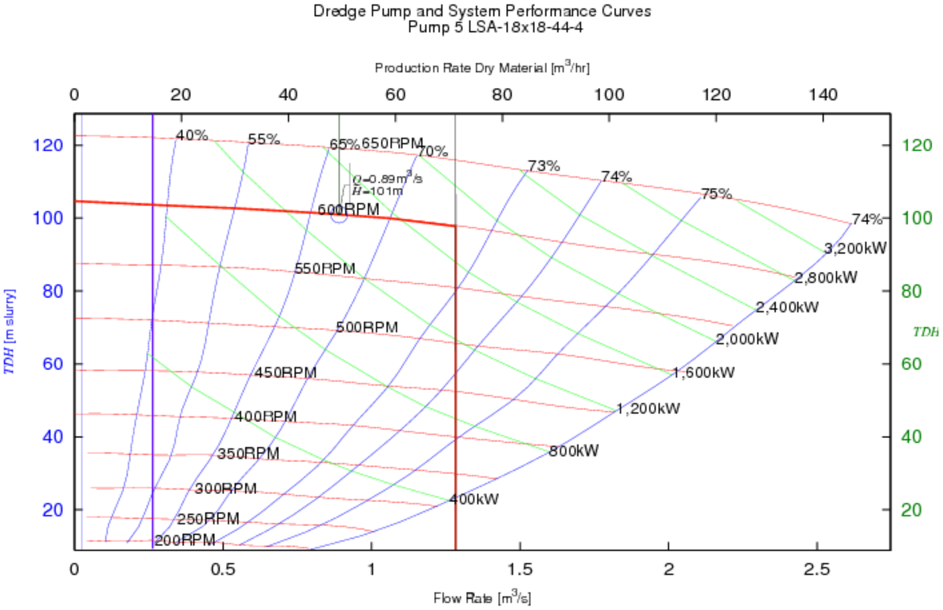


Fig. 59. Pump 5 curves for Dredge A in Savannah River on Project 3.

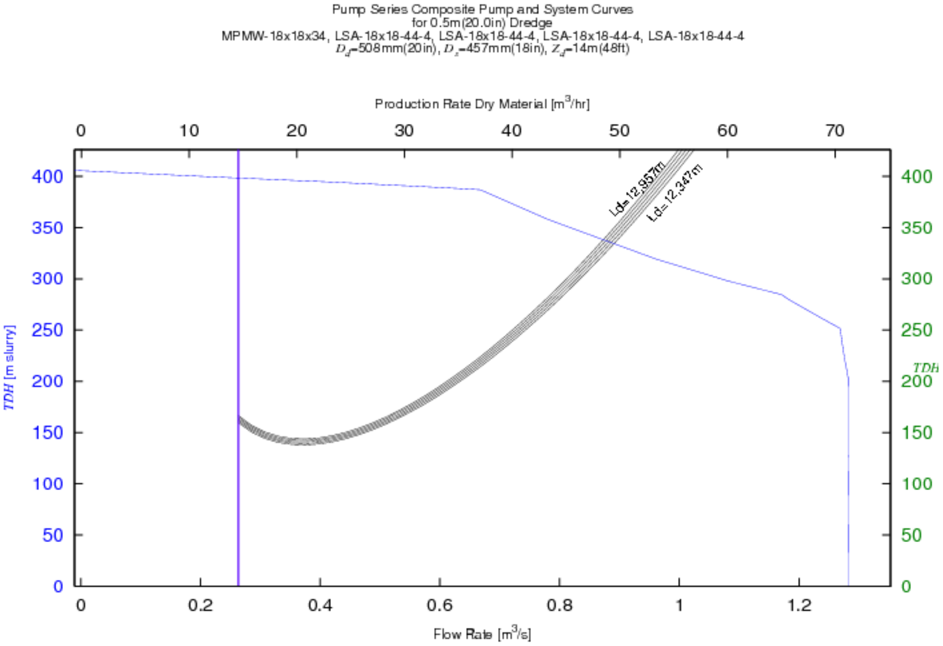


Fig. 60. Pump series composite curve for Dredge A in Savannah River on Project 3.

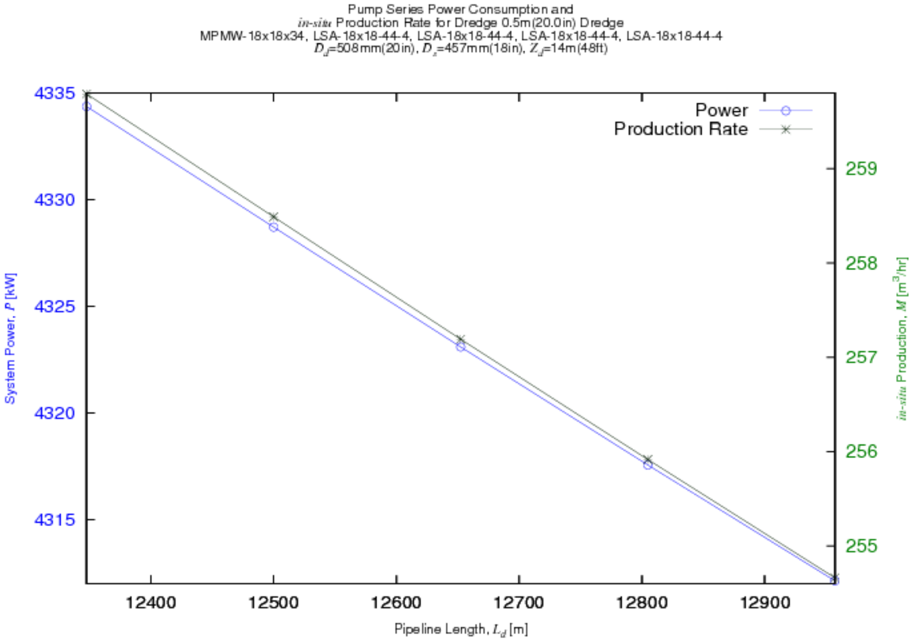


Fig. 61. Pump series performance metrics for Dredge A in Savannah River on Project 3.

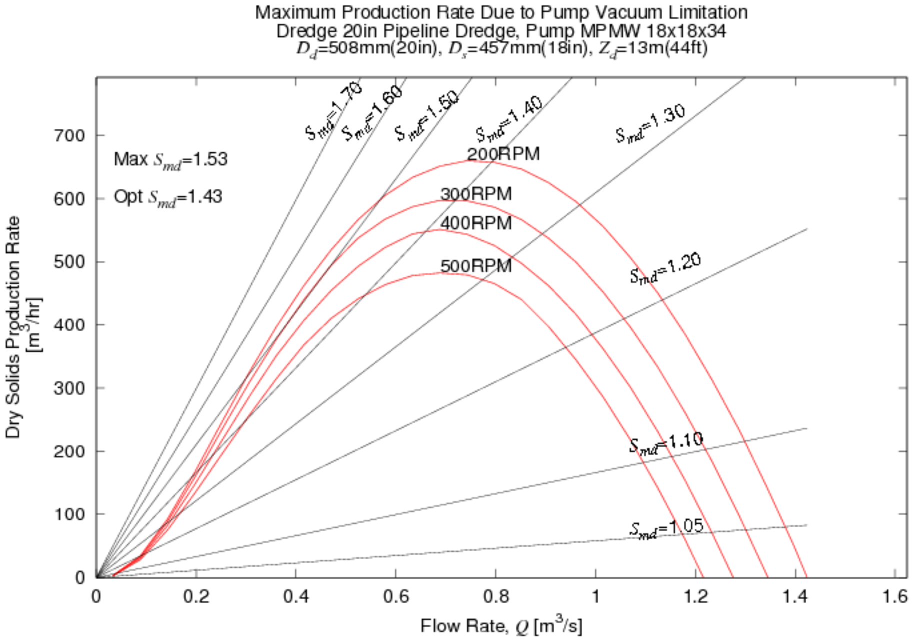


Fig. 62. Ladder pump maximum production curve for Dredge A in Savannah River on Project 3.

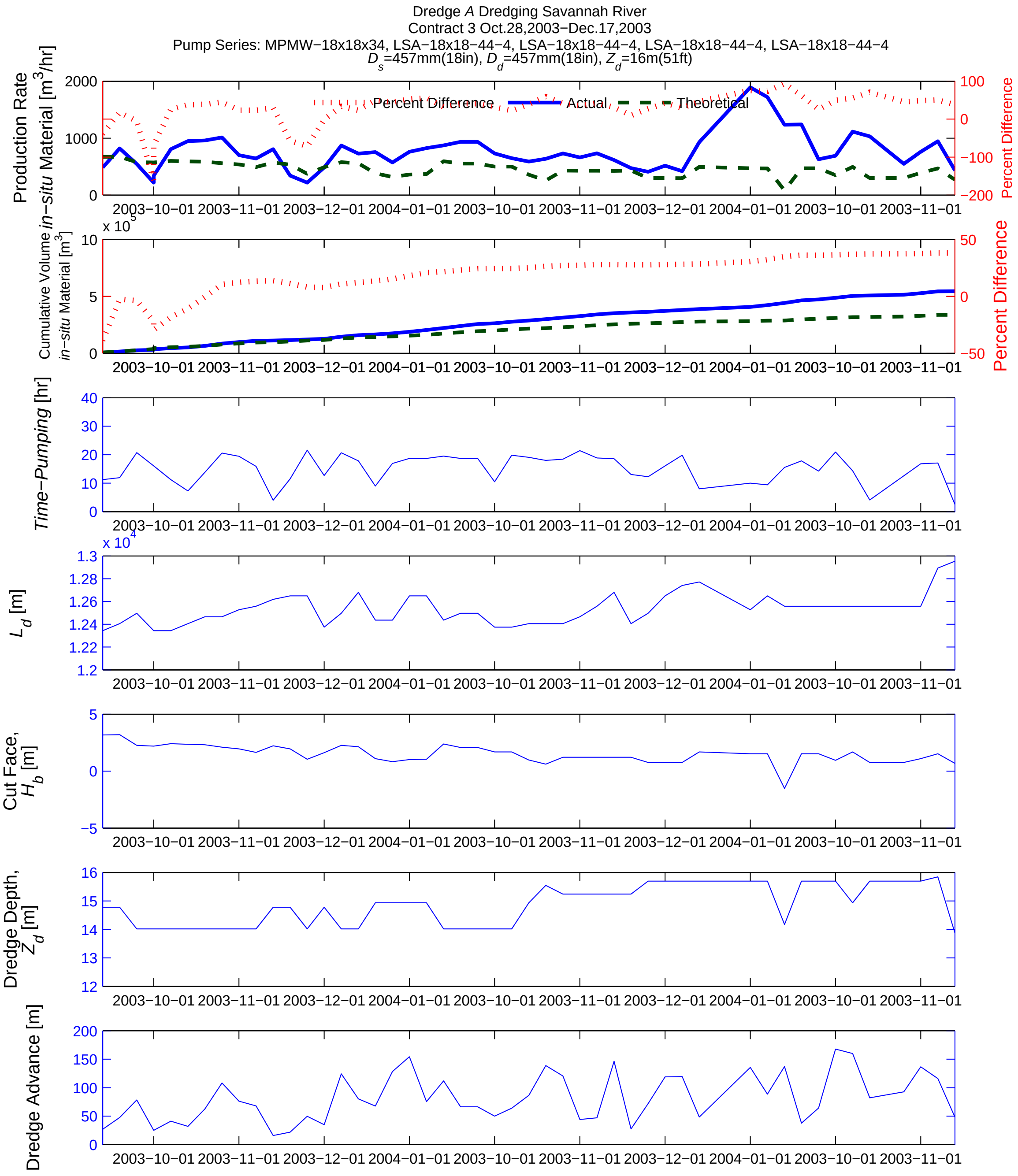


Fig. 63. Comparison between actual dredge production and theoretical dredge production for Dredge *A* in Savannah River on Project 3.

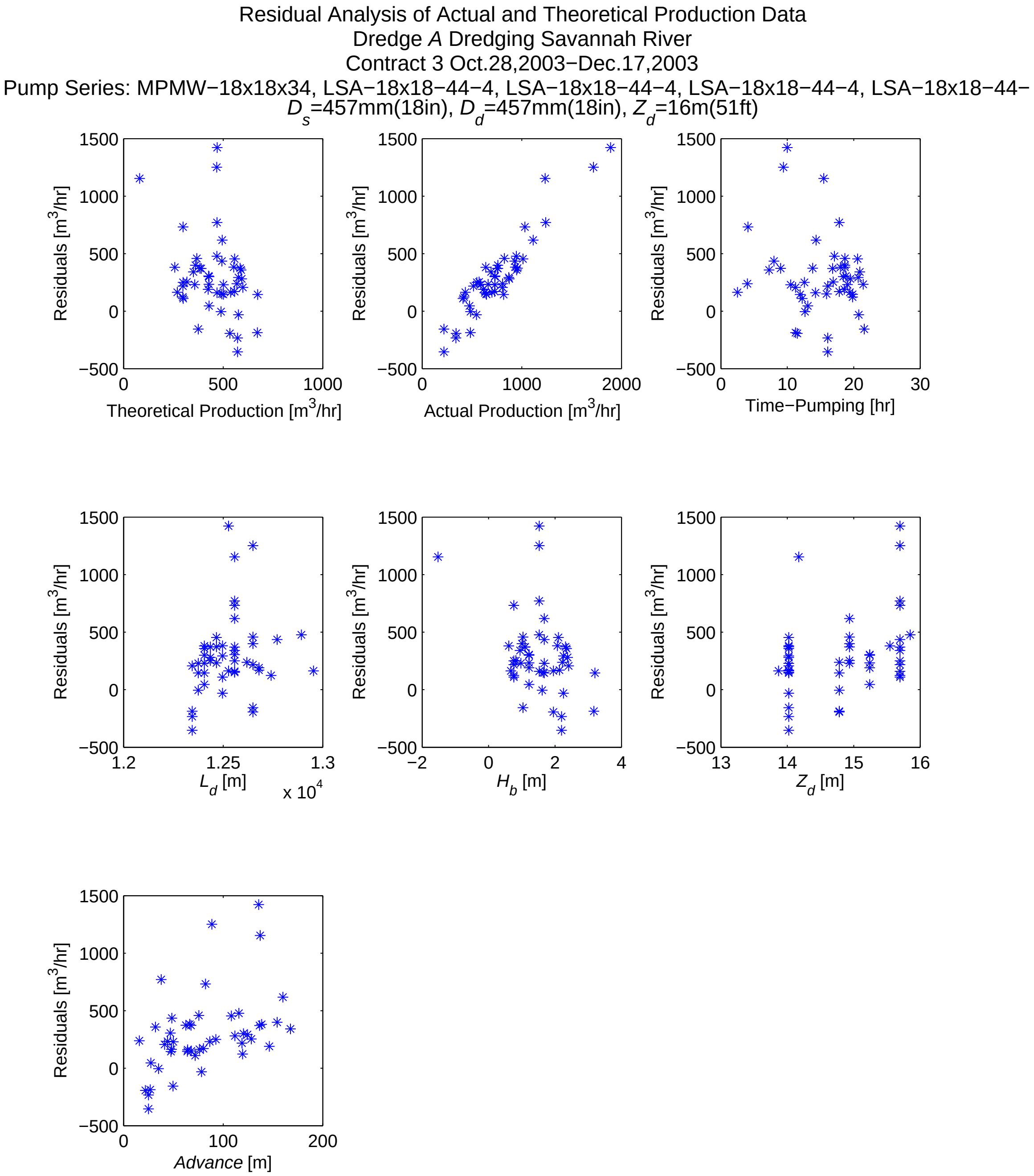


Fig. 64. Residual analysis between actual dredge production and theoretical dredge production for Dredge *A* in Savannah River on Project 3.

B. New Orleans District Project Data

The New Orleans U.S. Army Corps of Engineers District dredges 10.7Mm^3(14Myd^3) annually from the Atchafalaya River and 10.1Mm^3(13.2Myd^3) annually from the Mississippi River at Southwest Pass. Two pipeline dredge projects from each location provide daily dredge report data. These reports provide similar data parameters to those from Savannah District with the exception of no known Z_i. Table 39 describes these dredge projects.

Table 39. New Orleans district pipeline dredge project parameters.

Project Number	**Location**	**Dredge**	Z_d
4	Atchafalaya River	*B*	5.2m(17ft)
5	Mississippi River near Southwest Pass	*C*	15.5m(51ft)
6	Atchafalaya River	*B*	7.0m(23ft)
7	Mississippi River near Southwest Pass	*D*	12.5m(41ft)

1. Atchafalaya River Projects

Two projects along the Atchafalaya River provide daily dredge reports to compare to the Pipeline Analytical Program. Both projects used Dredge *B* 762mm(30in) cutter suction pipeline dredge. Table 40 describes *Venture*'s dredge parameters. Table 41 describes the dredge pump configuration.

Table 40. Dredge Bparameters

Dredge Parameter	**Value**
D_d	762mm(30in)
D_s	813mm(32in)
L_s	6.1m(20ft)
L_L	26.3m(83ft)
D_c	2.13m(7ft)
Z_{lp}	3.1m(-20ft)

Table 41. Dredge B pump parameters for Atchafalaya River on Projects 4 and 6.

	Name	D_i	**Power**	**Max RPM**
Ladder	LSA-18x18-44-4	863mm(34in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600

a. Project 4 Analytical Results

Figures 65–68 contain the Pipeline Analytical Program results for the pump and pipeline interaction. Figure 69 illustrates the composite pump series and pipeline performance curves. Figure 70 illustrates the performance metrics of production and power consumption with pipeline length. Figure 71 illustrates the maximum production capable of the first pump limited by cavitation. Figure 72 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 73 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

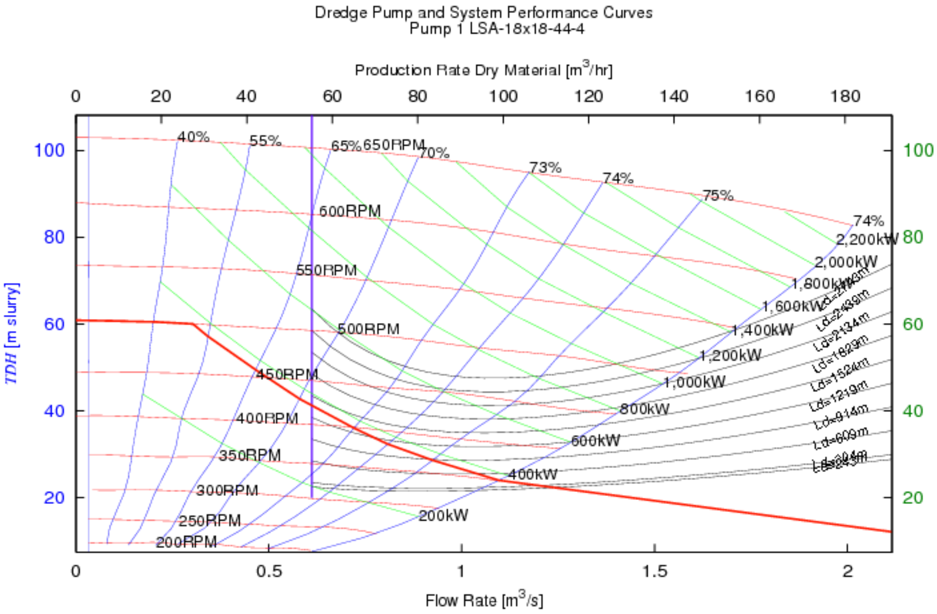


Fig. 65. Pump 1 curves for Dredge *B* in Atchafalaya River on Project 4.

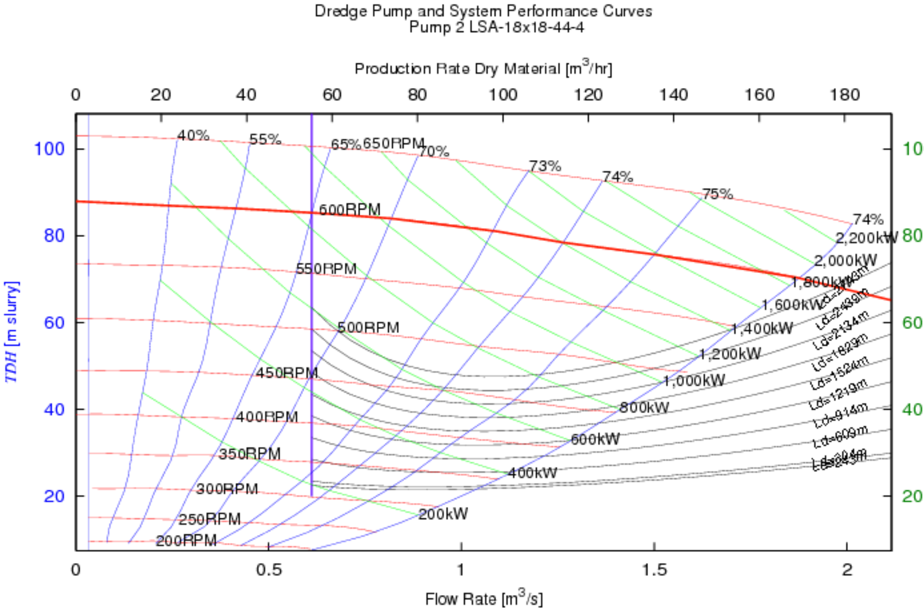


Fig. 66. Pump 2 curves for Dredge *B* in Atchafalaya River on Project 4.

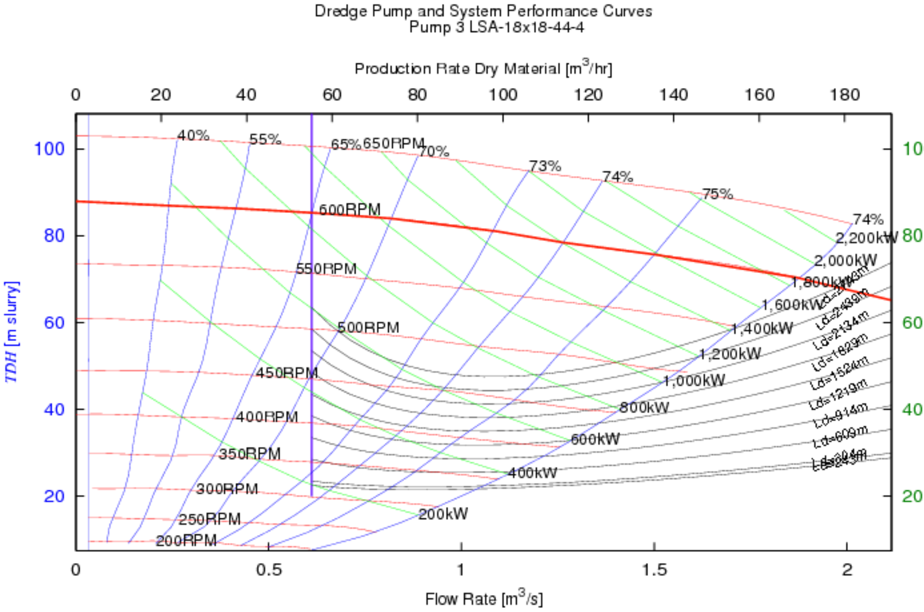


Fig. 67. Pump 3 curves for Dredge *B* in Atchafalaya River on Project 4.

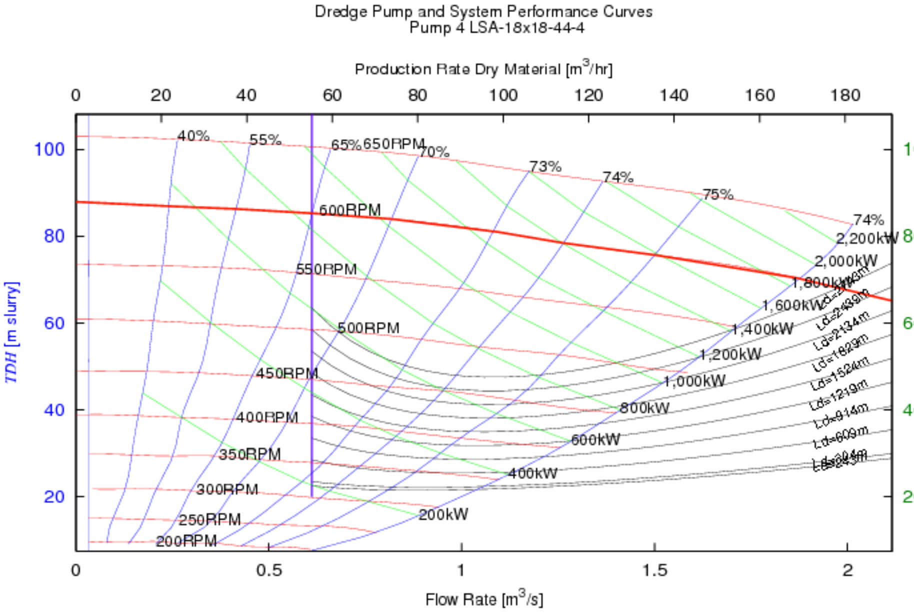


Fig. 68. Pump 4 curves for Dredge *B* in Atchafalaya River on Project 4.

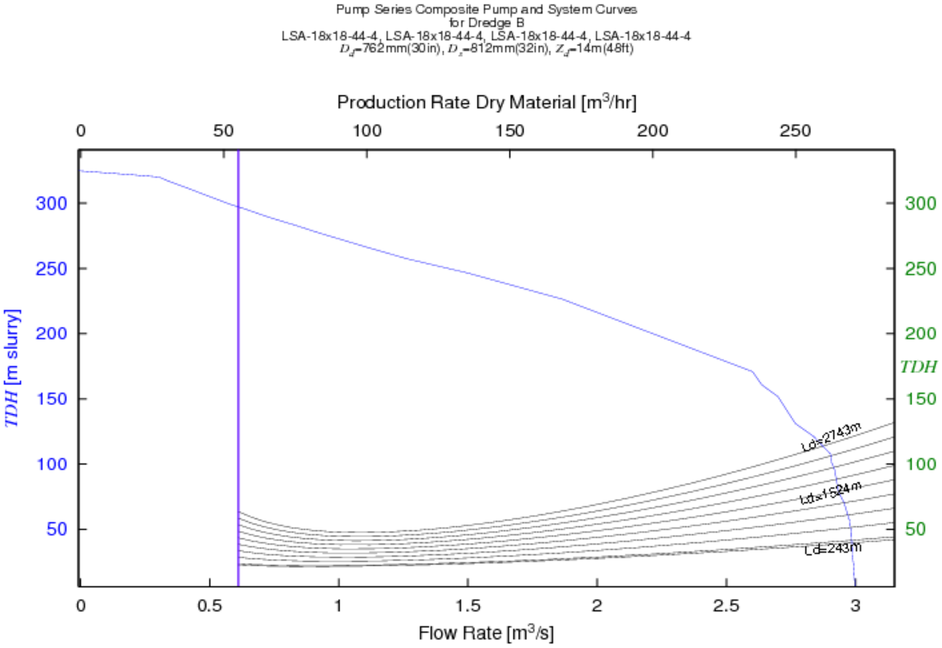


Fig. 69. Pump series composite curve for Dredge *B* in Atchafalaya River on Project 4.

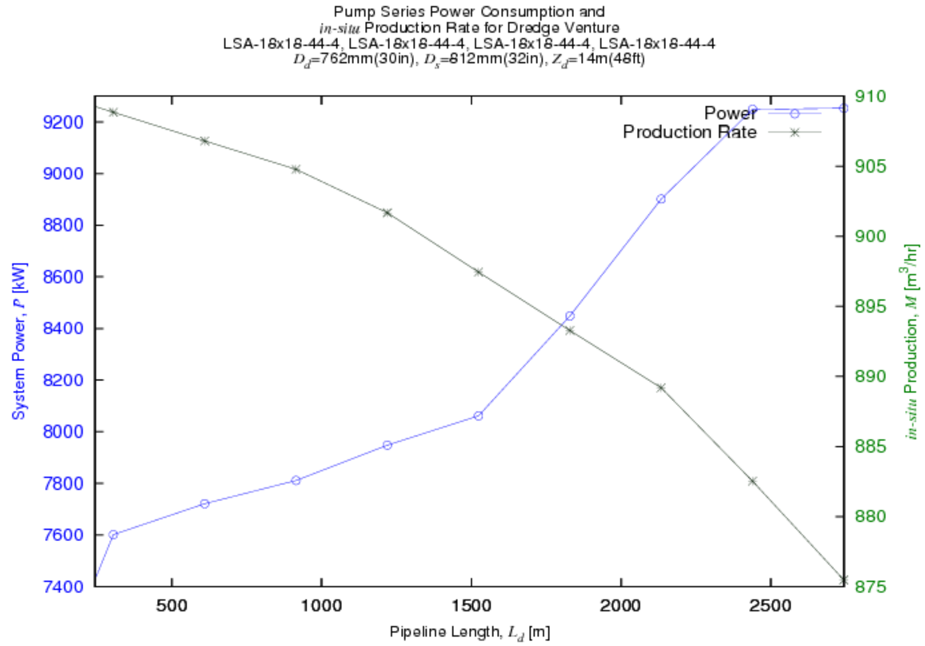


Fig. 70. Pump series performance metrics for Dredge B in Atchafalaya River on Project 4.

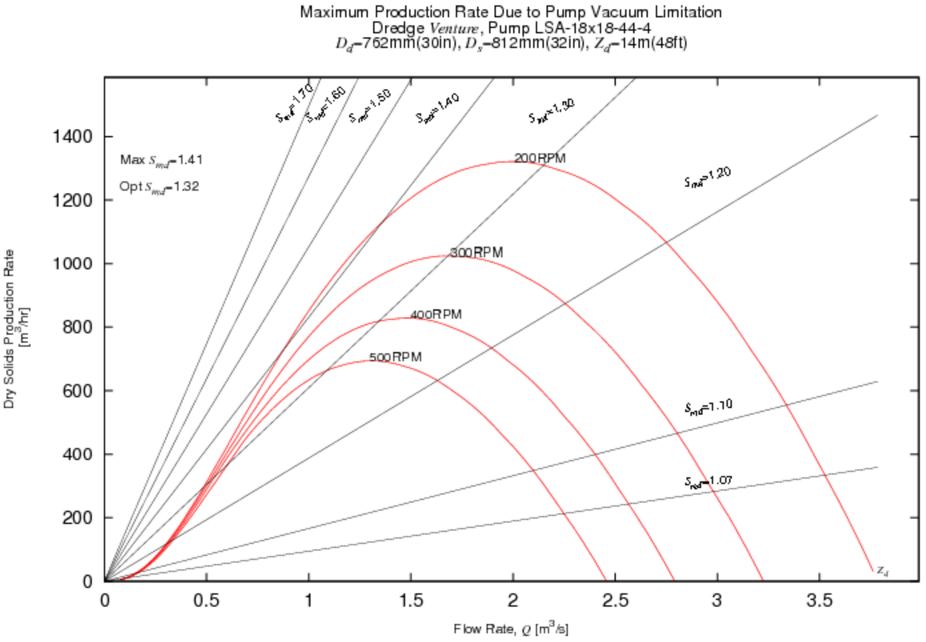


Fig. 71. Ladder pump maximum production curve for Dredge B in Atchafalaya River on Project 4.

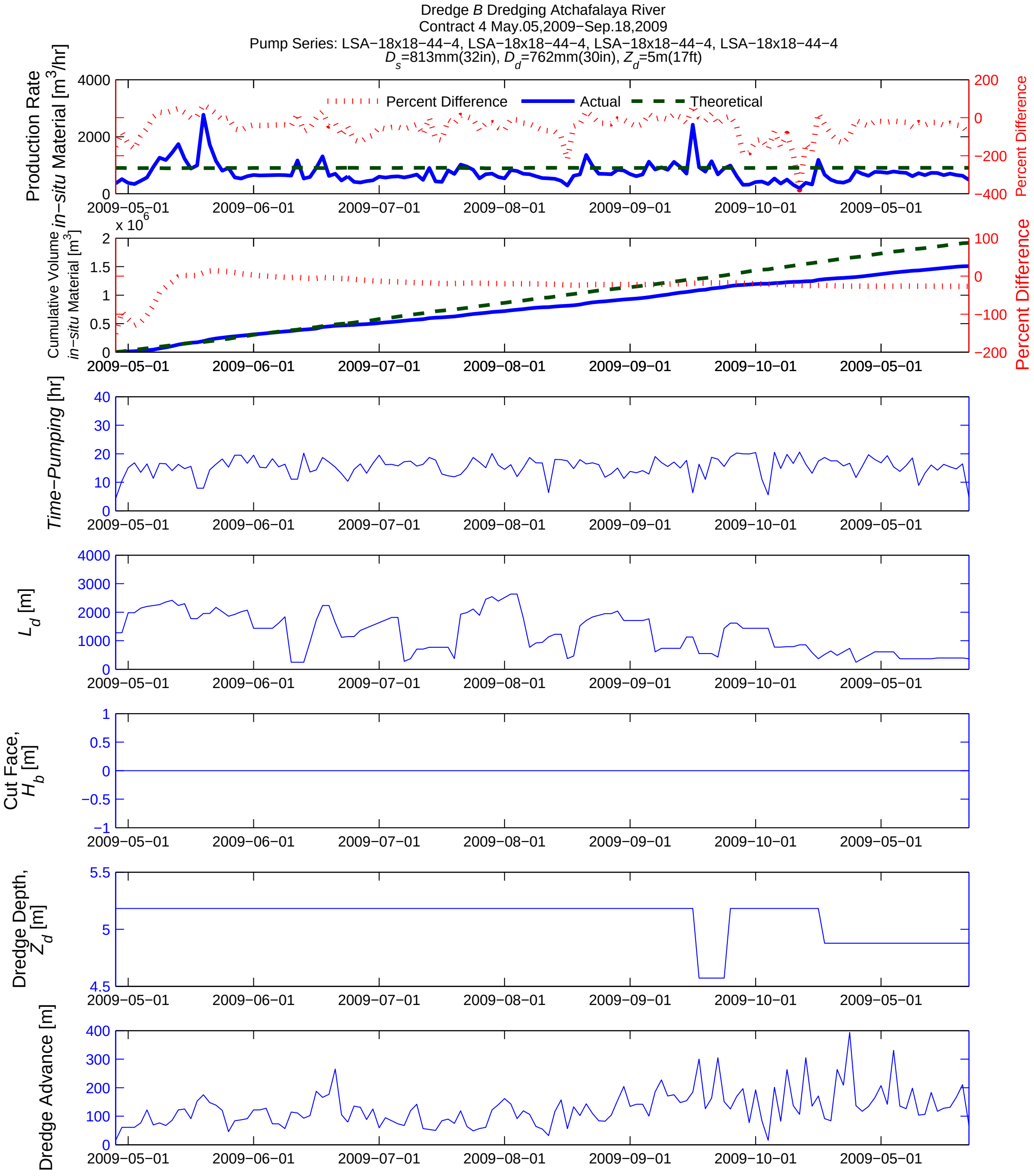


Fig. 72. Comparison between actual dredge production and theoretical dredge production for Dredge *B* in Atchafalaya River on Project 4.

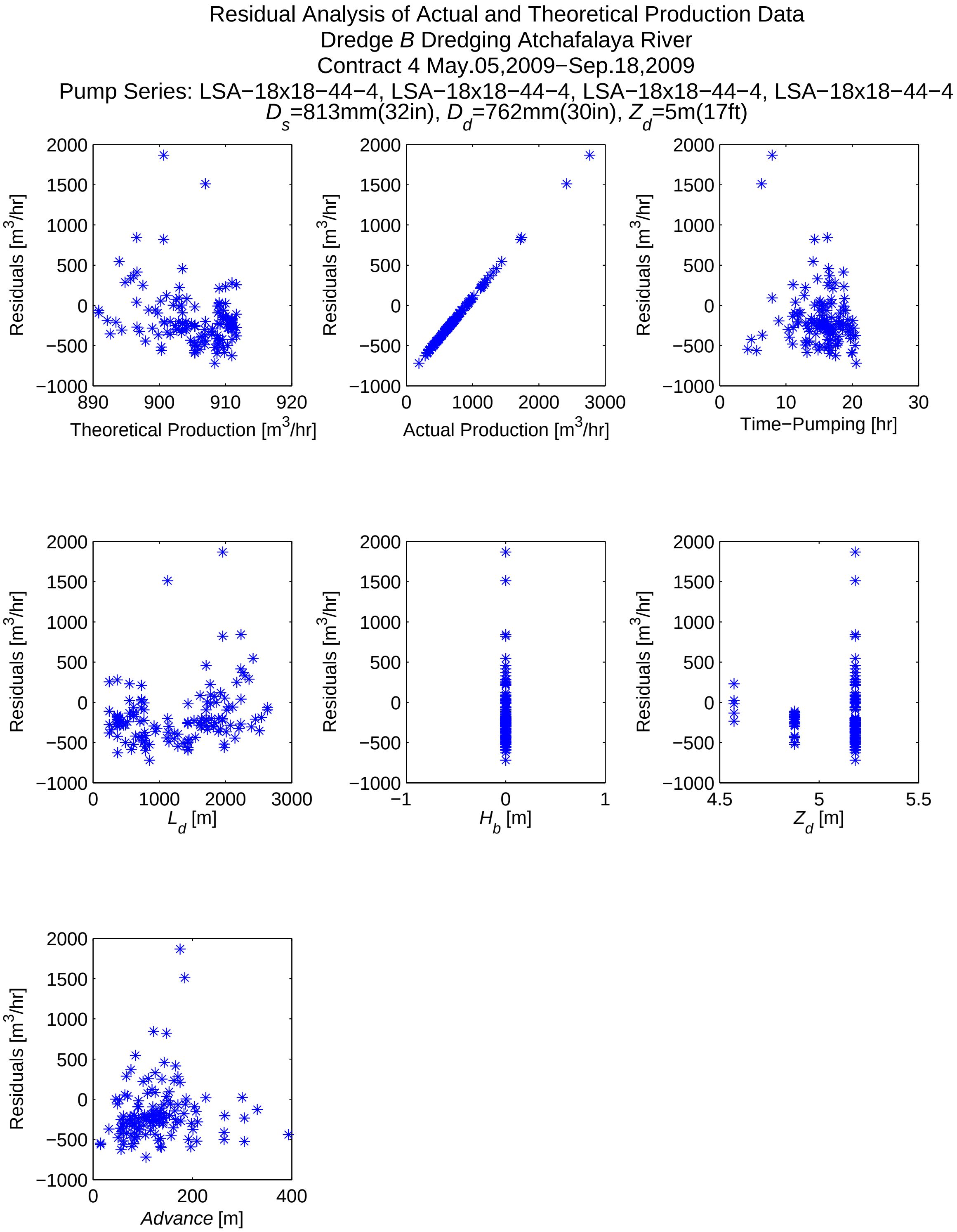


Fig. 73. Residual analysis between actual dredge production and theoretical dredge production for Dredge *B* in Atchafalaya River on Project 4.

b. Project 6 Analytical Results

Figures 74–77 contain the Pipeline Analytical Program results for the pump and pipeline interaction. Figure 78 illustrates the composite pump series and pipeline performance curves. Figure 79 illustrates the performance metrics of production and power consumption with pipeline length. Figure 80 illustrates the maximum production capable of the first pump limited by cavitation. Figure 81 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 82 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

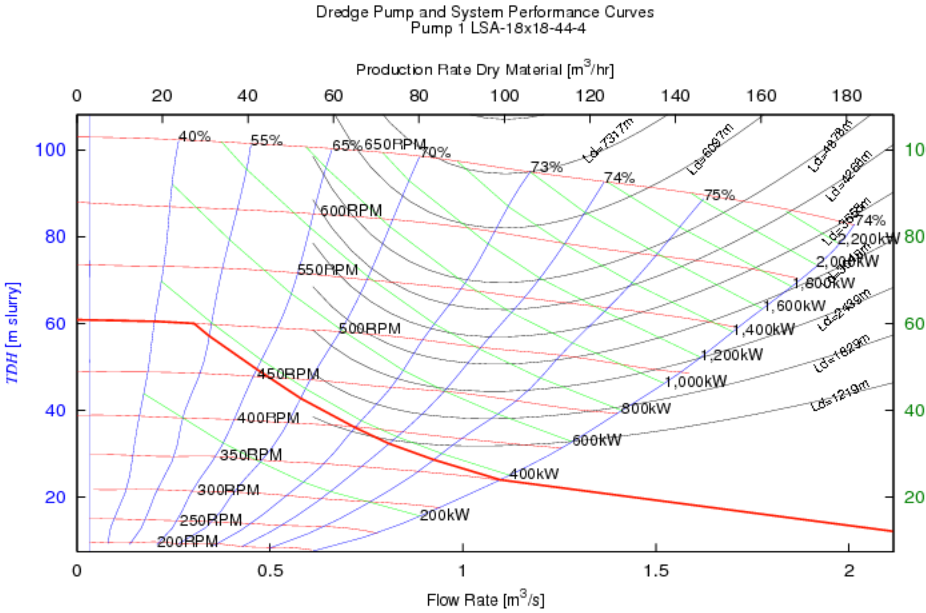


Fig. 74. Pump 1 curves for Dredge *B* in Atchafalaya River on Project 6.

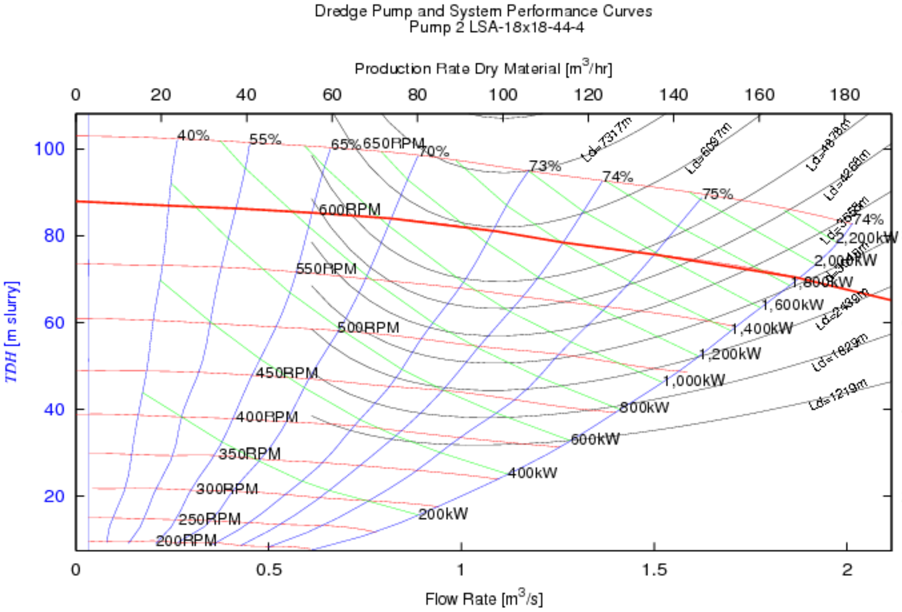


Fig. 75. Pump 2 curves for Dredge *B* in Atchafalaya River on Project 6.

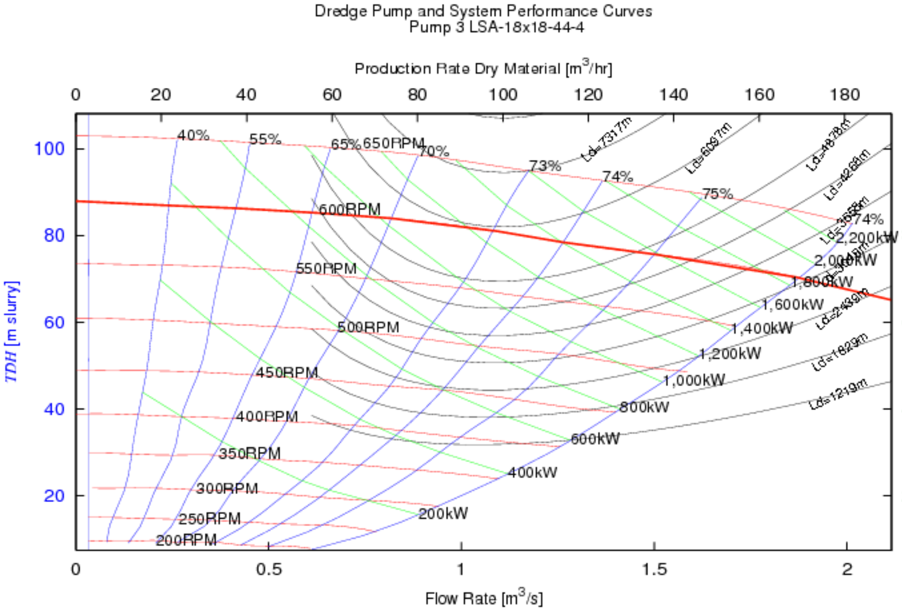


Fig. 76. Pump 3 curves for Dredge *B* in Atchafalaya River on Project 6.

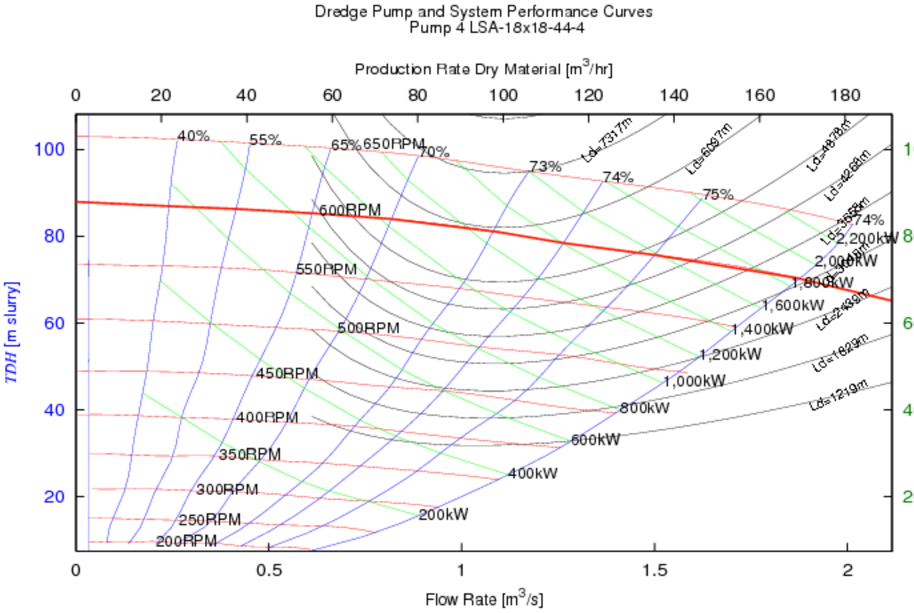


Fig. 77. Pump 4 curves for Dredge *B* in Atchafalaya River on Project 6.

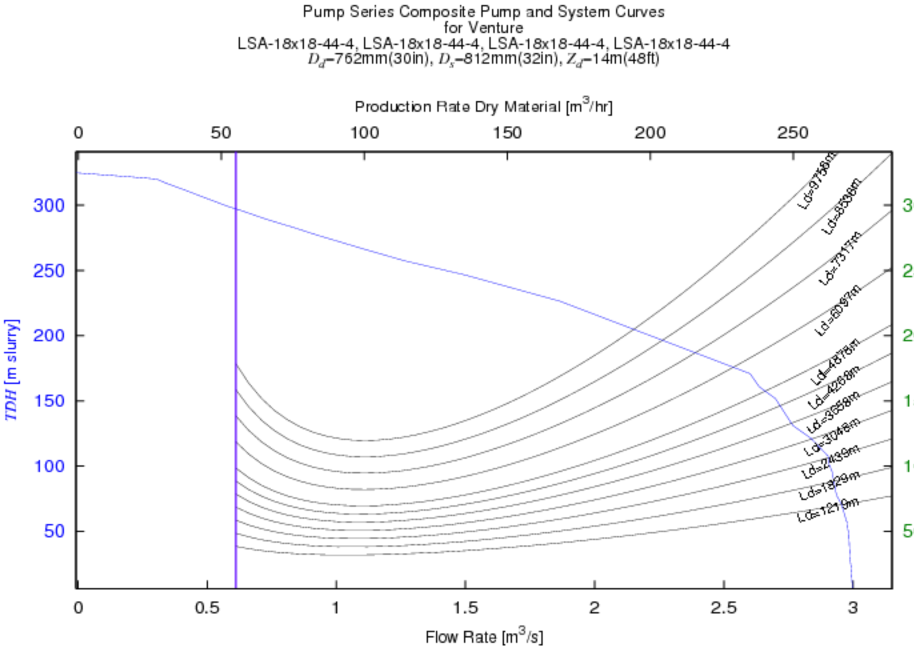


Fig. 78. Pump series composite curve for Dredge *B* in Atchafalaya River on Project 6.

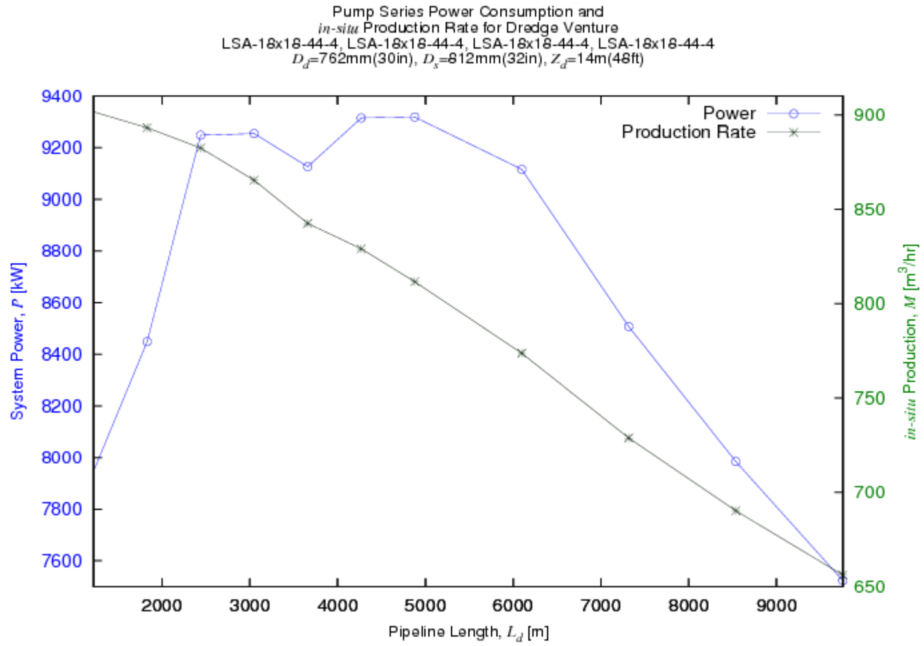


Fig. 79. Pump series performance metrics for Dredge B in Atchafalaya River on Project 6.

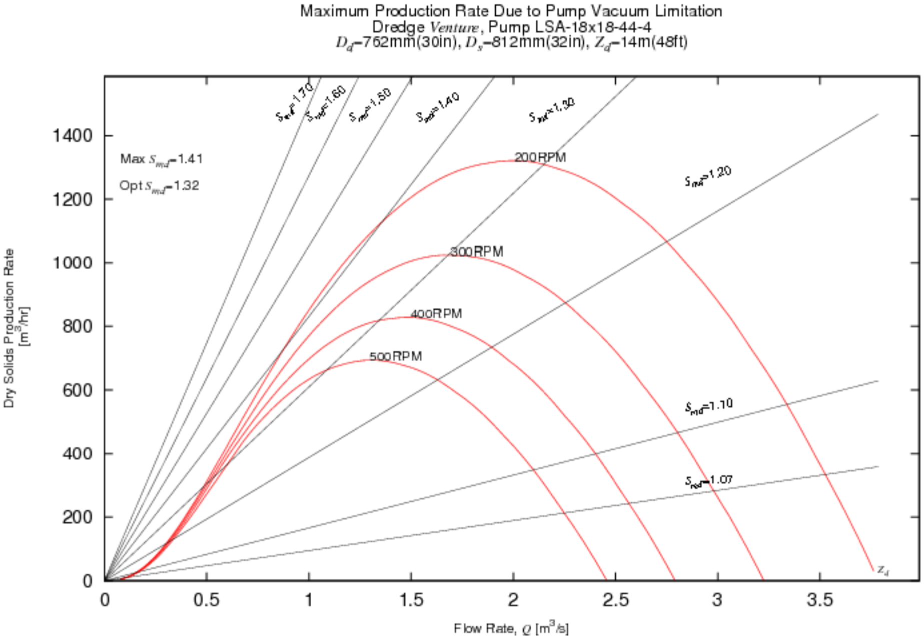


Fig. 80. Ladder pump maximum production curve for Dredge B in Atchafalaya River on Project 6.

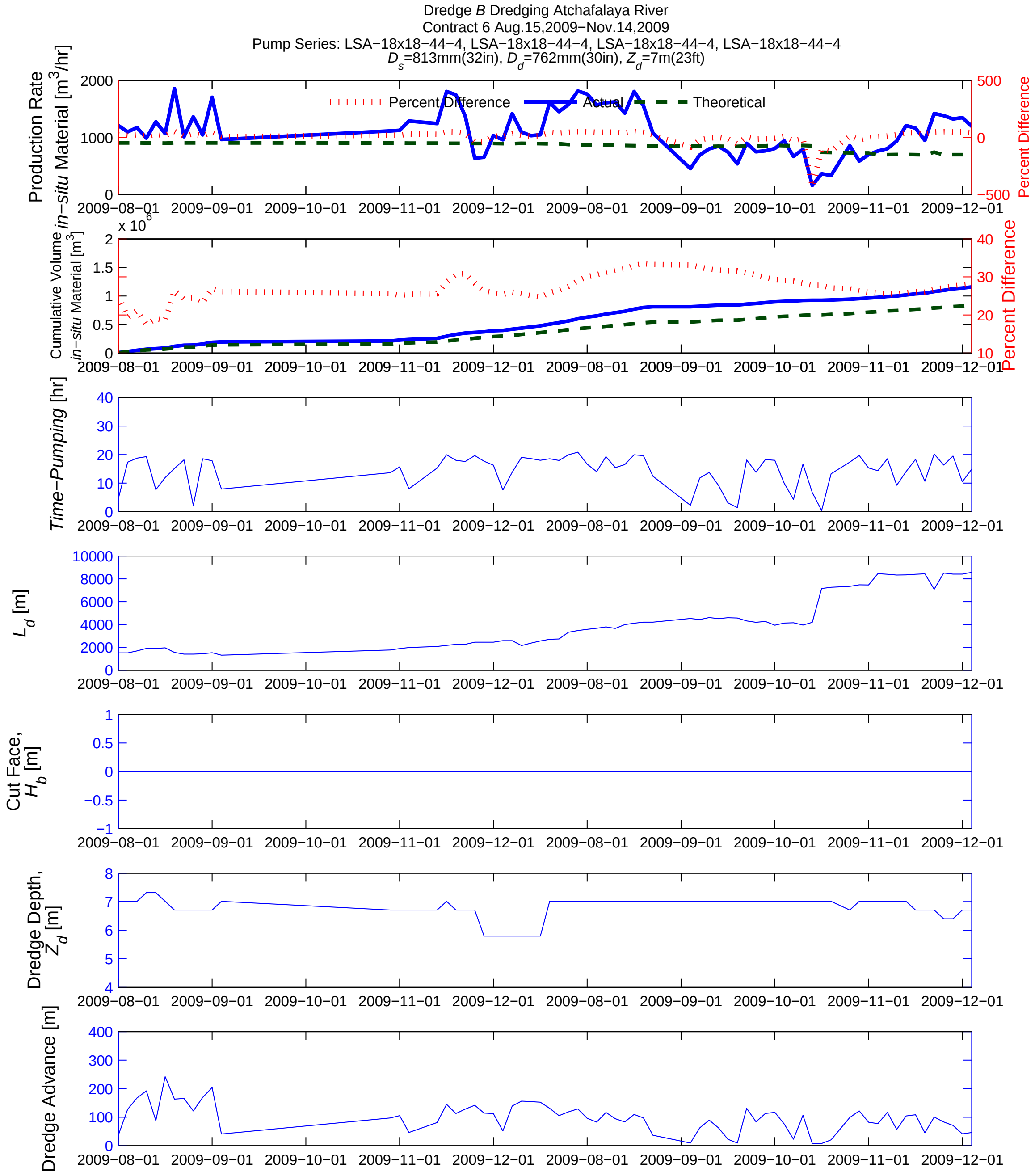


Fig. 81. Comparison between actual dredge production and theoretical dredge production for Dredge *B* in Atchafalaya River on Project 6.

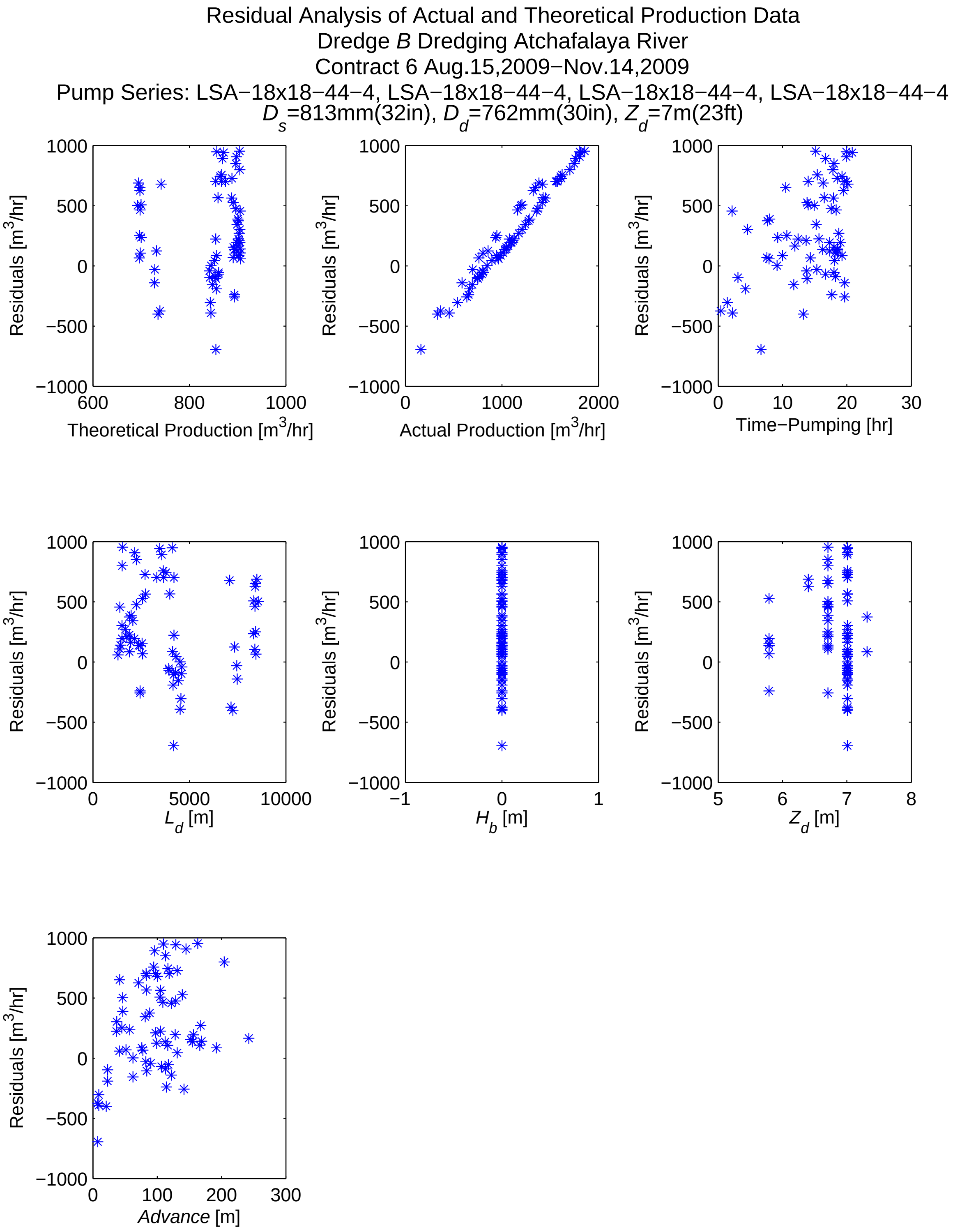


Fig. 82. Residual analysis between actual dredge production and theoretical dredge production for Dredge *B* in Atchafalaya River on Project 6.

2. Mississippi River Projects

Two projects along the Mississippi River near Southwest Pass provide daily dredge reports to compare to the Pipeline Analytical Program. The projects used Dredge *C* 762mm(30in) cutter suction pipeline dredge on Project 5 and Dredge *D* 762mm(30in) cutter suction pipeline dredge on Project 7. Table 42 describes Dredge *C*'s and Dredge *D*'s dredge parameters. Table 43 describes the dredge pump configuration for Dredge *C* and Table 44 describes the dredge pump configuration for Dredge *D*.

Table 42. Dredge *C* and *D* parameters

Dredge Parameter	**Value**
D_d	762mm(30in)
D_s	813mm(32in)
L_s	6.1m(20ft)
L_L	26.3m(83ft)
D_c	2.13m(7ft)
Z_{lp}	3.1m(-20ft)

Table 43. Dredge *C* pump parameters for Atchafalaya River on Project 5.

	Name	D_i	**Power**	**Max RPM**
Ladder	LSA-18x18-44-4	863mm(34in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,117mm(44in)	1,862kW(2,500bhp)	600

Table 44. Dredge *D* pump parameters for Atchafalaya River on Project 6.

	Name	D_i	**Power**	**Max RPM**
Ladder	LSA-18x18-44-4	1,117mm(44in)	372kW(500bhp)	500
Hull	LSA-18x18-44-4	1,829mm(72in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,829mm(72in)	1,862kW(2,500bhp)	600
Hull	LSA-18x18-44-4	1,829mm(72in)	1,862kW(2,500bhp)	600

a. Project 5 Analytical Results

Figures 83–86 contain the Pipeline Analytical Program results for the pump and pipeline interaction for Dredge *C*. Figure 87 illustrates the composite pump series and pipeline performance curves. Figure 88 illustrates the performance metrics of production and power consumption with pipeline length. Figure 89 illustrates the maximum production capable of the first pump limited by cavitation. Figure 90 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 91 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

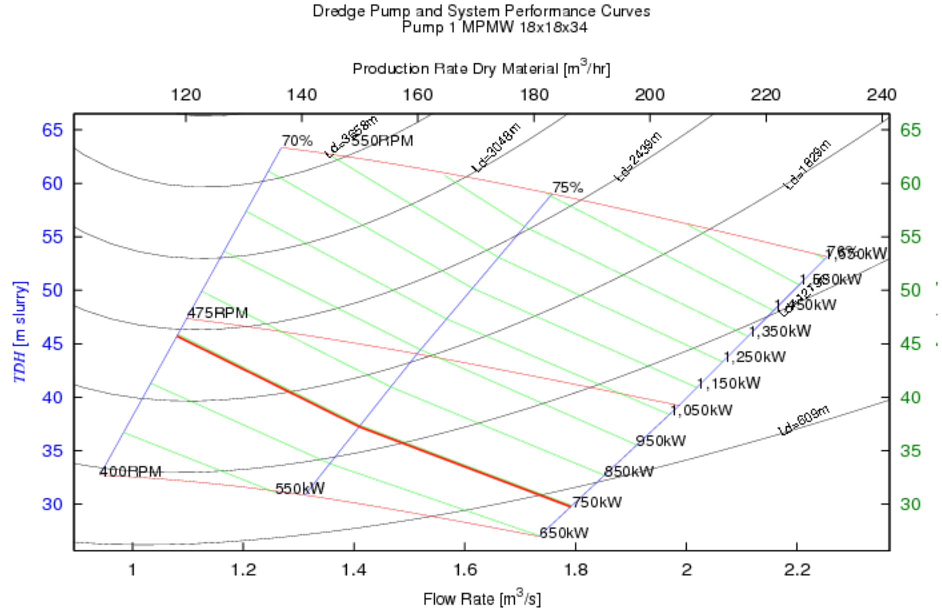


Fig. 83. Pump 1 curves for Dredge *C* in Mississippi River on Project 5.

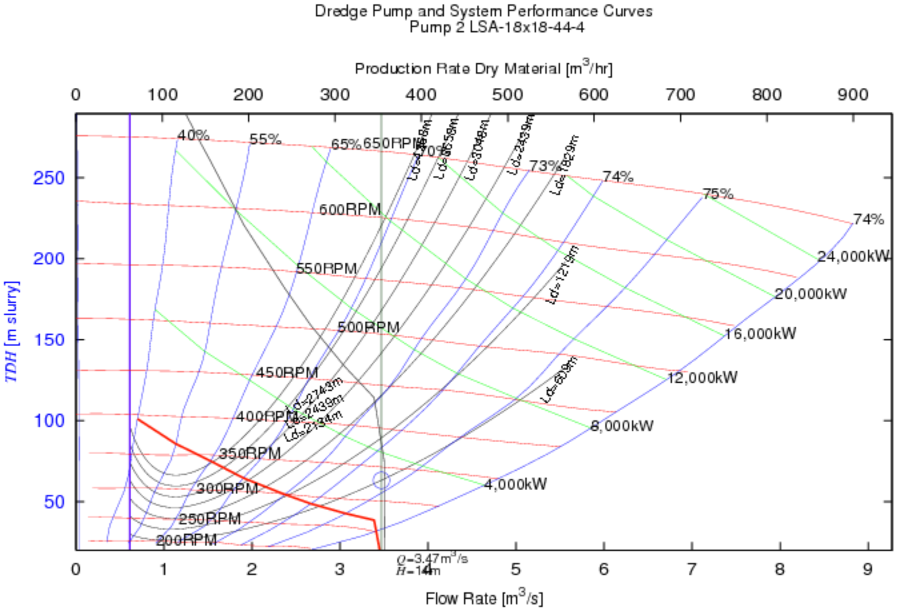


Fig. 84. Pump 2 curves for Dredge *C* in Mississippi River on Project 5.

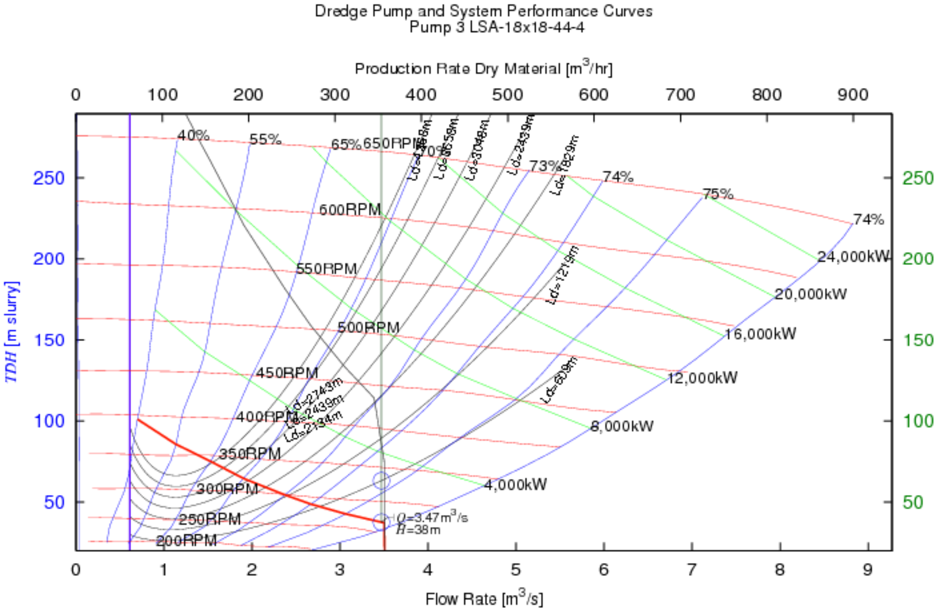


Fig. 85. Pump 3 curves for Dredge *C* in Mississippi River on Project 5.

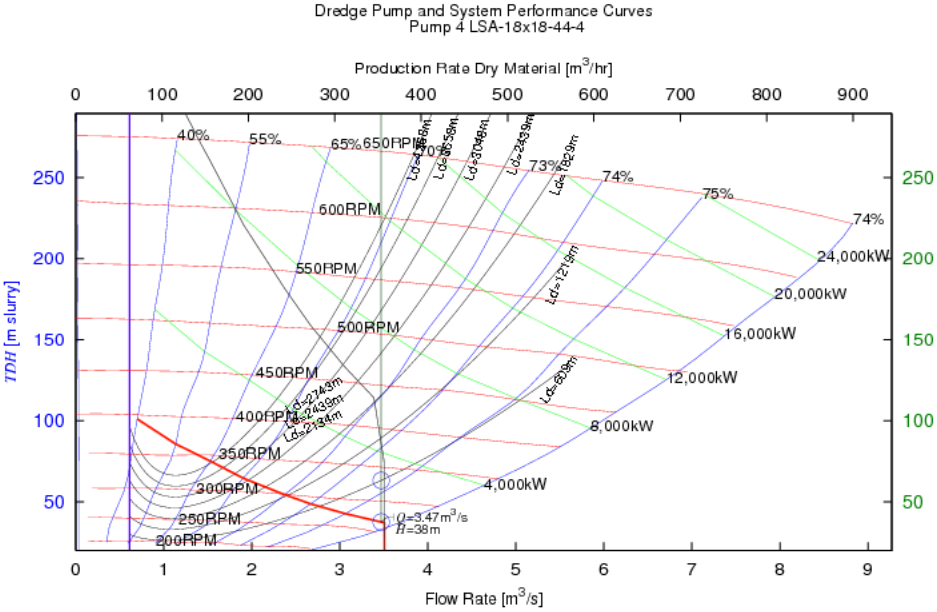


Fig. 86. Pump 4 curves for Dredge *C* in Mississippi River on Project 5.

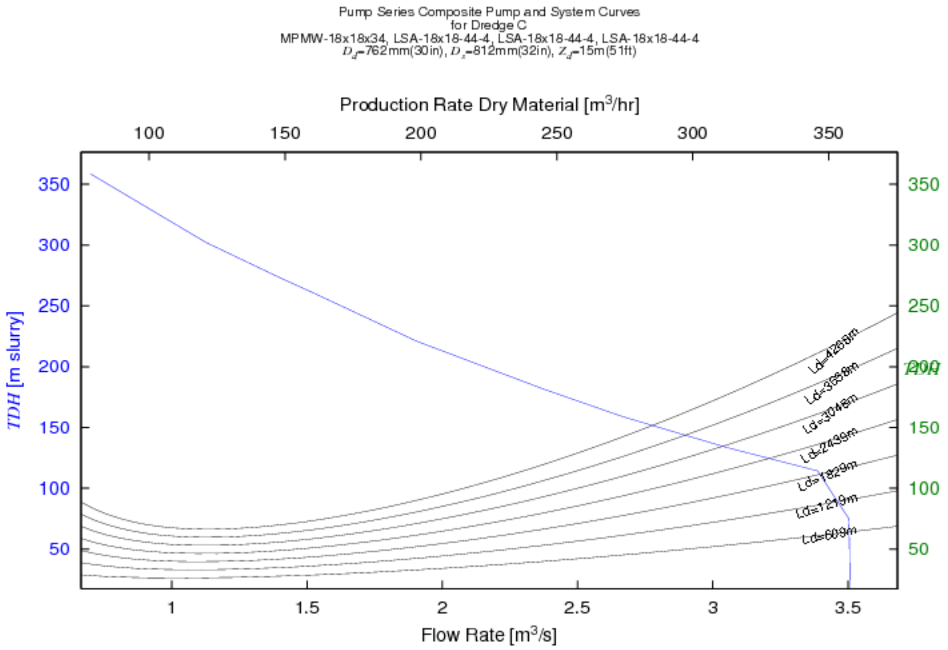


Fig. 87. Pump series composite curve for Dredge *C* in Mississippi River on Project 5.

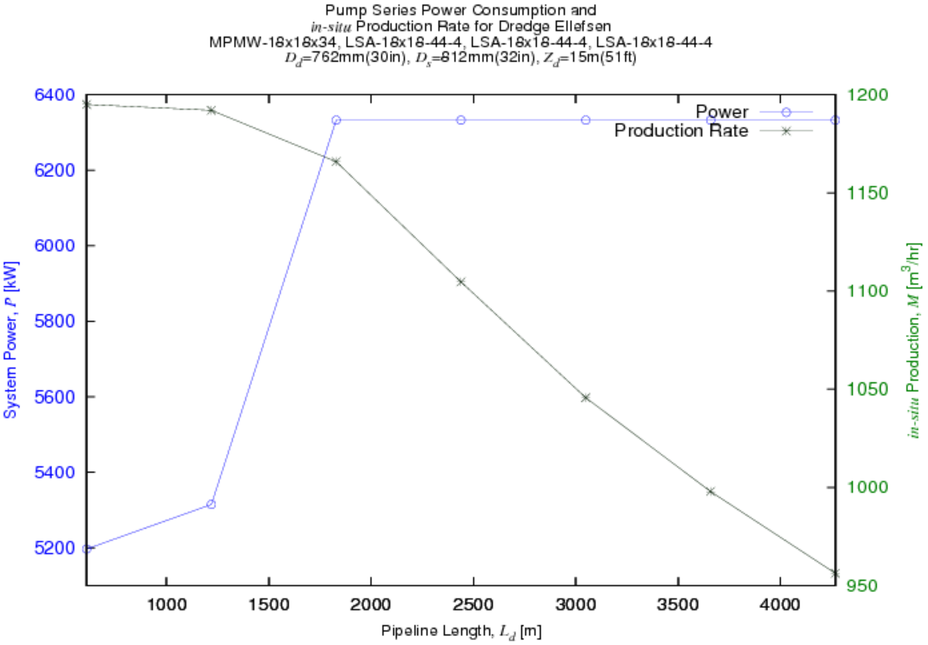


Fig. 88. Pump series performance metrics for Dredge *C* in Mississippi River on Project 5.

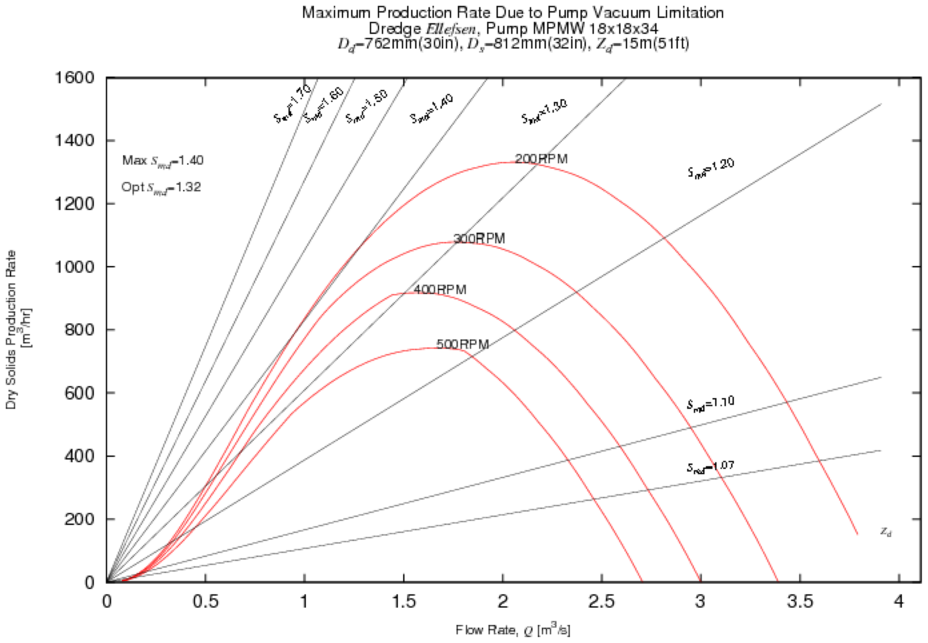


Fig. 89. Ladder pump maximum production curve for Dredge *C* in Mississippi River on Project 5.

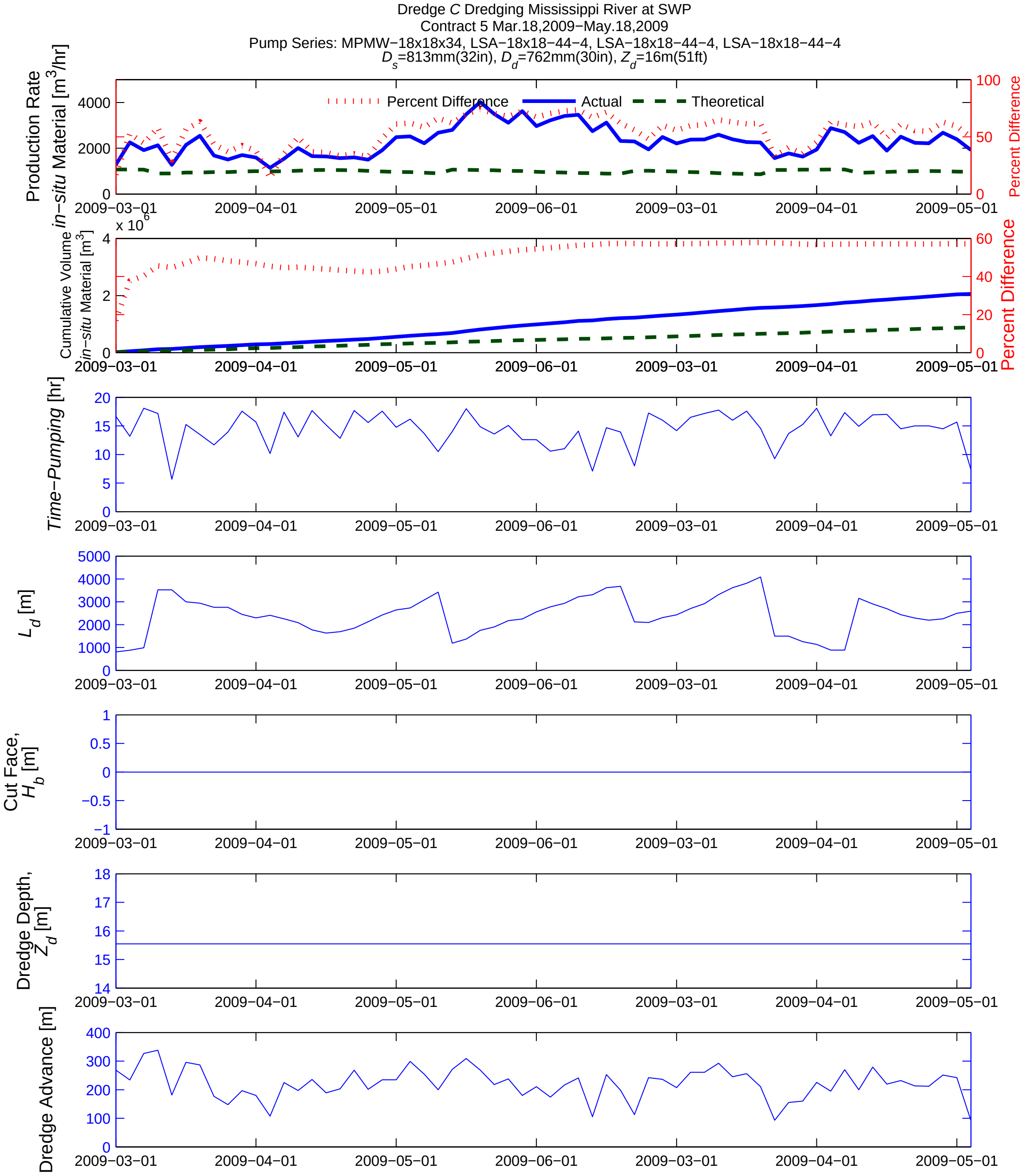


Fig. 90. Comparison between actual dredge production and theoretical dredge production for Dredge *C* in Mississippi River on Project 5.

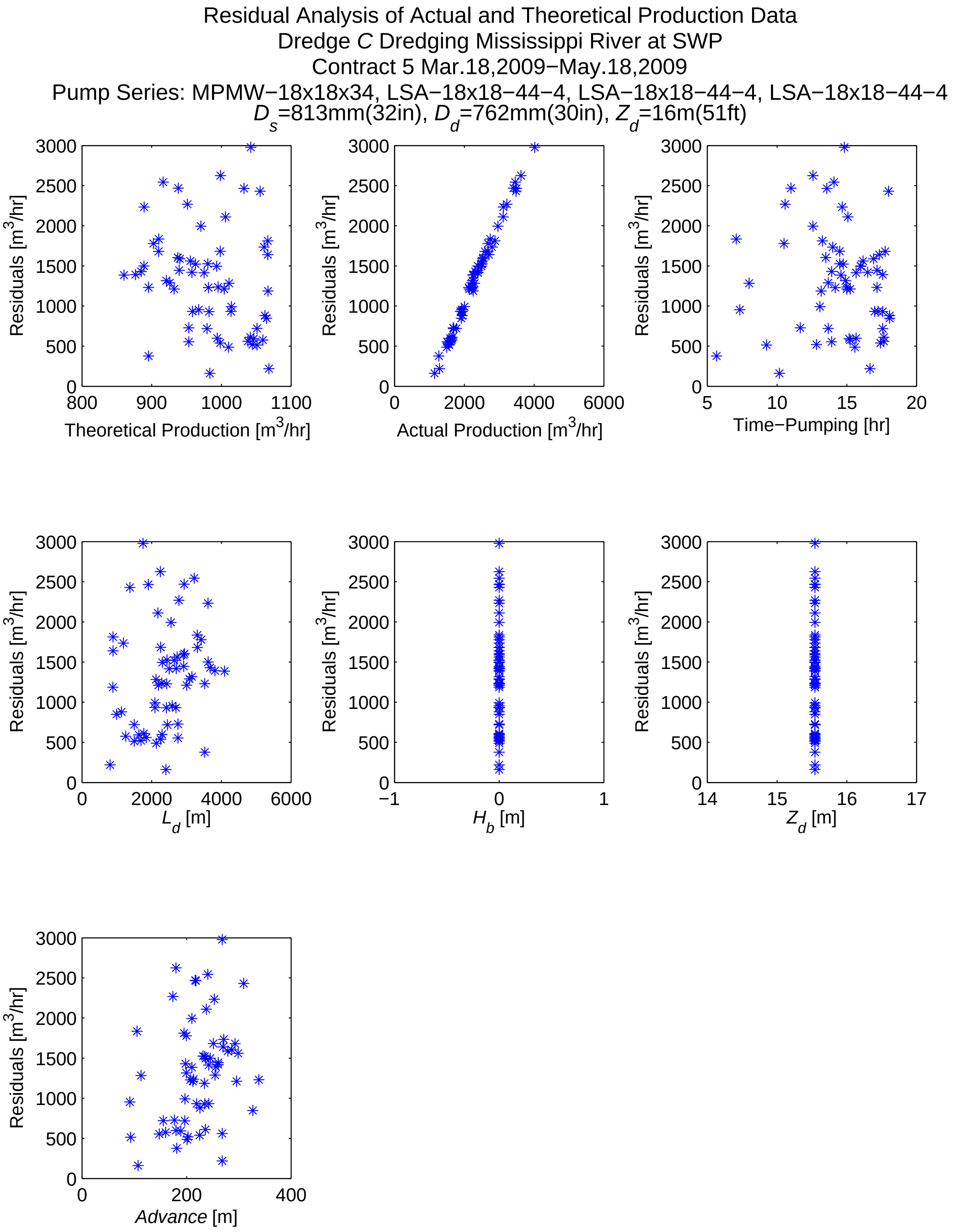


Fig. 91. Residual analysis between actual dredge production and theoretical dredge production for Dredge *C* in Mississippi River on Project 5.

b. Project 7 Analytical Results

Figures 92–95 contain the Pipeline Analytical Program results for the pump and pipeline interaction. Figure 96 illustrates the composite pump series and pipeline performance curves. Figure 97 illustrates the performance metrics of production and power consumption with pipeline length. Figure 98 illustrates the maximum production capable of the first pump limited by cavitation. Figure 99 shows the timeline comparison between actual dredge production and theoretical dredge production. Figure 100 contains the residual plot between the actual and theoretical production rates compared with the dredging parameters for data comparison.

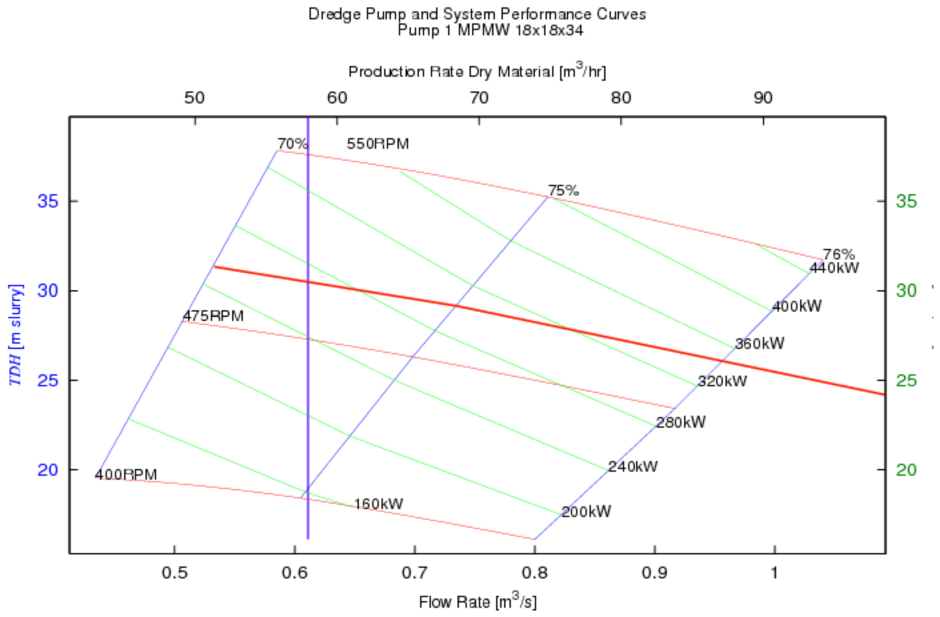


Fig. 92. Pump 1 curves for Dredge *D* in Mississippi River on Project 7.

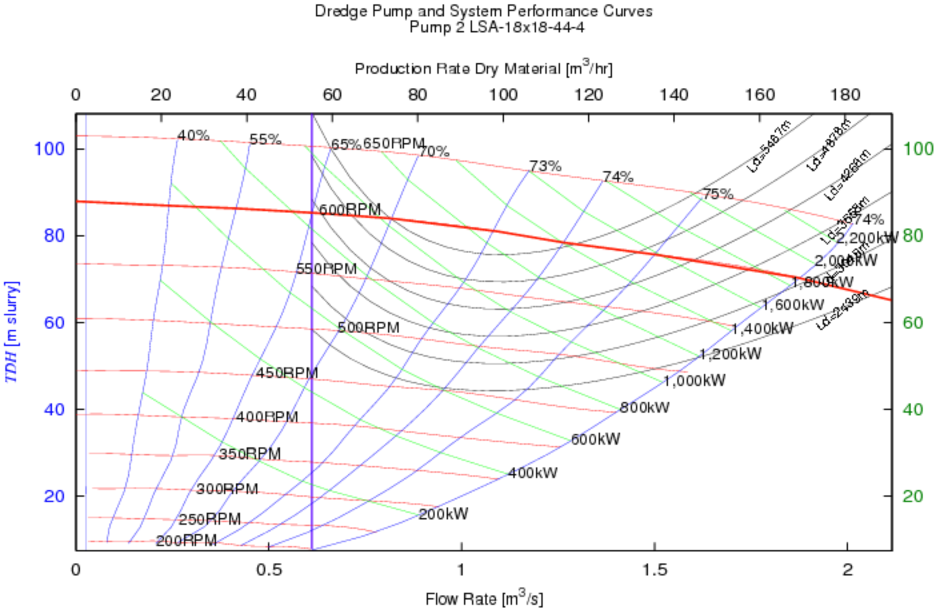


Fig. 93. Pump 2 curves for Dredge *D* in Mississippi River on Project 7.

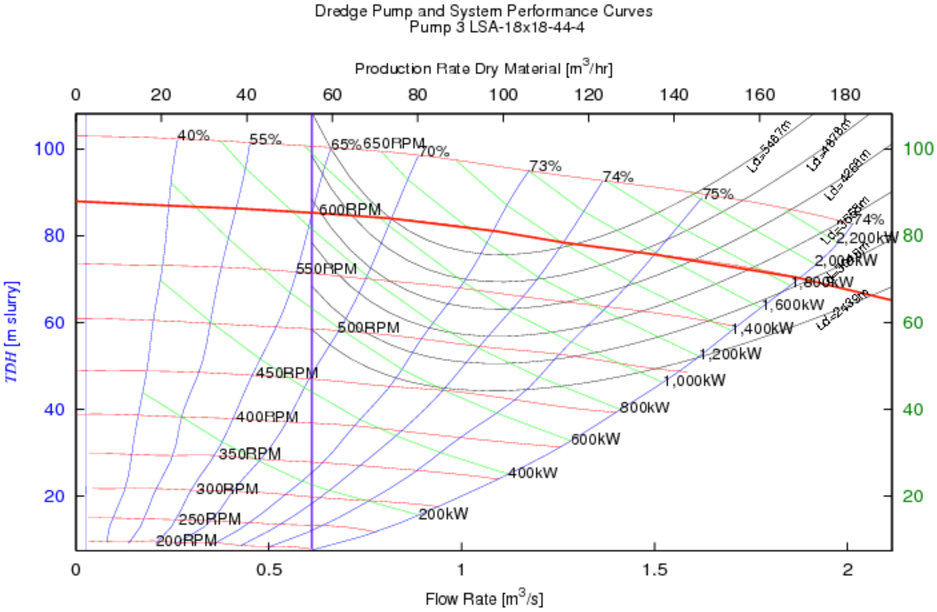


Fig. 94. Pump 3 curves for Dredge *D* in Mississippi River on Project 7.

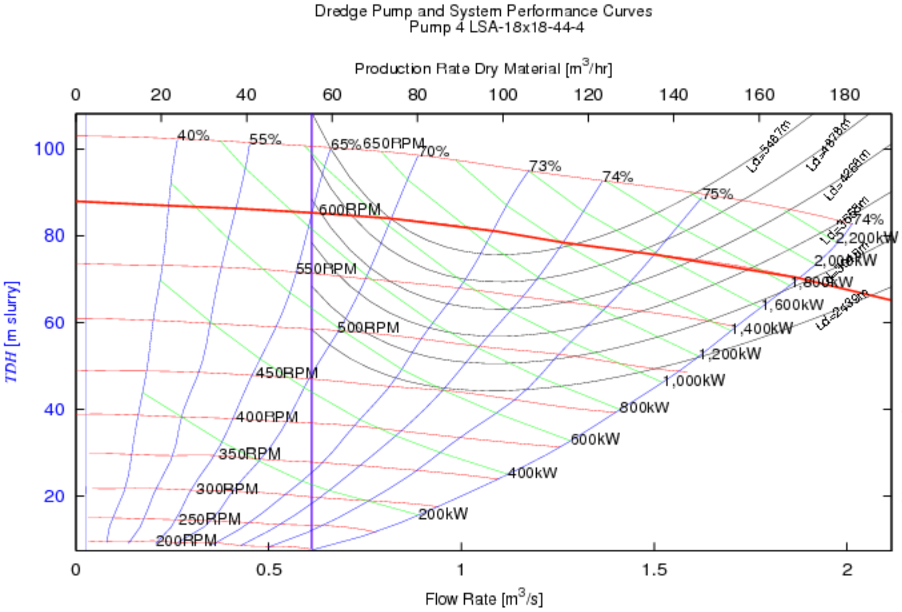


Fig. 95. Pump 4 curves for Dredge *D* in Mississippi River on Project 7.

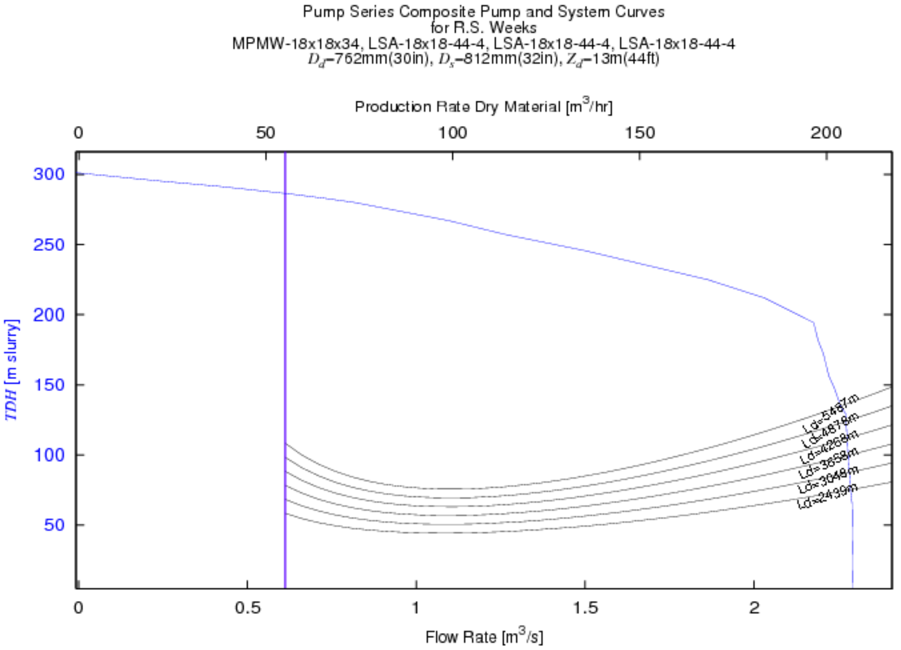


Fig. 96. Pump series composite curve for Dredge *D* in Mississippi River on Project 7.

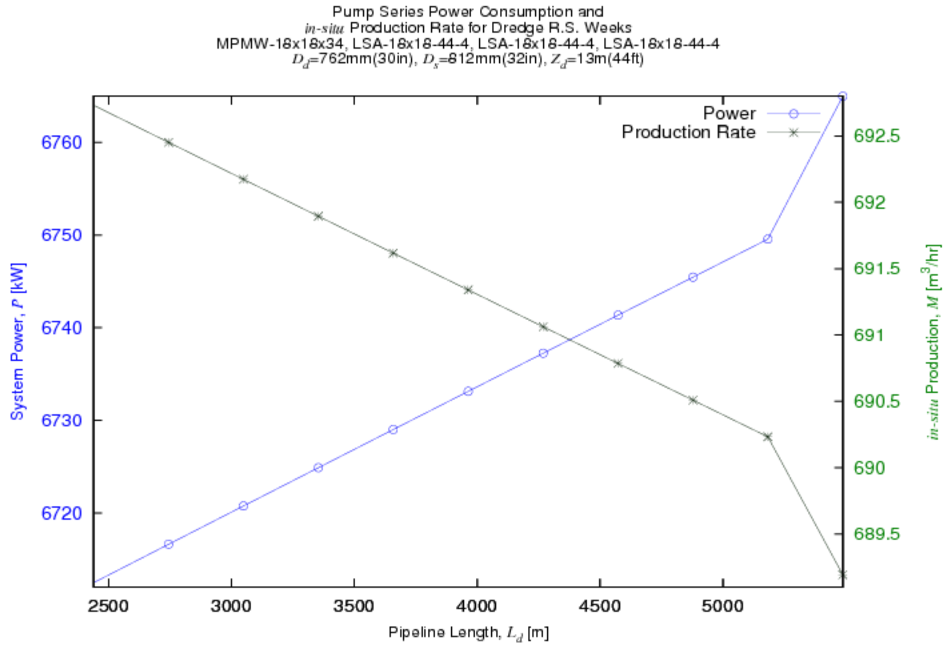


Fig. 97. Pump series performance metrics for Dredge D in Mississippi River on Project 7.

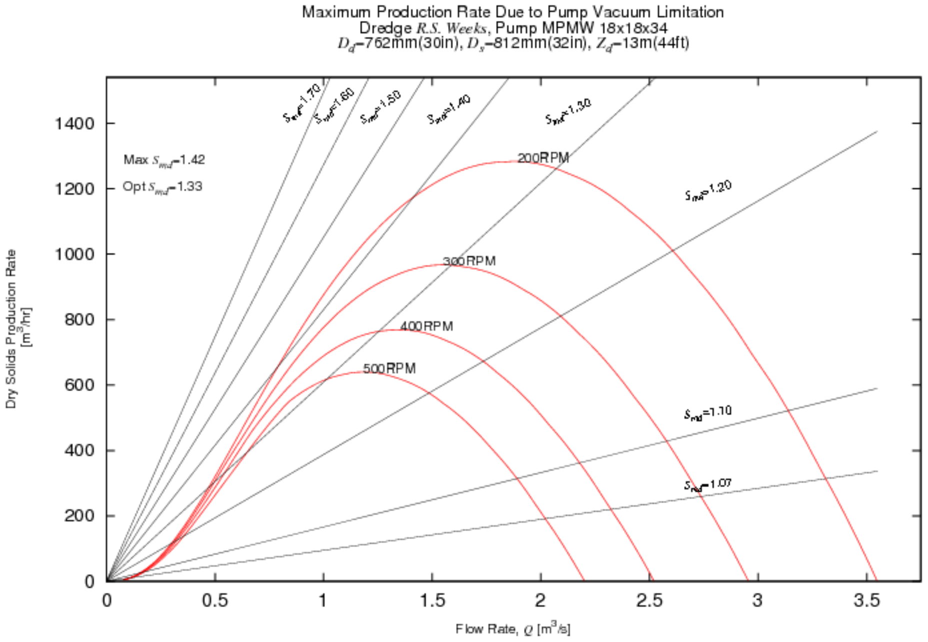


Fig. 98. Ladder pump maximum production curve for Dredge D in Mississippi River on Project 7.

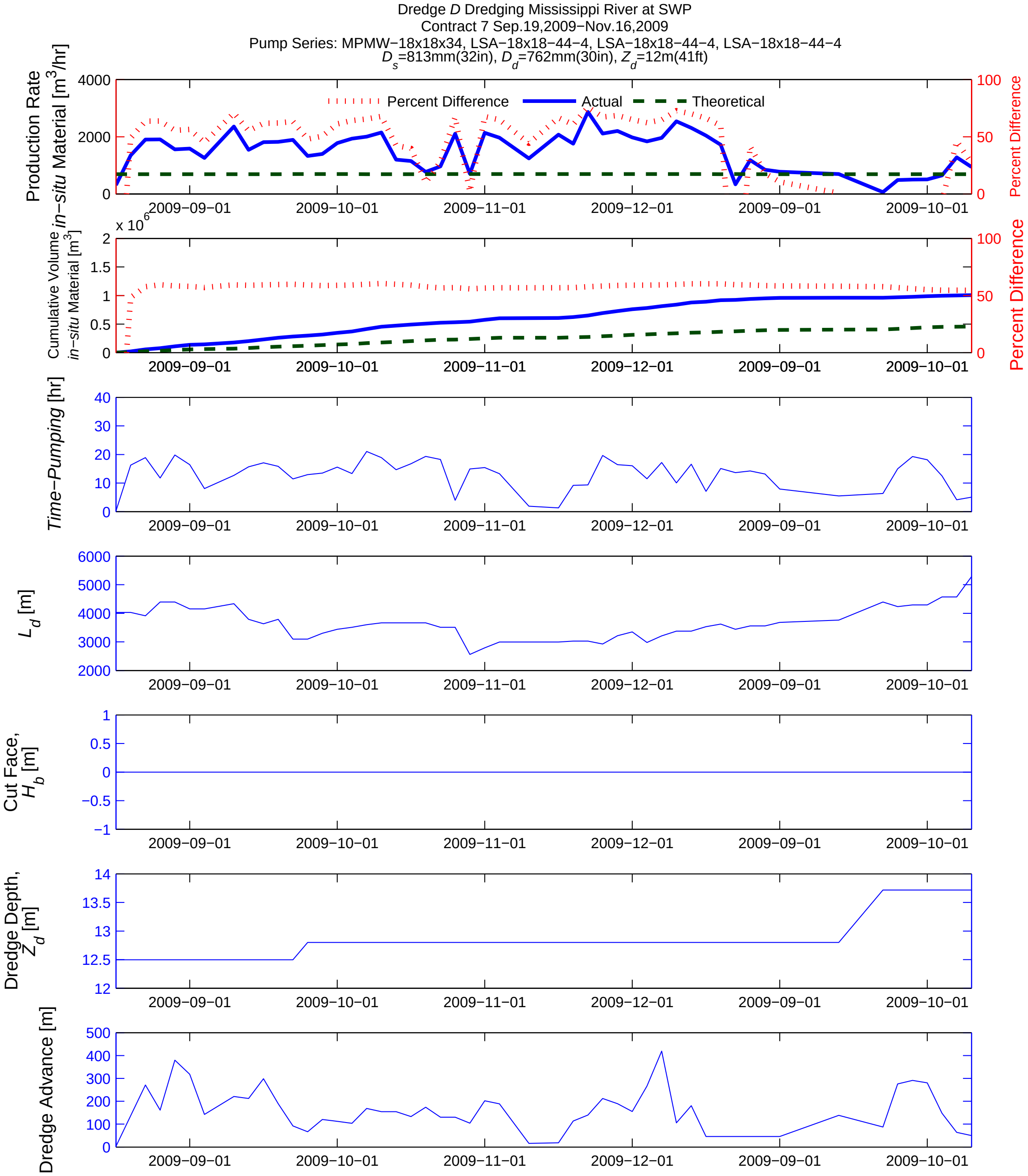


Fig. 99. Comparison between actual dredge production and theoretical dredge production for Dredge *D* in Mississippi River on Project 7.

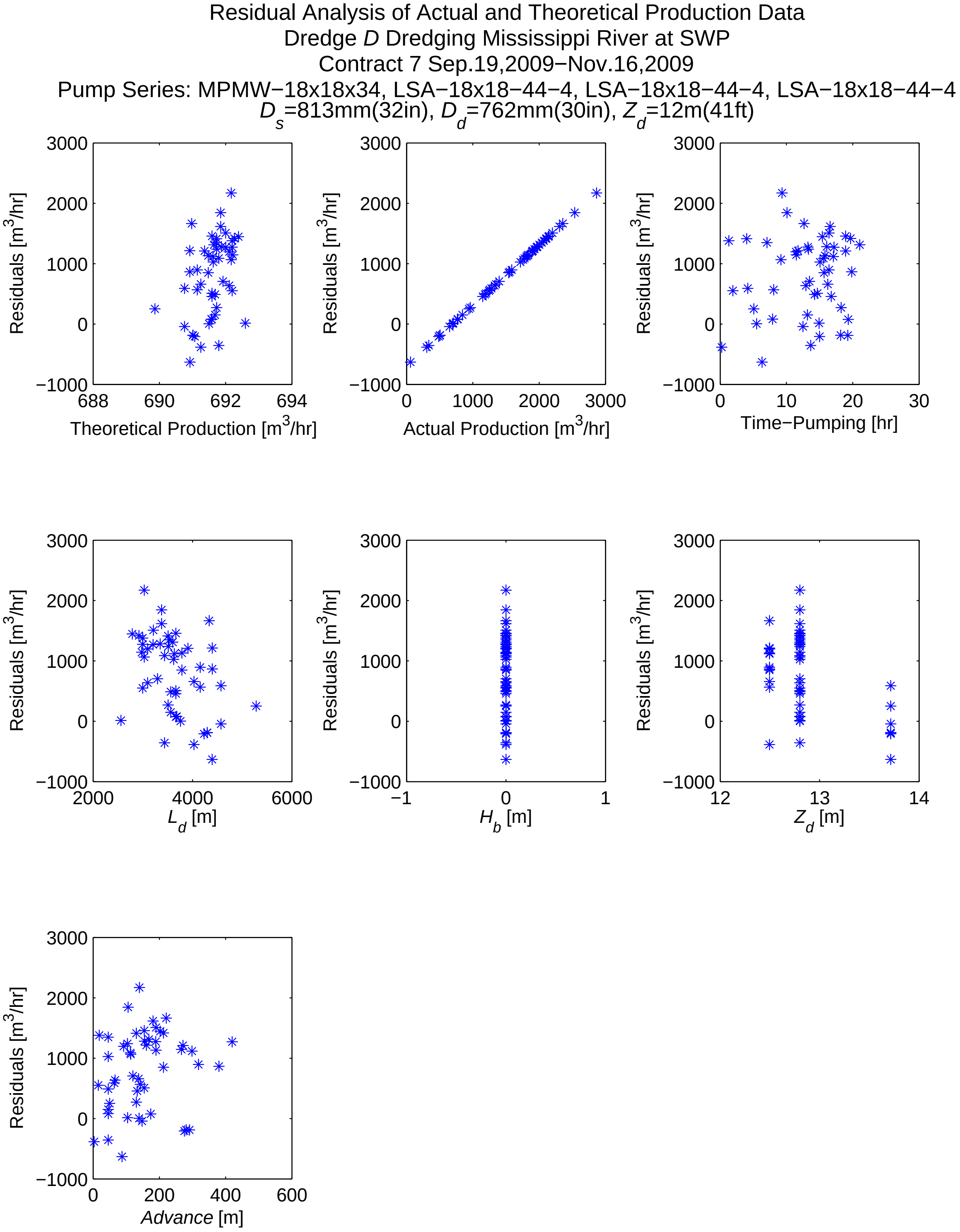


Fig. 100. Residual analysis between actual dredge production and theoretical dredge production for Dredge *D* in Mississippi River on Project 7.

C. Results and Discussion

The daily dredge reports provide valuable information as to the accuracy and validity of the Pipeline Analytical Program. These results represent a comparison of analytical results to field data spanning the entire duration of a pipeline dredge project. The results from this comparison showed that the Pipeline Analytical Program consistently underestimated the overall dredge production in all but one project. Table 45 indicates that the Pipeline Analytical Program underestimates the delivered sediment concentration, c_{vd}, capable of the dredge pump system. This assessment coincides with the results from the *Goetz* field analysis in which the Pipeline Analytical Program estimated a lower S_{md} than what the dredge was capable of even though the Pipeline Analytical Program calculated a higher production than what the *Goetz* actually achieved.

Table 45. Savannah and New Orleans district project daily dredge reports

Project Number	**Actual Final Production**	**Theoretical Final Production**	**% difference**
1	560,896m^3 (734,774yd^3)	342,396m^3 (448,539yd^3)	39.0
2	1,879,437m^3 (2,462,063yd^3)	1,363,019m^3 (1,785,554yd^3)	27.5
3	544,414m^3 (713,182yd^3)	337,591m^3 (442,245yd^3)	38.0
4	1,508,681m^3 (1,976,372yd^3)	1,914,702m^3 (2,508,260yd^3)	-26.9
5	2,053,719m^3 (2,690,371yd^3)	880,165m^3 (1,153,016yd^3)	57.1
6	1,156,588m^3 (1,515,130yd^3)	831,607m^3 (1,089,405yd^3)	28.1
7	1,005,816m^3 (1,317,619yd^3)	458,209m^3 (600,253yd^3)	54.4

CHAPTER VI

SPREADSHEET AND PIPELINE PROGRAM COMPARISON

The Pipeline Analytical Program and spreadsheet program applications determine the operation of a dredge pump and pipeline system. Both of these programs determine the total dynamic head (*TDH*) required to transport the material along a pipeline system and the *TDH* capable of a dredge pump series. Both the spreadsheet program and Pipeline Analytical Program construct the pipeline system curve from pipeline hydraulic and slurry transport principles. The Pipeline Analytical Program imports dredge pump curve data from pump manufacturing data sheets to determine the intersection of the pump and pipeline system curves at which the system will operate. The spreadsheet program constructs pump performance curves from dimensionless pump data using pump affinity laws based on impeller diameter and pump speed. Both applications determine dredge pump and pipeline system operating conditions based on pipeline system requirements and dredge pump capability. This report describes how the output of these two programs compare and contrast over a range of input parameters. Results from this analysis will illustrate the differences in these programs in terms of their methods and empirical formulas that determine the operating point of a pump and pipeline system.

A. Spreadsheet Program Calculations

The spreadsheet program calculates TDH of a pipeline system similarly to the Pipeline Analytical Programby using pipeline hydraulics and Wilson *et al.* (1997) slurry transport principles. However, the spreadsheet program uses different methods to calculate some of the pipeline metrics. The spreadsheet program determines

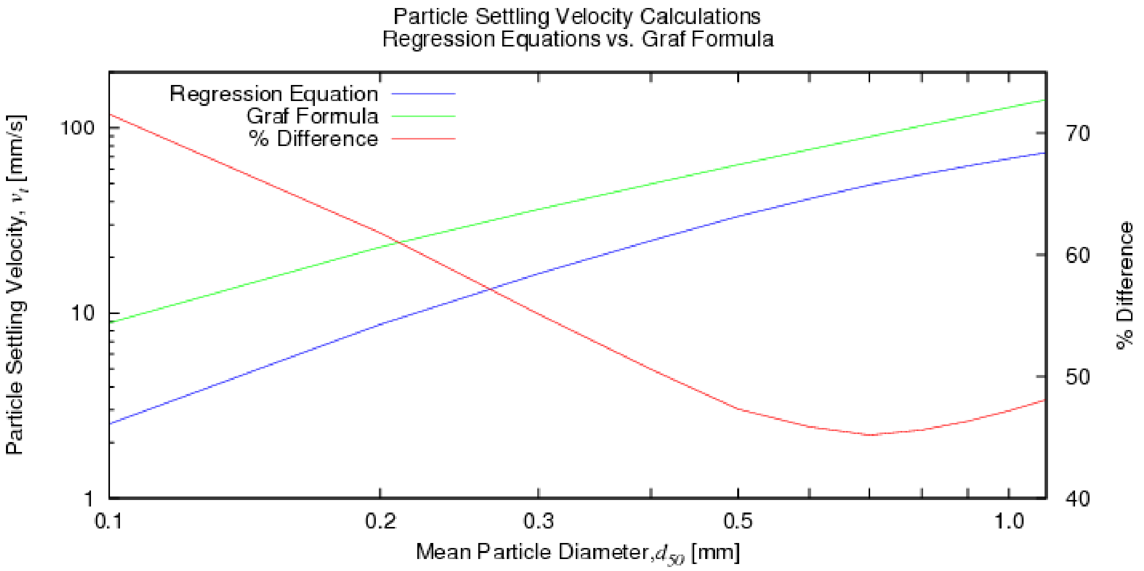


Fig. 101. Comparison of v_{ts} calculations by regression equations and Graf Formula.

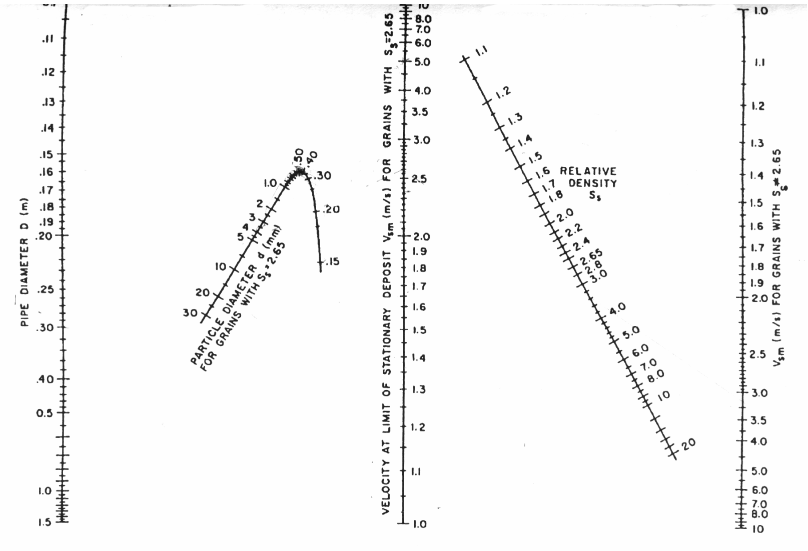
v_t using the simplified Graf Formula shown in Equation 6.1. Figure 101 illustrates the differences in v_{ts} by these respective formulae.

$$v_{ts} = \frac{134.14}{1000}\left(d_{50} - 0.039\right)^{0.972} \tag{6.1}$$

The spreadsheet program calculates V_{sm} from the Wilson *et al.* (1997) nomograph in Figure 102. Both the Matusek formula and the Wilson *et al.* (1997) nomograph methods use the d_{50} and D_d as parameters to calculate V_{sm}. However, the Matusek formula arrives at a more conservative estimate as Figure 103 illustrates.

The spreadsheet program calculates the operating point of a pump and pipeline system by establishing a set flow rate then determines if the pumps in series generate more *TDH* at this flow rate than the calculated *TDH* for the pipeline system. The spreadsheet program determines the operating flow rate as

$$Q_{op} = \left(V_{sm} + 0.3\left(V_h - V_{sm}\right)\right)\frac{\pi D_d^2}{4} \tag{6.2}$$



Nomographic chart for maximum velocity at limit of stationary deposition, from Wilson (1979).

Fig. 102. Wilson *et al.* (1997) nomograph for stationary bed velocity in slurry pipeline flow.

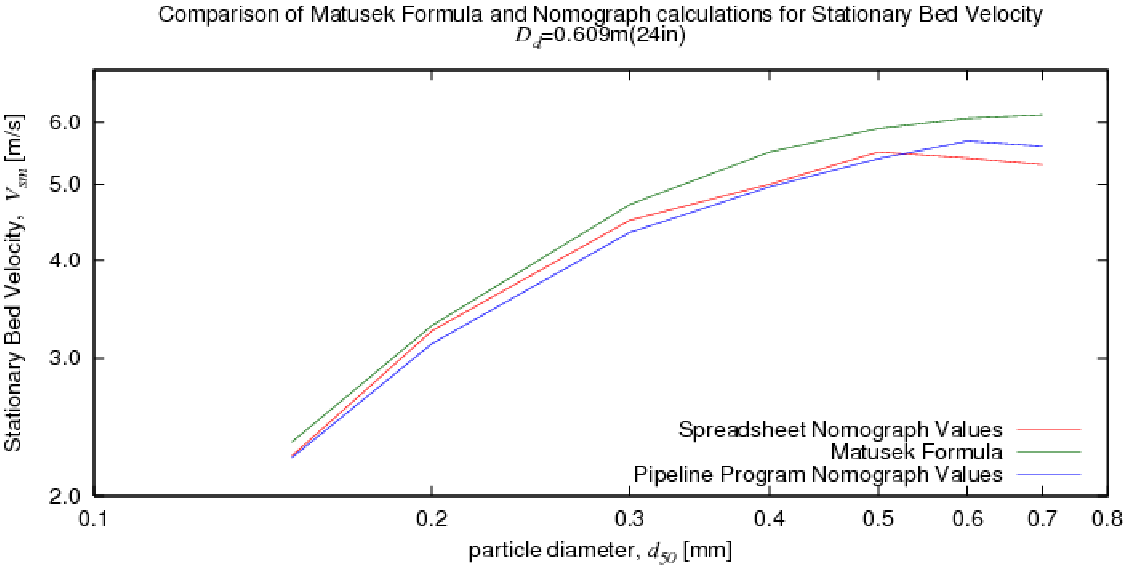


Fig. 103. Comparison of Wilson *et al.* (1997) nomograph to the Matusek Formula calculations for V_{sm}.

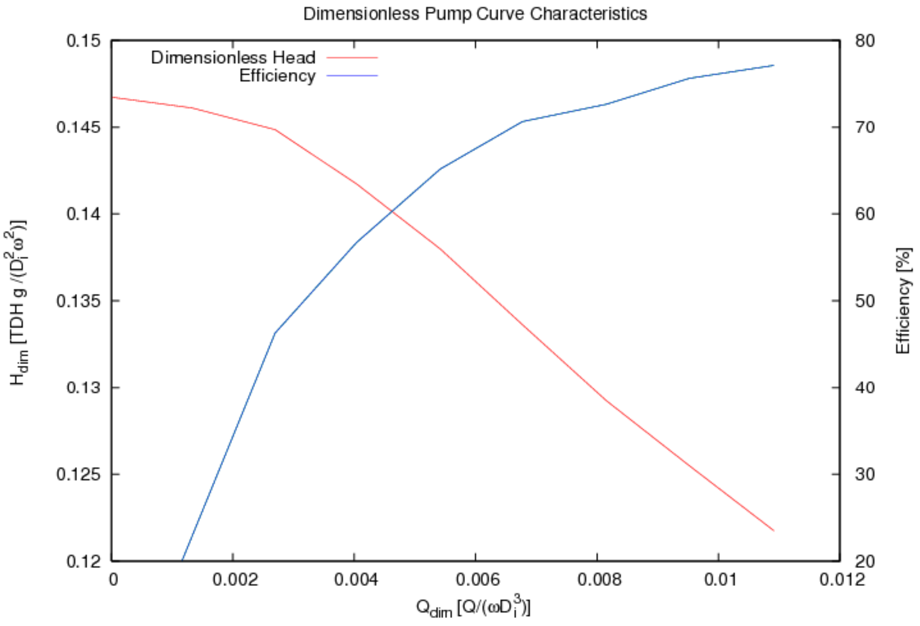


Fig. 104. Dimensionless dredge pump performance curves.

$$V_h = 26.04\,(v_{ts}D_d)^{\frac{1}{3}} \tag{6.3}$$

The spreadsheet program then calculate the pipeline system TDH_s at this flow rate from Equation 2.1. The spreadsheet program determines the pump series head at this flow rate from the pump's dimensionless pump curve illustrated in Figure 104. The spreadsheet program calculates the dimensionless flow rate for the system as:

$$Q_{dim} = \frac{Q}{\omega D_i^3} \tag{6.4}$$

where ω represents the angular pump speed in rad/s and D_i represents the pump impeller diameter in meters. The spreadsheet program reads the dimensionless head,

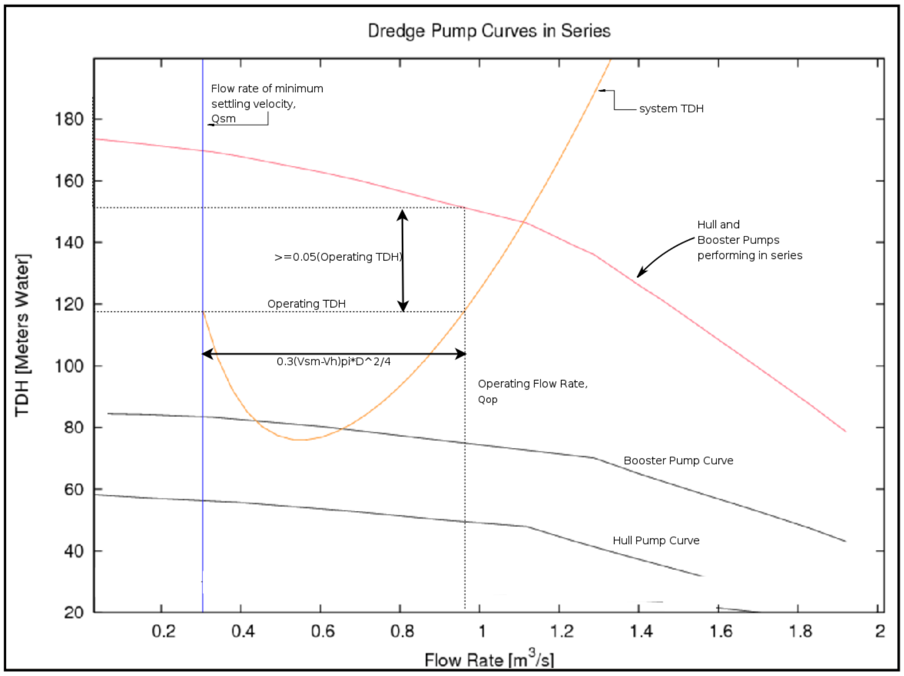


Fig. 105. The spreadsheet program calculated dredge pump and system performance curves for pumps in series.

H_{dim}, for each of the pumps at this corresponding dimensionless flow rate. The spreadsheet program calculates the *TDH* for each pump as:

$$H = H_{dim} \frac{\omega^2 D_i^2}{g} \tag{6.5}$$

The spreadsheet program sums up the *TDH* for each pump in the pump series to compute the total pump series *TDH*. The spreadsheet program calculates the difference in the pipeline system *TDH* and the pump series *TDH* at this flow rate. If the *TDH* capable by the pumps in series exceeds the system *TDH* by at least 5% as shown in Figure 105, the spreadsheet program declares this pump series a valid solution and returns the operating flow rate and system *TDH* as performance metrics.

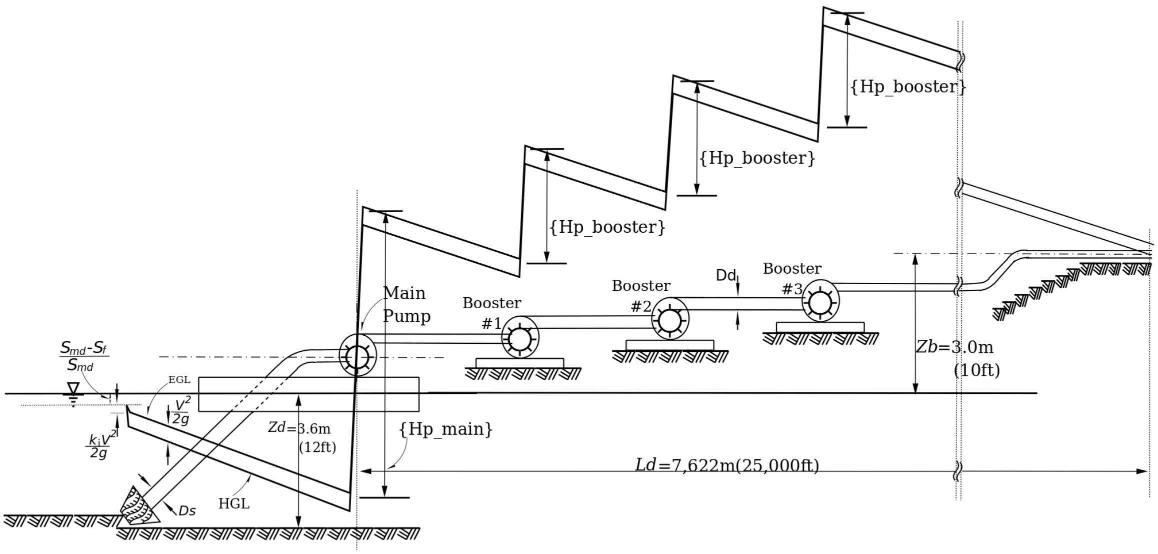


Fig. 106. Example application pump and pipeline configuration.

B. Example Pump and Pipeline Application

An example pipeline dredge application provides the input for both the spreadsheet program and Pipeline Analytical Program to compare their system output. d_{50} varies from 0.1 to 0.4mm, D_d varies from 0.61m(24in) to 0.81m(32in) and L_d of 7,622m(25,000ft). Table 46 contains the list of input variables for the pipeline dredge. Figure 106 illustrates this example pump and pipeline configuration. The pipeline dredge system uses 1 main dredge pump and 3 booster pumps all of the same model, LSA 18x18-44-3. The main pump uses a larger diameter impeller than the booster pumps. Table 47 describes the pump dimensions and parameters. The spreadsheet program accounts for this principle using dimensionless pump analysis. Figure 107 illustrates the dimensionless pump curve. The Pipeline Analytical Program uses two different pump curves for its analysis. Figures 108 and 109 illustrate these two pump curves. Analysis includes comparison of the pipeline system curves and comparison of the performance metrics the spreadsheet program and Pipeline Analytical Program .

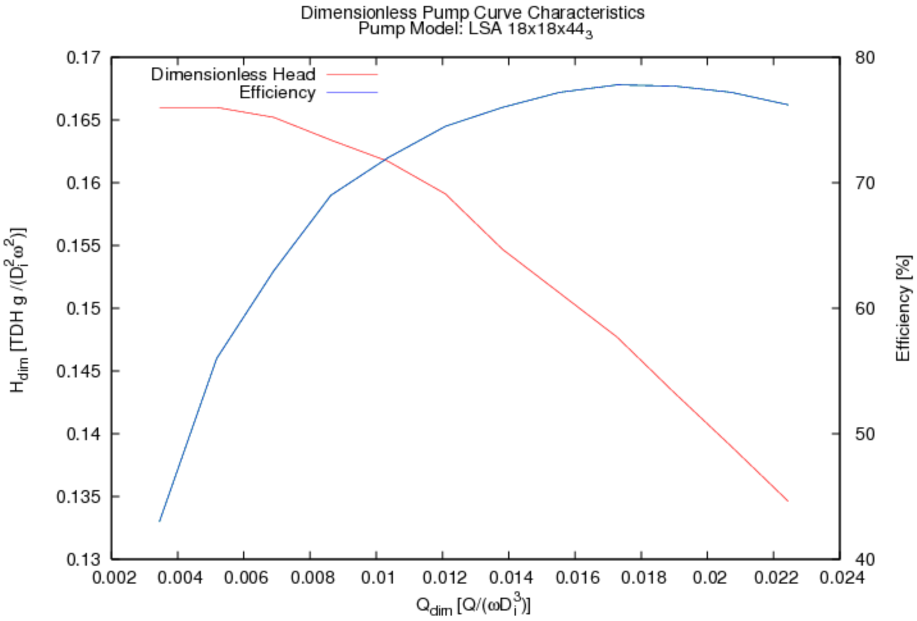


Fig. 107. LSA 18x18-44-3 dredge pump dimensionless performance curves.

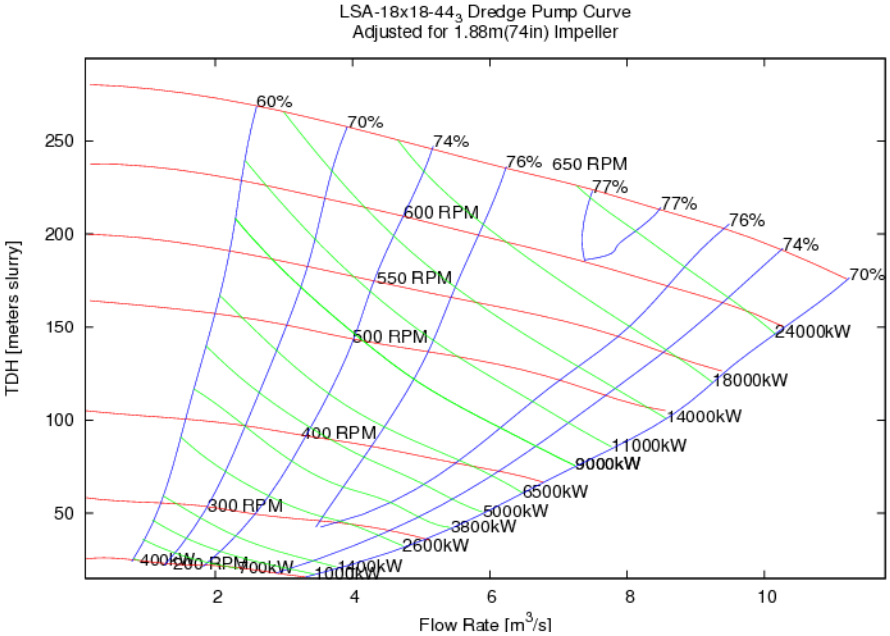


Fig. 108. LSA 18x18-44-3 pump curve for a 1.88m (74in) impeller used for the main dredge pump.

Table 46. Example application pipeline system and dredged material parameters.

Symbol	**Description**	**Value**
D_d	Discharge pipe diameter (m)	0.61, 0.66, 0.71, 0.76, 0.81m (24, 26, 28, 30, 32in)
D_s	Suction pipe diameter (m)	0.81m (32in)
L_s	Suction length (m)	15.2m (50ft)
Z_d	Digging depth (m)	3.67m (12ft)
Z_b	Discharge elevation (m)	3.05m (10ft)
d_{50}	Median sediment grain diameter (mm)	0.1, 0.2, 0.3, 0.4mm
S_{md}	Specific gravity of delivered dredged material	1.15

Analysis includes a comparison of the pipeline system curves of TDH that both the spreadsheet program and the Pipeline Analytical Program generated over a range of d_{50} and D_d. Analysis involved plotting the TDH over Q, illustrating the system curves. These plots included the minimum stationary bed velocity, V_{sm}, calculated by both the spreadsheet program and Pipeline Analytical Program. Figures 110(a)–114(d) show these graphs and illustrate how well the system curves and V_{sm} calculations coincide over a range of d_{50} and D_d.

Analysis also includes plotting the spreadsheet program and Pipeline Analytical Program calculated Q, TDH, P and $\dot{M}$ over a range of d_{50} and D_d while keeping L_d fixed at 7,622m(25,000ft). These plots indicate how much the calculated Q, TDH, P, and $\dot{M}$ varies between the spreadsheet program and the Pipeline Analytical Program. Tables 48–51 summarize the percent difference between these performance

Table 47. Example application dredge pump parameters.

Dredge Pump	**Pump Model**	**Impeller Diameter**	**Max Pump Speed**
Main Pump	LSA 18x18-44-3	1.88m(74in)	500RPM
Booster Pumps	LSA 18x18-44-3	1.68m(66in)	450RPM

metrics and Figures 115–123 illustrate the percent differences between them. The data analysis computes the performance metrics percent differences as

$$\text{Percent Difference} = \frac{X_{PLP} - X_{SS}}{X_{SS}} \times 100\% \qquad (6.6)$$

where X_{PLP} and X_{SS} represent the Pipeline Analytical Program and spreadsheet program performance metrics, respectively for Q, P, $\dot{M}$, and TDH.

Table 48. Flow rate, Q, % difference for Pipeline Analytical Program and spreadsheet program.

	D_d				
d_{50}	0.61m(24in)	0.66m(26in)	0.71m(28in)	0.76m(30in)	0.81m(32in)
0.10	228.59	222.97	223.55	219.23	213.34
0.20	92.33	88.29	89.15	87.32	84.11
0.30	47.30	43.27	42.76	40.85	37.61
0.40	28.62	24.38	23.01	20.11	16.70

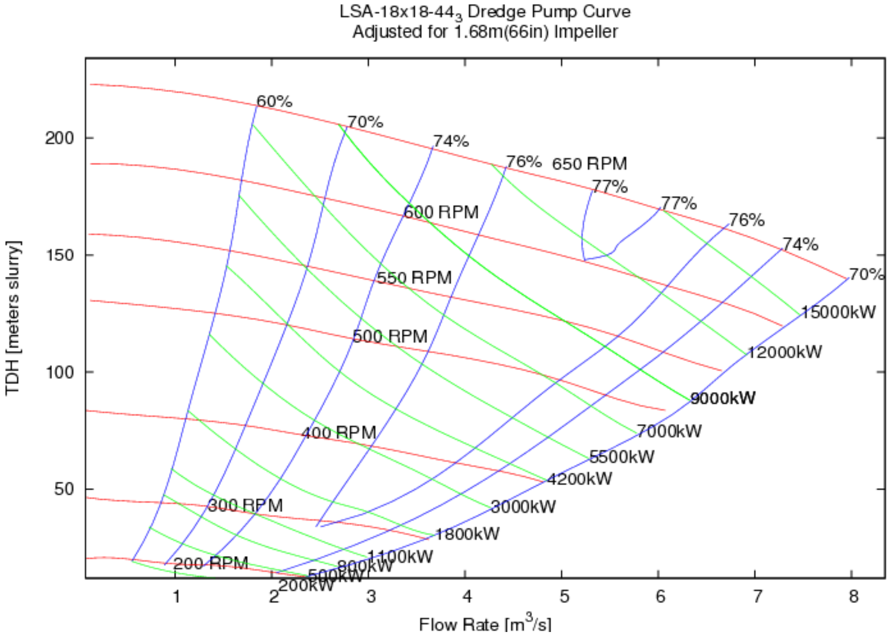
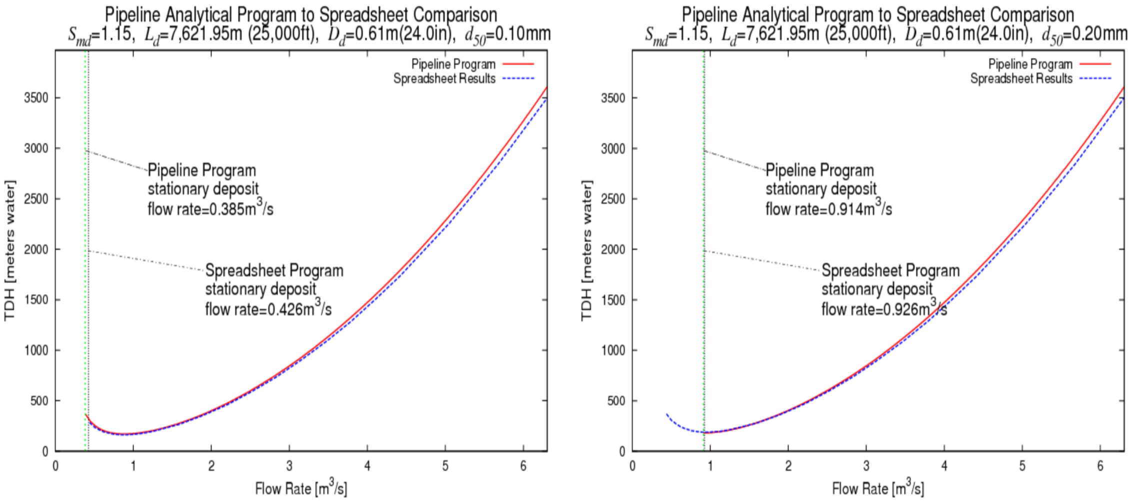


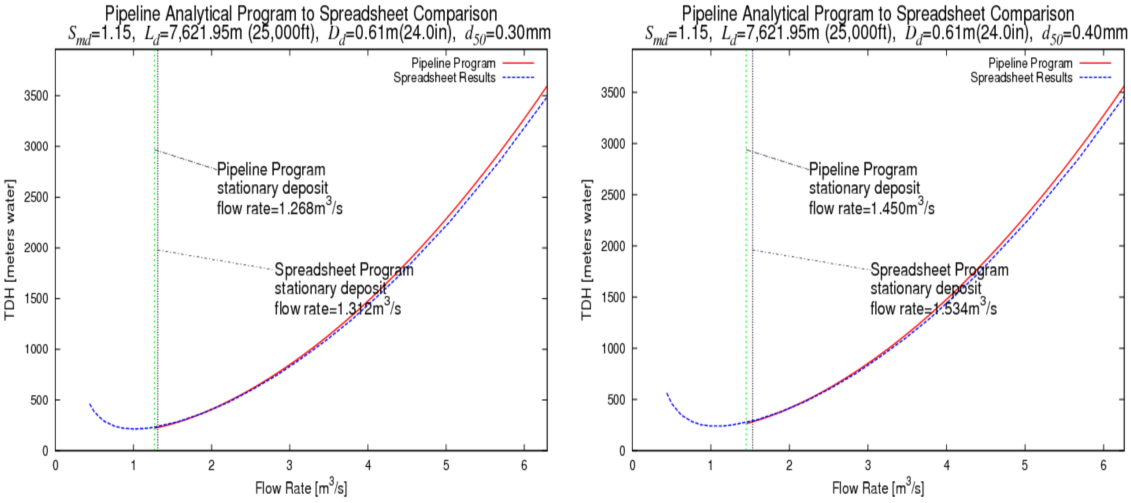
Fig. 109. LSA 18x18-44-3 pump curve for a 1.68m (66in) impeller used for the 3 booster dredge pumps.

Table 49. *TDH* % difference for Pipeline Analytical Program and spreadsheet program.

	D_d				
d_{50}	0.61(24)	0.66(26)	0.71(28)	0.76(30)	0.81(32)
0.10	-2.22	-6.42	-12.18	-18.17	-23.76
0.20	-2.23	-6.17	-11.54	-17.06	-22.22
0.30	-1.81	-5.31	-10.35	-15.43	-19.39
0.40	-1.34	-4.62	-9.25	-13.20	-17.15

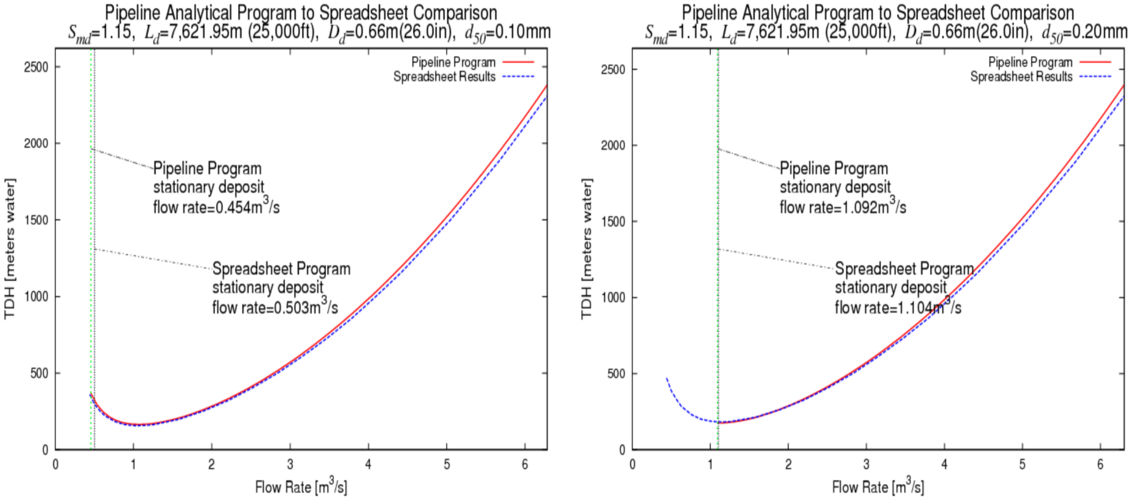


(a) $d_{50} = 0.1$mm (b) $d_{50} = 0.2$mm

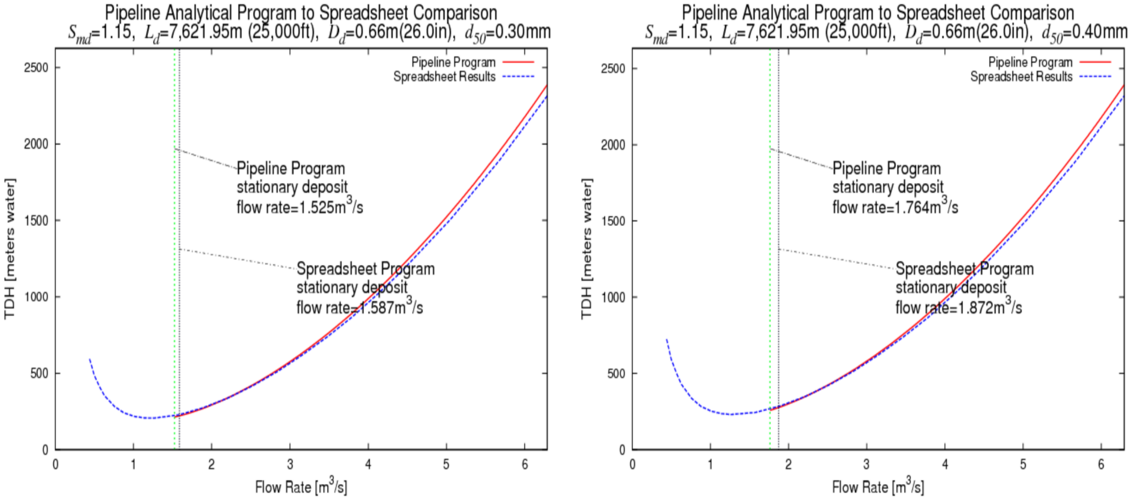


(c) $d_{50} = 0.3$mm (d) $d_{50} = 0.4$mm

Fig. 110. Comparison of Pipeline Analytical Program and spreadsheet program pipeline system curve over 0.1–0.4mm d_{50} range with a L_d=7,622m(25,000ft) and D_d=0.61m(24in).

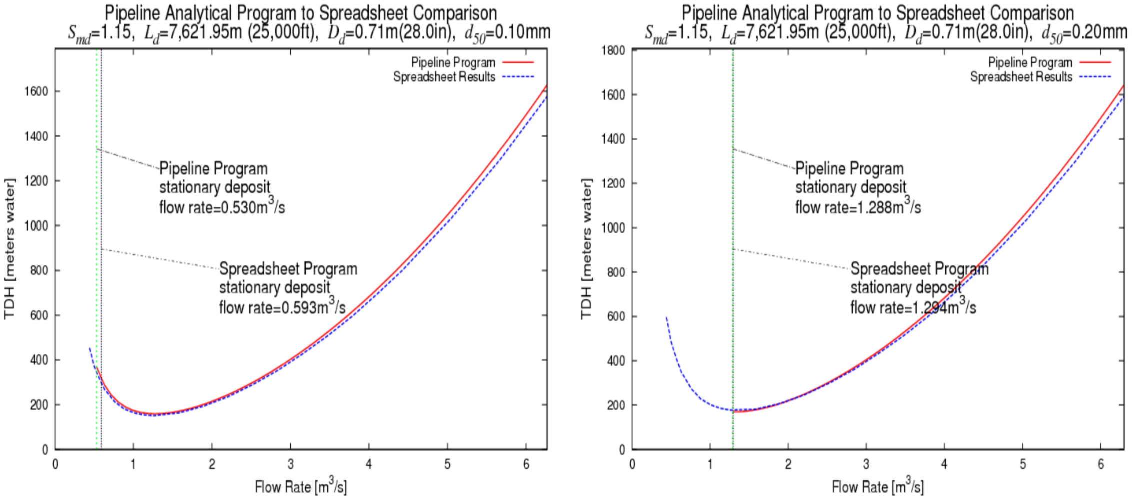


(a) $d_{50} = 0.1$mm　　(b) $d_{50} = 0.2$mm



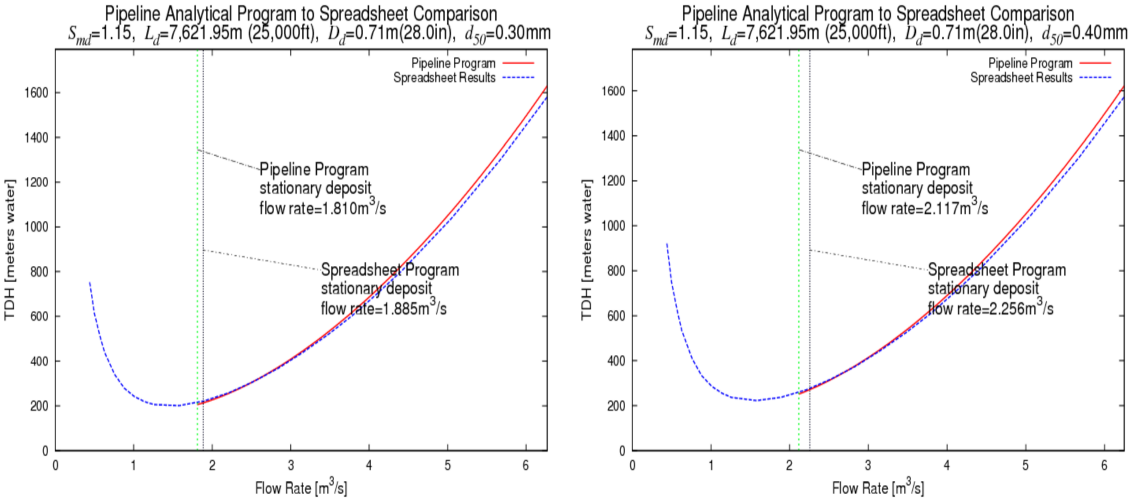
(c) $d_{50} = 0.3$mm　　(d) $d_{50} = 0.4$mm

Fig. 111. Comparison of Pipeline Analytical Program and spreadsheet program pipeline system curve over 0.1–0.4mm d_{50} range with a L_d=7,622m(25,000ft) and D_d=0.66m(26in).



(a) $d_{50} = 0.1$mm

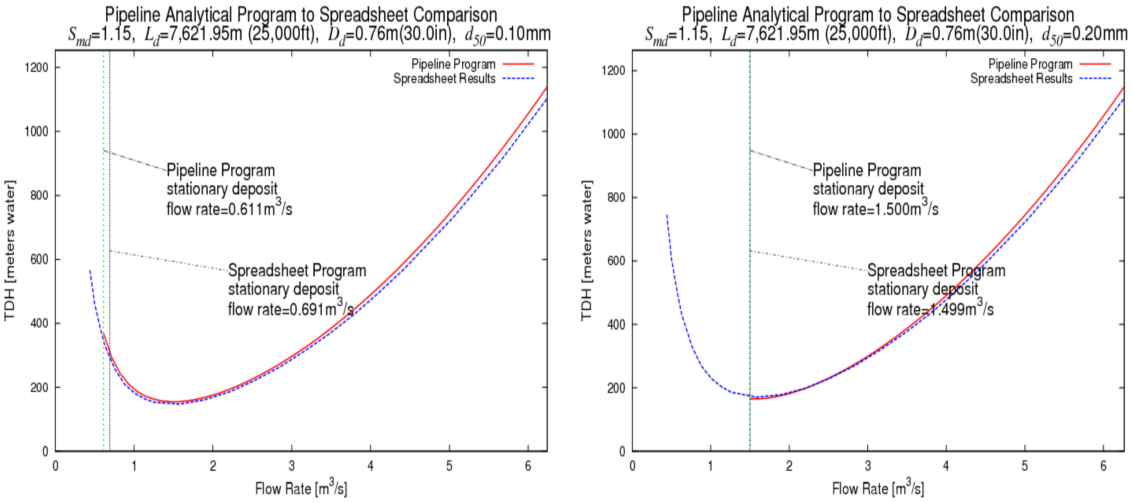
(b) $d_{50} = 0.2$mm



(c) $d_{50} = 0.3$mm

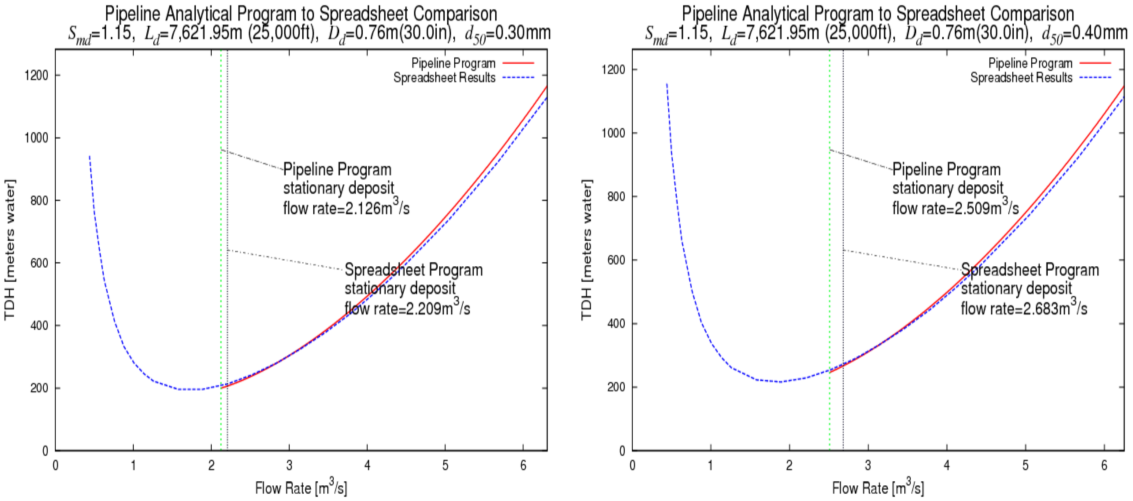
(d) $d_{50} = 0.4$mm

Fig. 112. Comparison of Pipeline Analytical Program and spreadsheet program pipeline system curve over 0.1–0.4mm d_{50} range with a L_d=7,622m(25,000ft) and D_d=0.71m(28in).



(a) $d_{50} = 0.1$mm

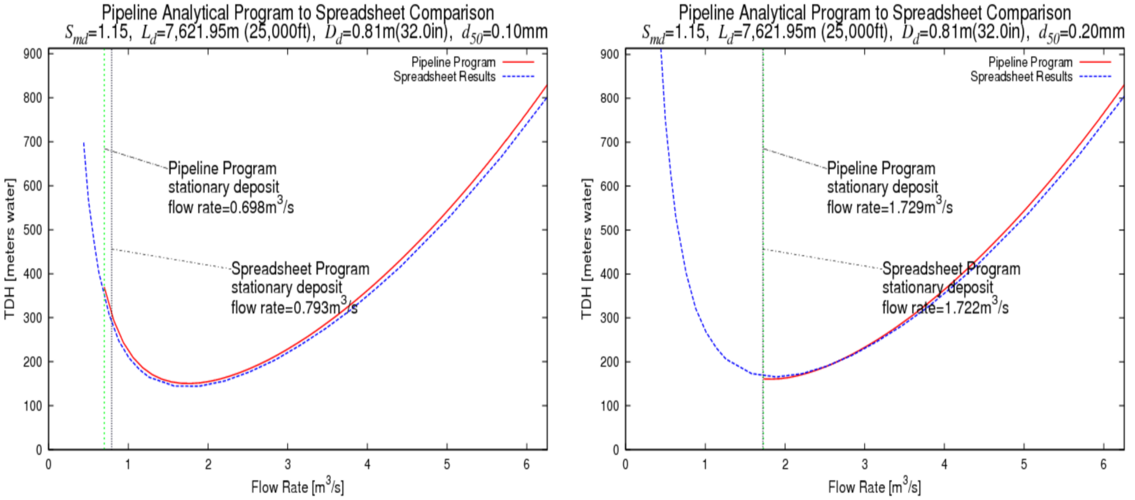
(b) $d_{50} = 0.2$mm



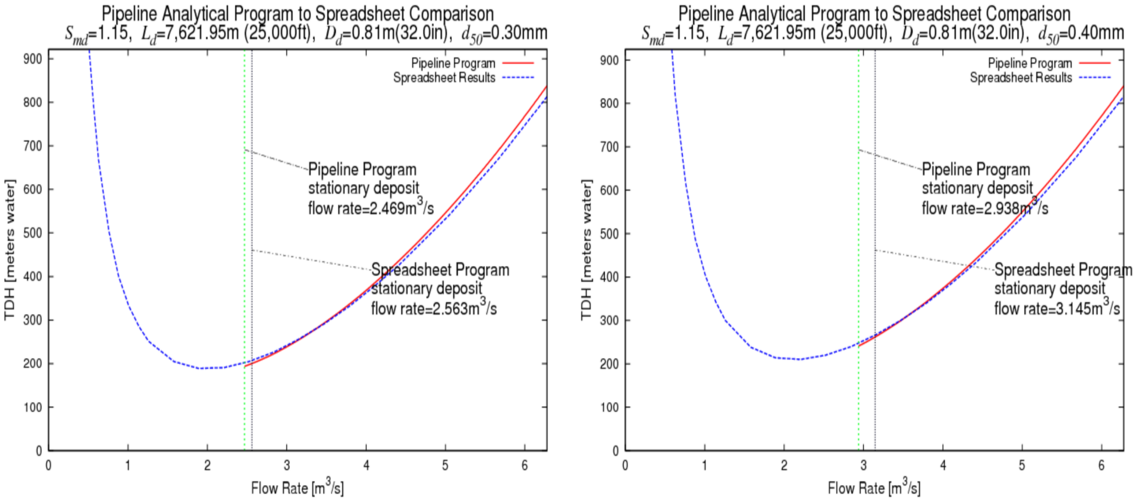
(c) $d_{50} = 0.3$mm

(d) $d_{50} = 0.4$mm

Fig. 113. Comparison of Pipeline Analytical Program and spreadsheet program pipeline system curve over 0.1–0.4mm d_{50} range with a L_d=7,622m(25,000ft) and D_d=0.762m(30in).



(a) $d_{50} = 0.1$mm (b) $d_{50} = 0.2$mm



(c) $d_{50} = 0.3$mm (d) $d_{50} = 0.4$mm

Fig. 114. Comparison of Pipeline Analytical Program and spreadsheet program pipeline system curve over 0.1–0.4mm d_{50} range with a L_d=7,622m(25,000ft) and D_d=0.813m(32in).

Table 50. Power % difference for Pipeline Analytical Program and spreadsheet program.

	D_d				
d_{50}	0.61(24)	0.66(26)	0.71(28)	0.76(30)	0.81(32)
0.10	77.10	82.15	83.54	83.31	80.55
0.20	45.04	46.06	43.20	39.15	32.96
0.30	26.85	26.38	20.45	15.27	10.24
0.40	18.11	15.17	9.37	3.92	-1.67

Table 51. Production rate, $\dot{M}$, % difference for Pipeline Analytical Program and spreadsheet program.

	D_d				
d_{50}	0.61(24)	0.66(26)	0.71(28)	0.76(30)	0.81(32)
0.10	225.83	227.76	224.02	218.28	212.84
0.20	90.04	90.68	89.19	86.65	83.52
0.30	45.54	44.87	42.72	39.92	36.91
0.40	26.81	25.59	22.65	19.20	15.85

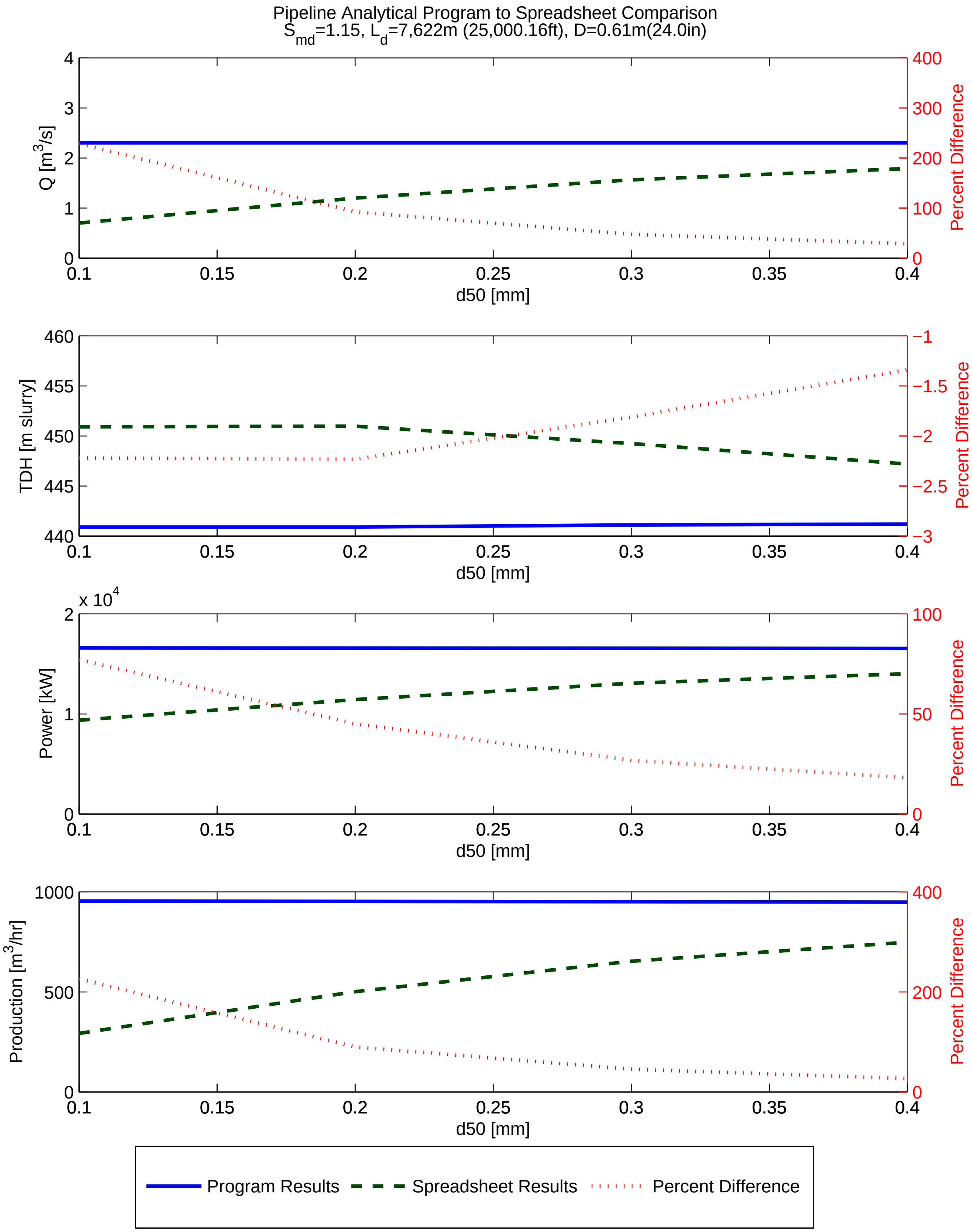


Fig. 115. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.1-0.4mm d_{50} range with a L_d=7,621m(25,000ft) and D_d=0.61m(24in).

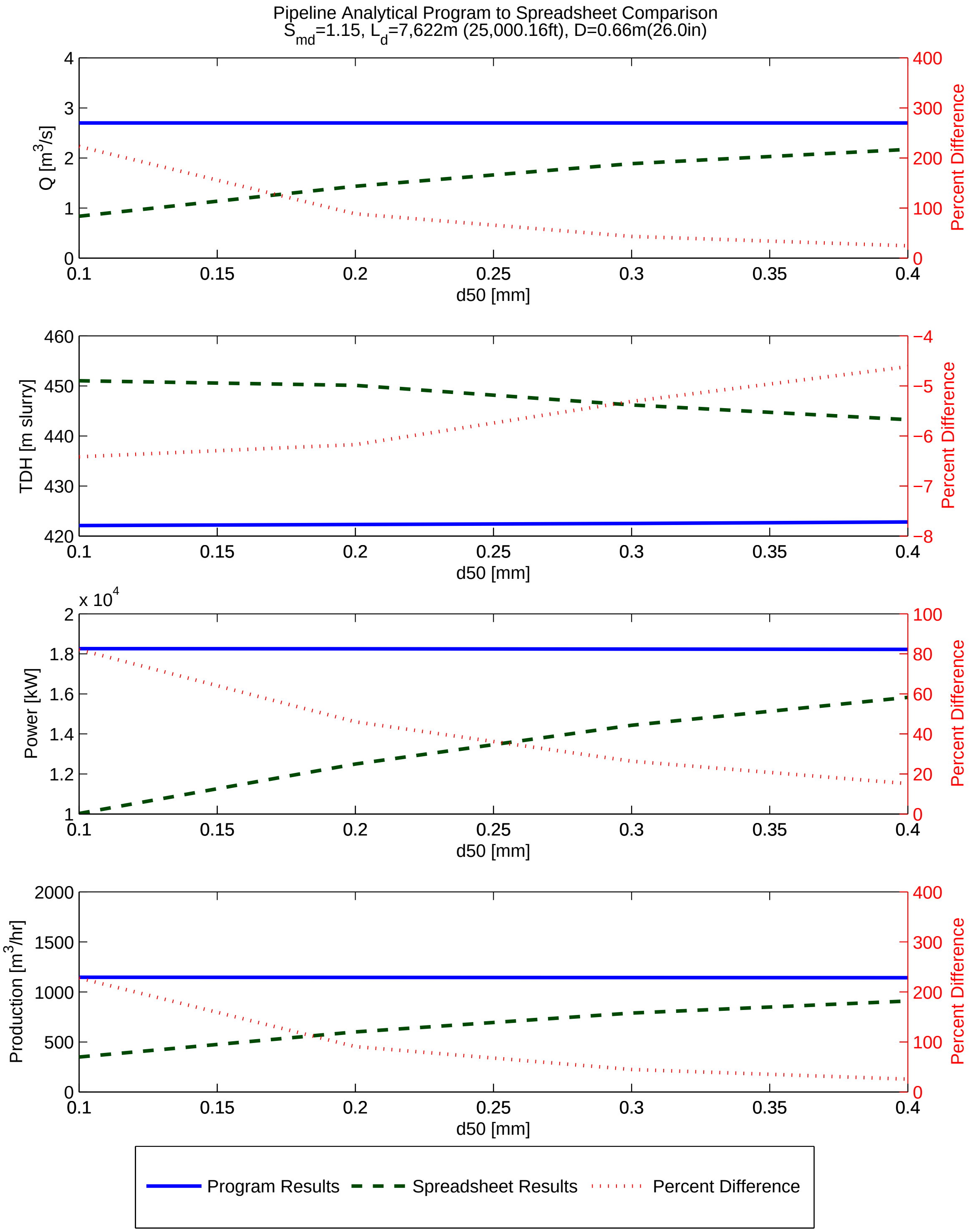


Fig. 116. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.1-0.4mm d_{50} range with a L_d=7,621m(25,000ft) and D_d=0.66m(26in).

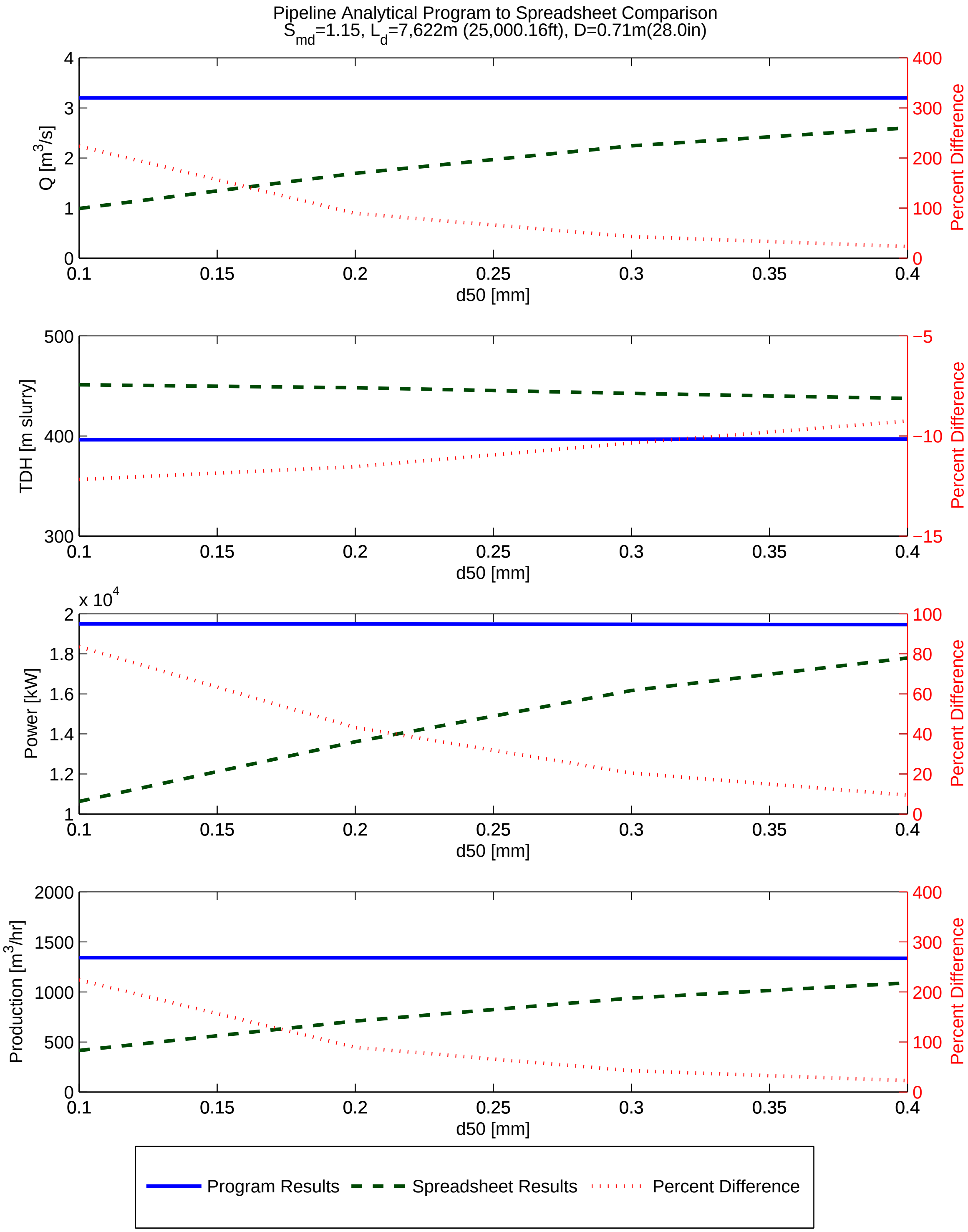


Fig. 117. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.1-0.4mm d_{50} range with a L_d=7,621m(25,000ft) and D_d=0.71m(28in).

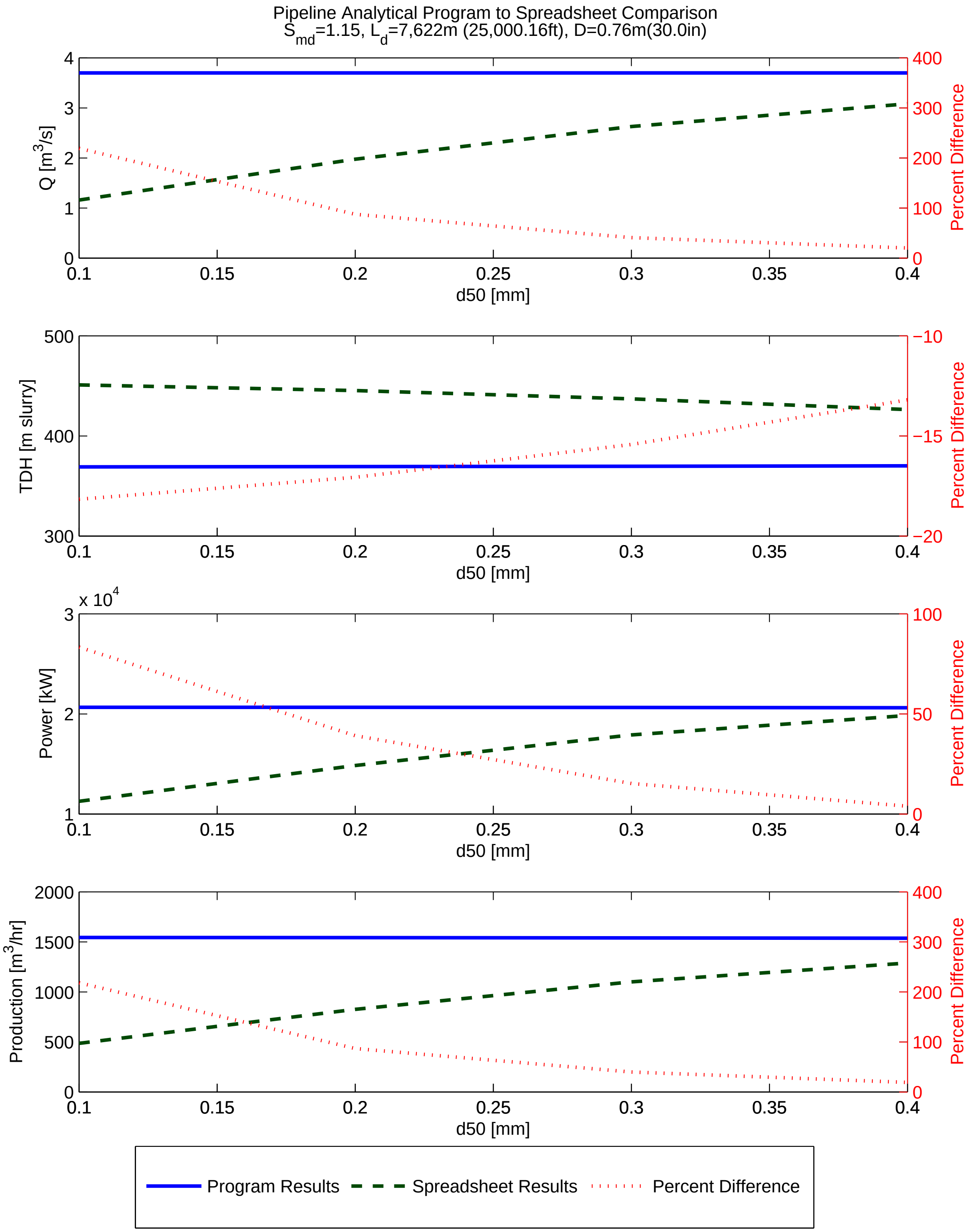


Fig. 118. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.1-0.4mm d_{50} range with a L_d=7,621m(25,000ft) and D_d=0.76m(30in).

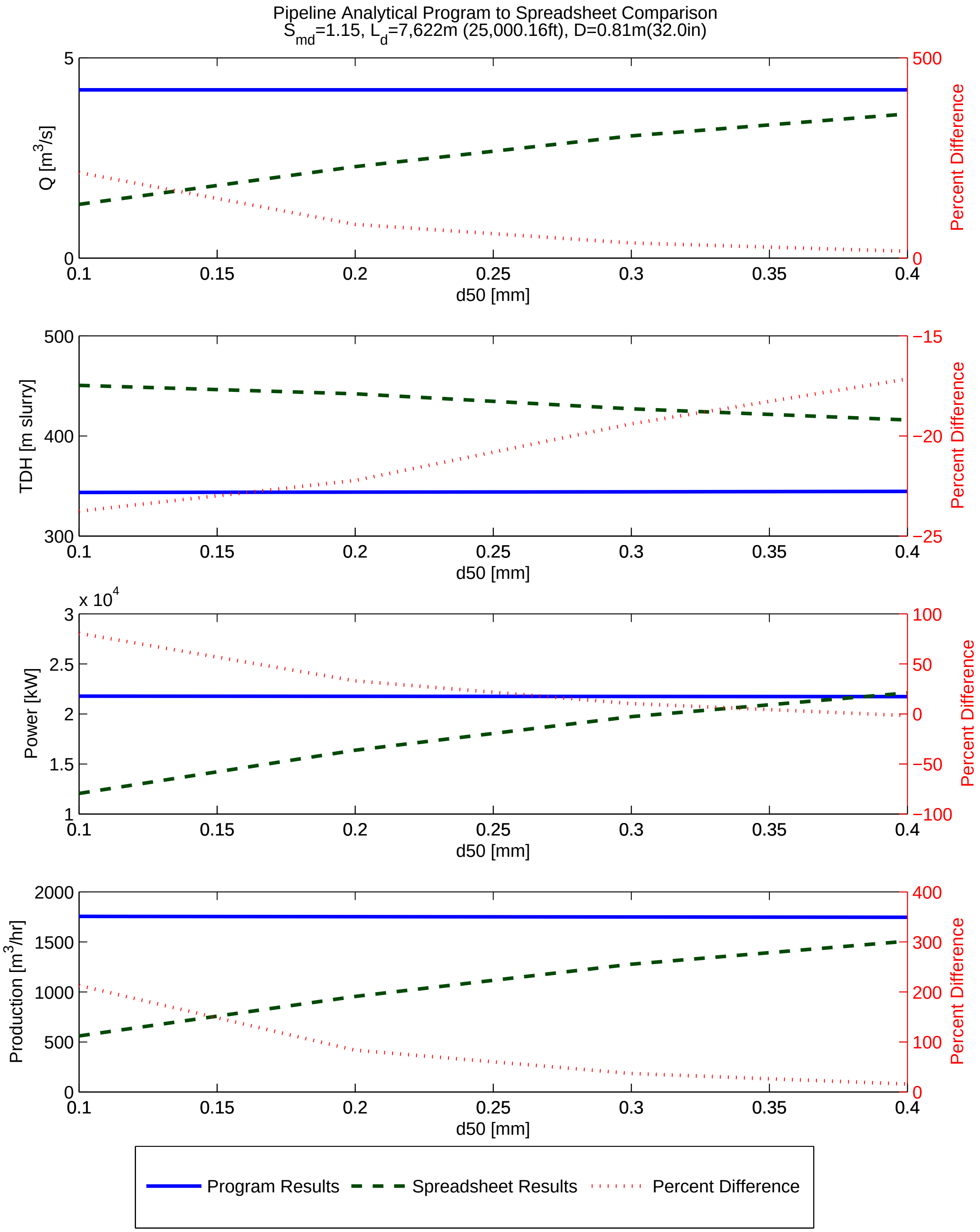


Fig. 119. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.1-0.4mm d_{50} range with a L_d=7,621m(25,000ft) and D_d=0.81m(32in).

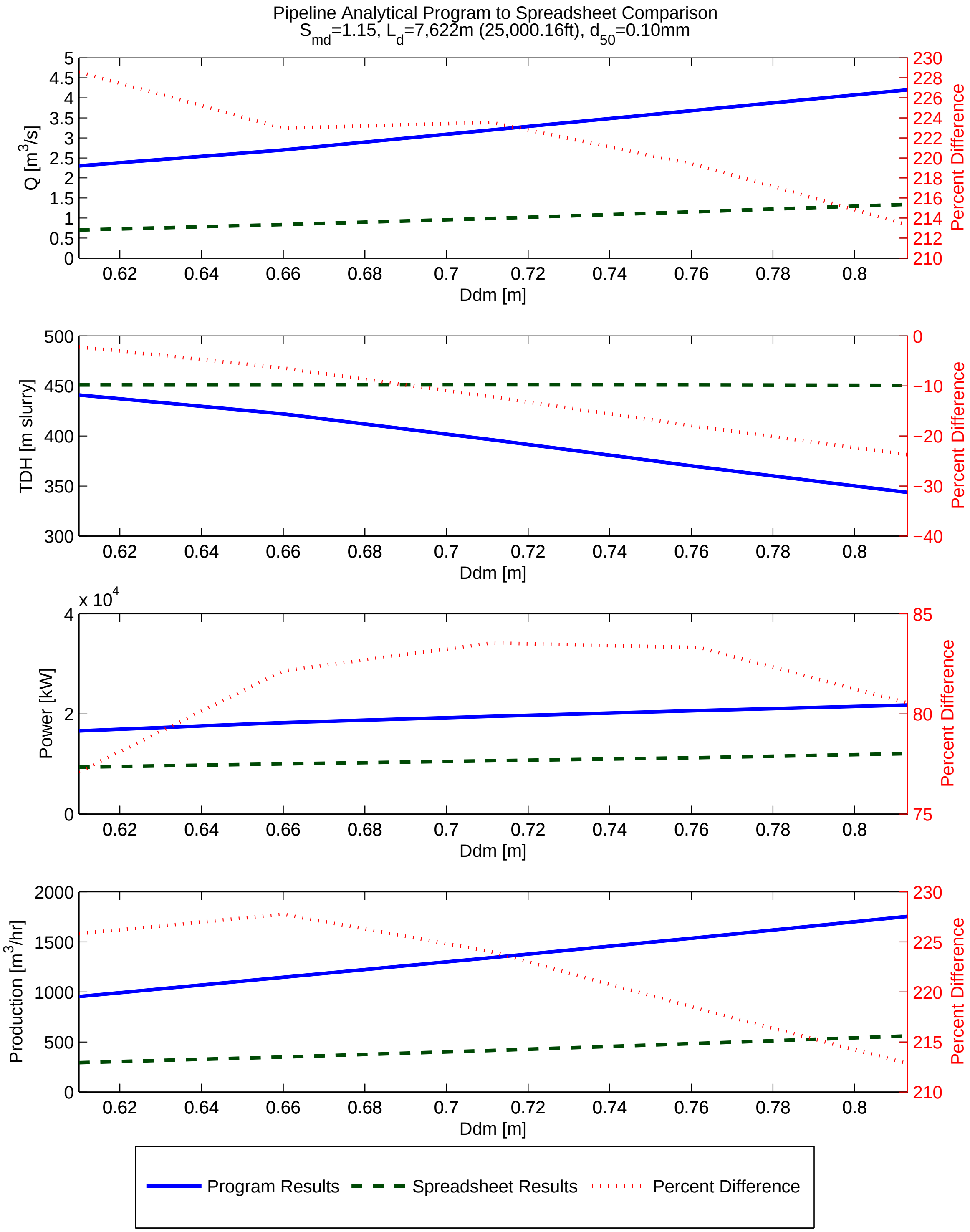


Fig. 120. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.61-0.81m(24-32in) D_d range with a L_d=7,621m(25,000ft) and d_{50}=0.1mm.

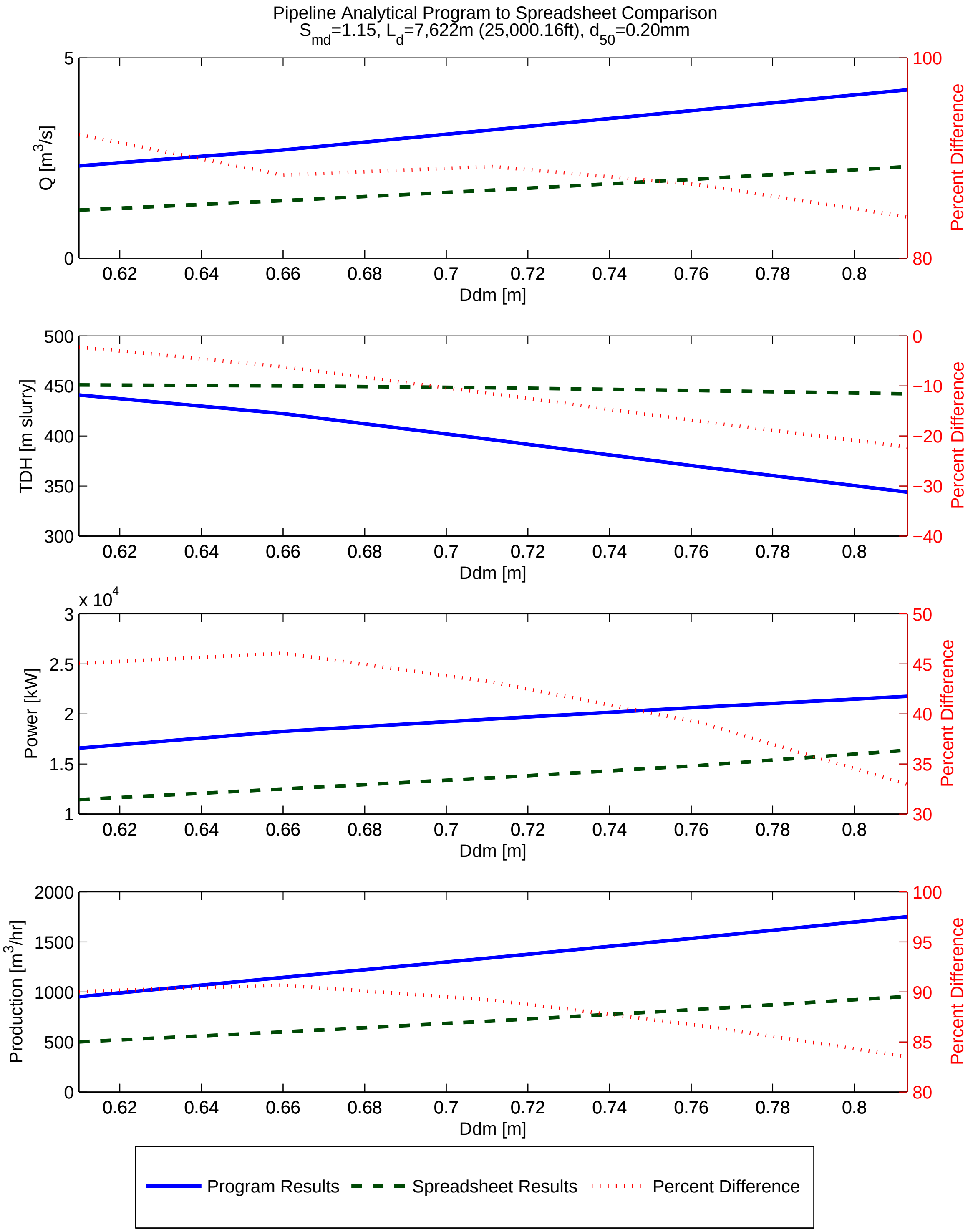


Fig. 121. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.61-0.81m(24-32in) D_d range with a L_d=7,621m(25,000ft) and d_{50}=0.2mm.

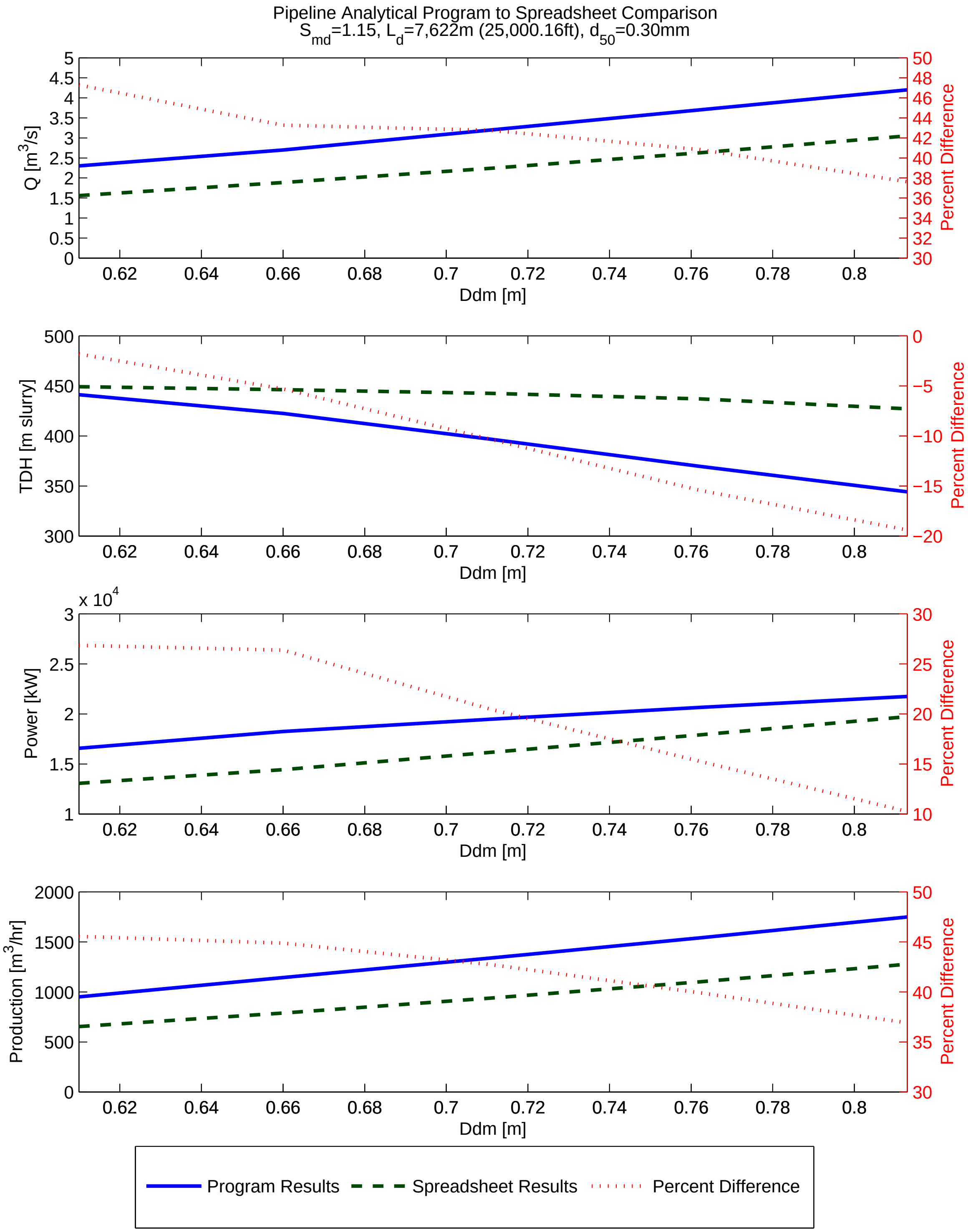


Fig. 122. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.61-0.81m(24-32in) D_d range with a L_d=7,621m(25,000ft) and d_{50}=0.3mm.

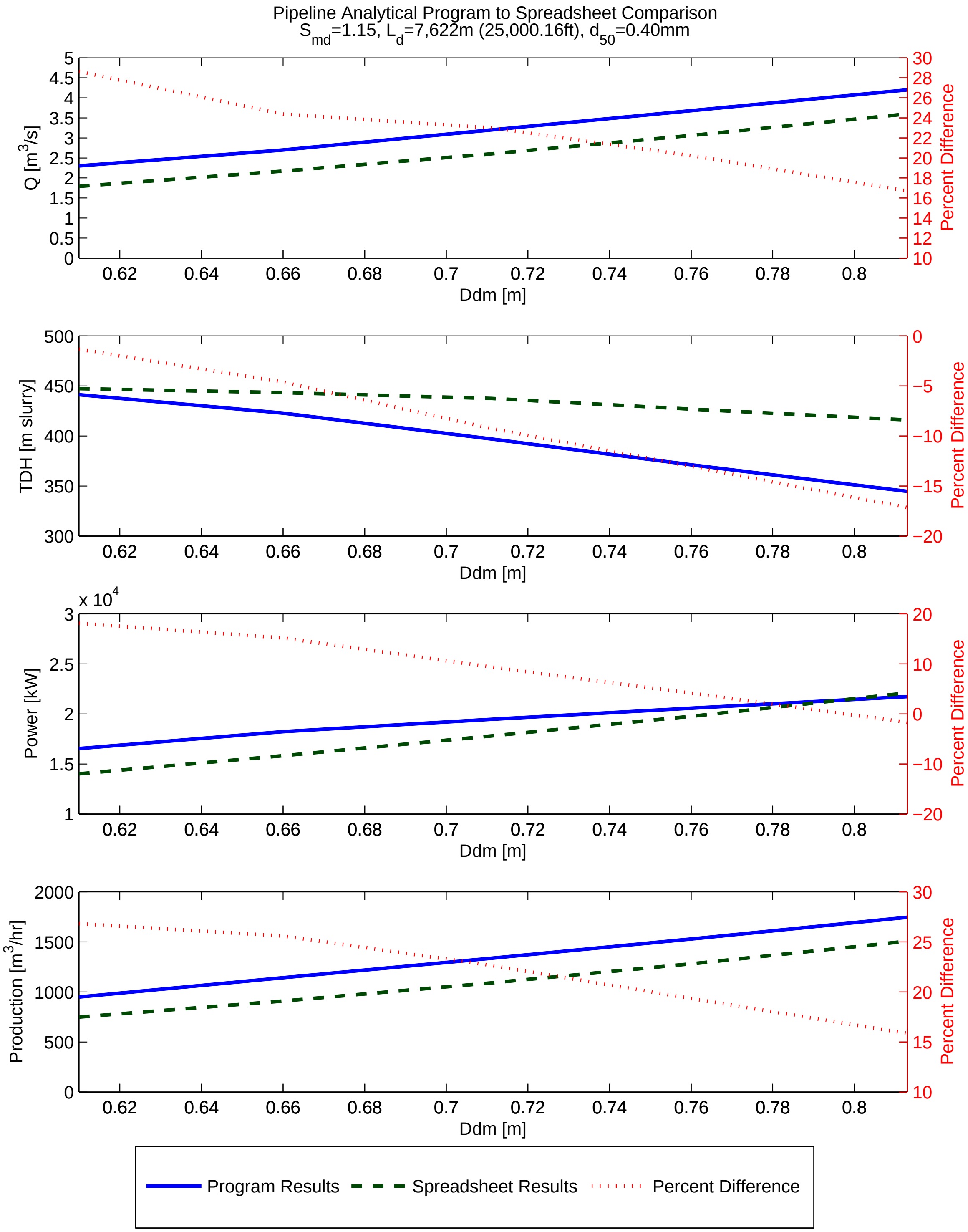


Fig. 123. Comparison of Pipeline Analytical Program and spreadsheet program performance metrics over a 0.61-0.81m(24-32in) D_d range with a L_d=7,621m(25,000ft) and d_{50}=0.4mm.

C. Results and Discussion

The pipeline system curves in Figures 110(a)–114(d) show concurrence between the Pipeline Analytical Program and spreadsheet program calculated *TDH* due to friction losses. Most of the difference occurs due to the difference in the particle settling velocity, v_t, which directly affects friction gradient, i_m. The graphics further indicate concurrence between V_{sm} calculated by both Pipeline Analytical Program and spreadsheet program. Both programs use the Wilson *et al.* (1997) nomograph to calculate V_{sm}. The only exception being that the Pipeline Analytical Program accounts for S_{md} when calculating the V_{sm}. However, this did not seem to make much difference in the overall result.

Figures 115–123 and Tables 48–51 show strong division between the spreadsheet program and Pipeline Analytical Program performance metrics at lower d_{50} values and strong similarities at higher d_{50}. Primarily, Q varies by 228.59% for d_{50} of 0.1mm between the spreadsheet program and Pipeline Analytical Program calculations. Conversely, these values vary by 16.70% for d_{50} of 0.4mm according to Figures 115–123 and Tables 48–51.

Both the Pipeline Analytical Program and the spreadsheet program solved for the performance metrics of Q, *TDH*, P and $\dot{M}$ of the dredged material slurry. The Pipeline Analytical Program consistently calculated higher flow rate and production rate values of the dredged material than the spreadsheet program calculations. Figures 115–123 indicate that the Pipeline Analytical Program calculated relatively small change in Q and *TDH* for varying values of d_{50} and constant D_d. The spreadsheet program, however, calculated significant increase with d_{50}. The Pipeline Analytical Program as well as the spreadsheet program calculated increasing Q when increasing D_d and holding d_{50} constant. The Pipeline Analytical Program and Pipeline Analytical Program calculated decreasing TDH for increasing D_d. The Pipeline Analytical Program determines the operating Q and TDH by the intersection of the pump and pipeline system curves. Increasing D_d decreases the hydraulic friction the pumps need to overcome. The pump curve and pipeline system curve will intersect at a higher Q. Increasing d_{50}, however, only slightly increases hydraulic friction causing the pump and pipeline system curves to intersect at a lower Q. The spreadsheet program bases flow rate on V_{sm} which will vary significantly with changes in d_{50} and D_d. The spreadsheet program will then determine TDH from the pump curve at this flow rate regardless of the system curve TDH. As a result, the spreadsheet program and Pipeline Analytical Program will calculate different values for Q and TDH. How different depends on the d_{50} and D_d.

The difference between the Pipeline Analytical Program and spreadsheet program calculation for Q, TDH, P and $\dot{M}$ varied the greatest for small d_{50} and the least for larger d_{50} values. This is primarily due to the spreadsheet program calculation of V_{sm} increasing for increasing d_{50} values. According to Figures 115–123, TDH calculations coincide better between the spreadsheet program and Pipeline Analytical Program for higher flow rates. Thus, the Pipeline Analytical Program and spreadsheet program will agree better at the higher flow rates required at larger d_{50} values.

D. Conclusions

The Pipeline Analytical Program and spreadsheet program both provide key performance metrics for a dredge pump series and pipeline system. Their results for pipeline system curves coincided well based on pipeline hydraulics and slurry transport principles. The Pipeline Analytical Program and spreadsheet program calculations for Q vary significantly especially for smaller d_{50} and D_d values, but agree better at larger

d_{50} and D_d values, according to Tables 48–51 and Figures 115–123.

The spreadsheet program and Pipeline Analytical Program calculate similar values for the V_{sm}based on the Wilson *et al.* (1997) nomograph. The Pipeline Analytical Program uses the V_{sm} value as a check to verify that the pump system can deliver a minimum Q value. The spreadsheet program uses V_{sm} to directly calculate the system operating flow rate. The difference in particle settling velocity calculations, v_t, made only slight difference in *TDH* calculation between the spreadsheet program and Pipeline Analytical Program. The spreadsheet program uses the Graf formula for calculating v_t which coincides well with the regression equations the Pipeline Analytical Program uses at d_{50} values typical for sand, which is where this analysis concentrated.

Finally, the Pipeline Analytical Program and spreadsheet program vary in the sense that the Pipeline Analytical Program determines the intersection between the pump series and pipeline system curves while the spreadsheet program determines whether or not the pump series can deliver the required *TDH* for a pipeline system at a given flow rate. Both methods arrive at a sound engineering conclusion. The Pipeline Analytical Program relies on the premise that all operating conditions will remain constant while the spreadsheet program takes into account that operating conditions such as d_{50} or S_{md} can change during the operating cycle of the pipeline dredge. Therefore, both the Pipeline Analytical Program and spreadsheet program provide suitable platforms to test either theory to determine which will work best for a particular application.

CHAPTER VII

MODEL VALIDATION

Model validation compares and contrasts the cost and scheduling results of the DKBES and spreadsheet program. Model Validation Analysis uses the parameters from the Savannah and New Orleans District dredge projects in Chapter V. Analysis includes direct comparison of the cost and time calculations for each sub-activity and task as well as comparison between time calculations of the DKBES and spreadsheet program to the actual dredging time.

A. Model Analysis

Model analysis compares time and cost calculations broken down by sub-activities and tasks. The DKBES and spreadsheet program used identical values for the dredge pump and pipeline parameters. Both programs rely on default values for unknown parameters such as towing distance, dredge ladder length, cutterhead diameter, minor head loss factors. Tables 52– 58 show comparison of time and cost from the DKBES and spreadsheet program. Figures 124–130 illustrate the Gantt chart output by the DKBES. Table 59 compares the calculated DKBES and spreadsheet program dredging time to the actual project dredge time.

Table 52. Model validation cost summary for Dredge *A* on Project 1.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	27,549.28	4.50	43,086.18	6.00
Transfer	24,198.48	1.50	7,480.11	0.20
Prepare After Transfer	11,866.91	2.24	29,063.04	5.00
Dredge Navigation Channel	3,661,899.44	117.18	6,150,917.26	292.47
Demobilization				
Prepare For Transfer	9,325.84	1.35	18,633.04	3.00
Transfer	24,198.48	1.50	7,495.11	0.20
Prepare For Storage	6,134.45	1.00	7,703.04	1.00
Dredge Project Total	3,765,172.87	126.03	6,264,377.79	307.87

Table 53. Model validation cost summary for Dredge *A* on Project 2.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	26,914.49	4.50	45,013.02	6.00
Transfer	24,170.36	1.50	7,936.75	0.20
Prepare After Transfer	11,425.71	2.16	29,803.88	5.00
Dredge Navigation Channel	15,618,734.52	448.07	21,384,907.55	829.79
Demobilization				
Prepare For Transfer	9,019.22	1.30	19,185.16	3.00
Transfer	24,170.36	1.50	7,951.75	0.20
Prepare For Storage	6,106.16	1.00	8,091.44	1.00
Dredge Project Total	15,720,540.83	456.87	21,502,889.55	845.19

Table 54. Model validation cost summary for Dredge A on Project 3.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	50,344.51	5.38	135,178.82	11.00
Transfer	25,367.81	1.50	8,905.55	0.20
Prepare After Transfer	26,101.39	4.33	110,819.44	9.00
Dredge Navigation Channel	5,756,756.60	135.43	11,789,732.58	350.79
Demobilization				
Prepare For Transfer	20,335.92	2.60	63,133.52	5.00
Transfer	25,367.81	1.50	8,920.55	0.20
Prepare For Storage	7,202.32	1.00	14,147.60	1.00
Dredge Project Total	5,911,476.34	146.41	12,130,838.06	377.19

Table 55. Model validation cost summary for Dredge *B* on Project 4.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	52,573.02	7.50	60,714.54	6.00
Transfer	31,478.63	1.50	11,602.59	0.20
Prepare After Transfer	14,234.64	1.98	37,888.72	5.00
Dredge Navigation Channel	9,797,041.49	110.15	22,102,246.49	279.37
Demobilization				
Prepare For Transfer	11,760.79	1.19	24,745.12	3.00
Transfer	31,478.63	1.50	11,617.59	0.20
Prepare For Storage	8,407.61	1.00	11,151.52	1.00
Dredge Project Total	9,946,974.80	121.83	22,259,966.58	294.77

Table 56. Model validation cost summary for Dredge *C* on Project 5.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	57,599.76	7.50	74,414.14	7.00
Transfer	31,792.70	1.50	11,739.97	0.20
Prepare After Transfer	17,545.46	2.47	51,362.92	6.00
Dredge Navigation Channel	10,601,874.35	138.49	30,403,269.29	380.30
Demobilization				
Prepare For Transfer	14,188.71	1.48	35,918.52	4.00
Transfer	31,792.70	1.50	11,754.97	0.20
Prepare For Storage	8,576.14	1.00	12,201.92	1.00
Dredge Project Total	10,763,369.81	150.47	30,600,661.72	398.70

Table 57. Model validation cost summary for Dredge *B* on Project 6.

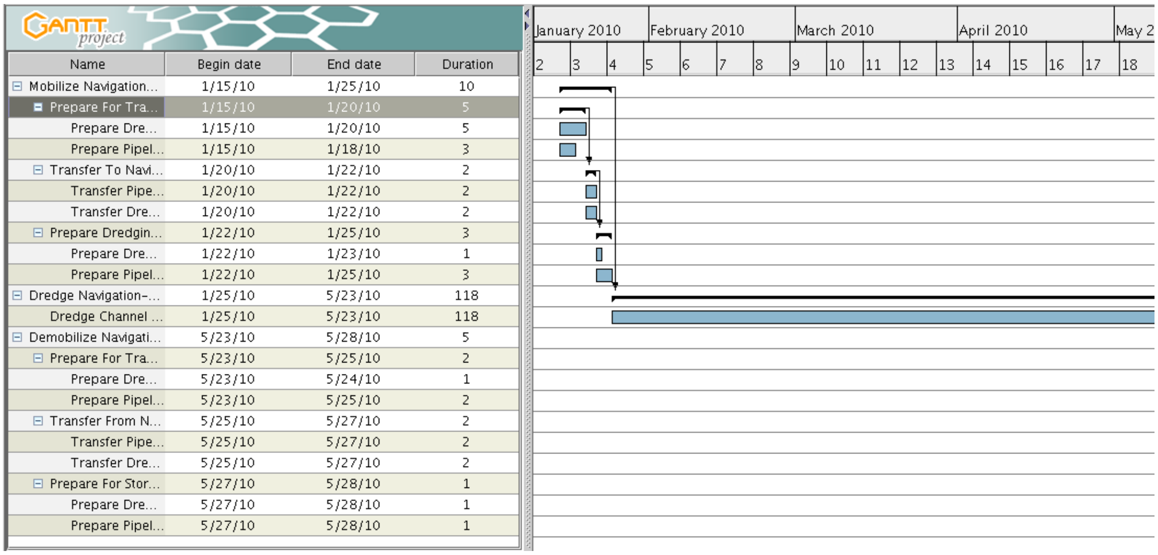
Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	71,971.39	7.50	120,528.54	9.00
Transfer	32,783.20	1.50	12,163.33	0.20
Prepare After Transfer	26,045.31	3.56	86,070.12	7.00
Dredge Navigation Channel	9,014,604.40	107.27	17,670,917.54	214.17
Demobilization				
Prepare For Transfer	21,130.20	2.13	51,338.52	4.00
Transfer	32,783.20	1.50	12,178.33	0.20
Prepare For Storage	9,088.35	1.00	15,681.92	1.00
Dredge Project Total	9,208,406.05	119.91	17,968,878.29	235.57

Table 58. Model validation cost summary for Dredge *D* on Project 7.

Activity / Task	**DKBES**		**Spreadsheet**	
	Cost [$]	Days	Cost [$]	Days
Mobilization				
Prepare For Transfer	48,626.84	7.50	44,633.42	4.50
Transfer	31,257.45	1.50	11,505.92	0.20
Prepare After Transfer	11,480.97	1.55	21,904.48	3.00
Dredge Navigation Channel	7,257,345.27	73.45	14,626,233.61	186.25
Demobilization				
Prepare For Transfer	9,854.78	1.00	16,279.56	2.00
Transfer	31,257.45	1.50	11,520.92	0.20
Prepare For Storage	8,288.91	1.00	10,304.64	1.00
Dredge Project Total	7,398,111.68	84.95	14,742,382.55	197.15

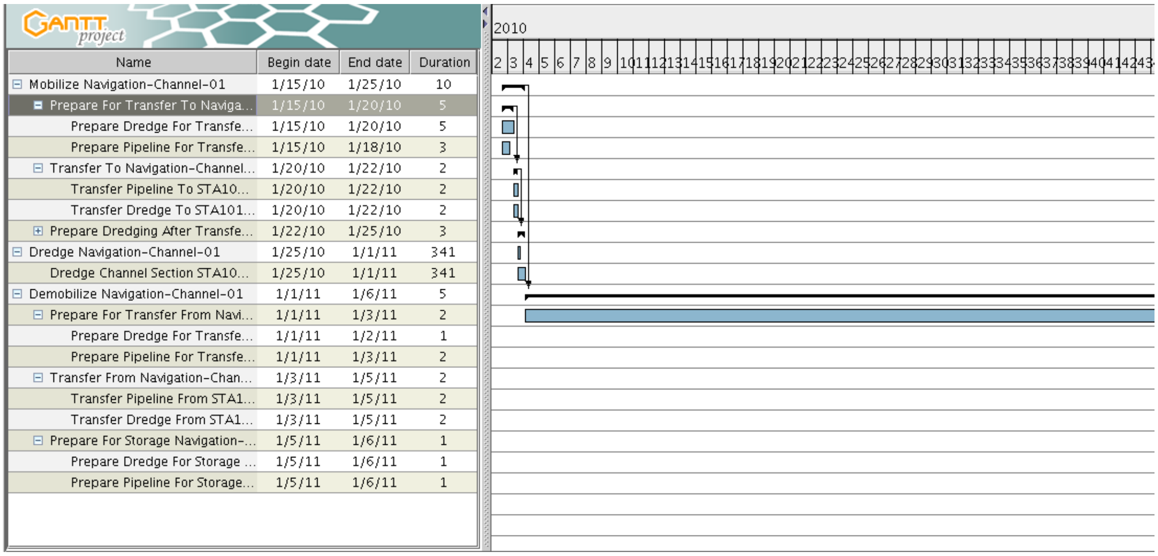
Table 59. Model validation time comparison.

Project	Actual Days	**DKBES**			**Spreadsheet**		
		Days	Diff	%Diff	Days	Diff	%Diff
1	43	117	-74	-172%	292	-249	-579%
2	88	448	-360	-409%	829	-741	-842%
3	50	135	-85	-170%	350	-300	-601%
4	136	110	25	19%	279	-143	-105%
5	61	138	-77	-127%	380	-319	-523%
6	91	107	-16	-17%	214	-123	-135%
7	58	73	-15	-26%	186	-128	-221%



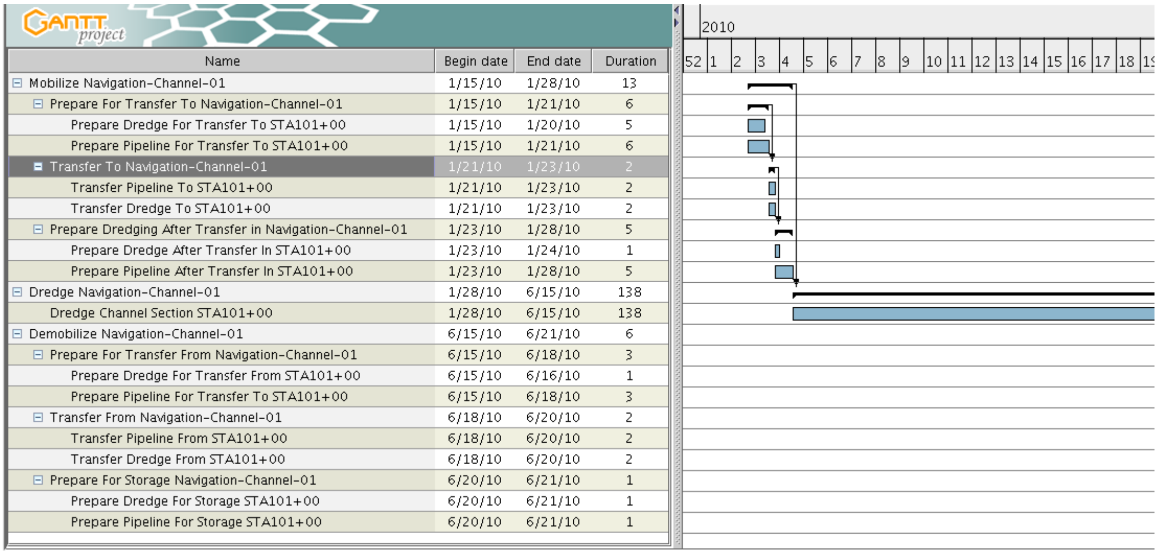
Name	Begin date	End date	Duration
Mobilize Navigation...	1/15/10	1/25/10	10
Prepare For Tra...	1/15/10	1/20/10	5
Prepare Dre...	1/15/10	1/20/10	5
Prepare Pipel...	1/15/10	1/18/10	3
Transfer To Navi...	1/20/10	1/22/10	2
Transfer Pipe...	1/20/10	1/22/10	2
Transfer Dre...	1/20/10	1/22/10	2
Prepare Dredgin...	1/22/10	1/25/10	3
Prepare Dre...	1/22/10	1/23/10	1
Prepare Pipel...	1/22/10	1/25/10	3
Dredge Navigation-...	1/25/10	5/23/10	118
Dredge Channel ...	1/25/10	5/23/10	118
Demobilize Navigati...	5/23/10	5/28/10	5
Prepare For Tra...	5/23/10	5/25/10	2
Prepare Dre...	5/23/10	5/24/10	1
Prepare Pipel...	5/23/10	5/25/10	2
Transfer From N...	5/25/10	5/27/10	2
Transfer Pipe...	5/25/10	5/27/10	2
Transfer Dre...	5/25/10	5/27/10	2
Prepare For Stor...	5/27/10	5/28/10	1
Prepare Dre...	5/27/10	5/28/10	1
Prepare Pipel...	5/27/10	5/28/10	1

Fig. 124. DKBES Gantt chart output for Dredge *A* on Project 1.



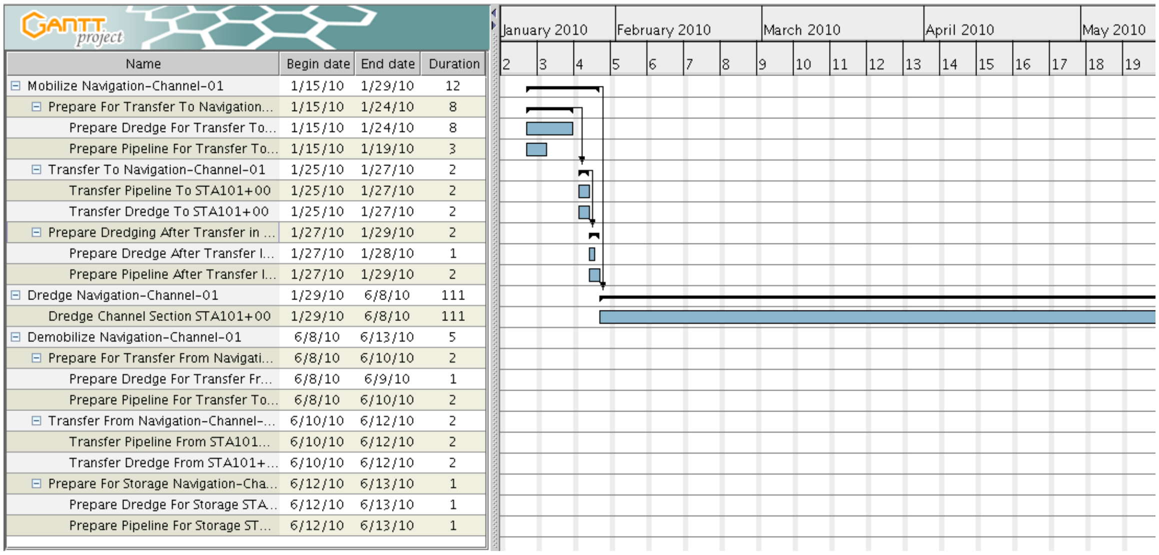
Name	Begin date	End date	Duration
Mobilize Navigation-Channel-01	1/15/10	1/25/10	10
Prepare For Transfer To Naviga...	1/15/10	1/20/10	5
Prepare Dredge For Transfe...	1/15/10	1/20/10	5
Prepare Pipeline For Transfe...	1/15/10	1/18/10	3
Transfer To Navigation-Channel...	1/20/10	1/22/10	2
Transfer Pipeline To STA10...	1/20/10	1/22/10	2
Transfer Dredge To STA101...	1/20/10	1/22/10	2
Prepare Dredging After Transfe...	1/22/10	1/25/10	3
Dredge Navigation-Channel-01	1/25/10	1/1/11	341
Dredge Channel Section STA10...	1/25/10	1/1/11	341
Demobilize Navigation-Channel-01	1/1/11	1/6/11	5
Prepare For Transfer From Navi...	1/1/11	1/3/11	2
Prepare Dredge For Transfe...	1/1/11	1/2/11	1
Prepare Pipeline For Transfe...	1/1/11	1/3/11	2
Transfer From Navigation-Chan...	1/3/11	1/5/11	2
Transfer Pipeline From STA1...	1/3/11	1/5/11	2
Transfer Dredge From STA1...	1/3/11	1/5/11	2
Prepare For Storage Navigation-...	1/5/11	1/6/11	1
Prepare Dredge For Storage ...	1/5/11	1/6/11	1
Prepare Pipeline For Storage...	1/5/11	1/6/11	1

Fig. 125. DKBES Gantt chart output for Dredge *A* on Project 2.



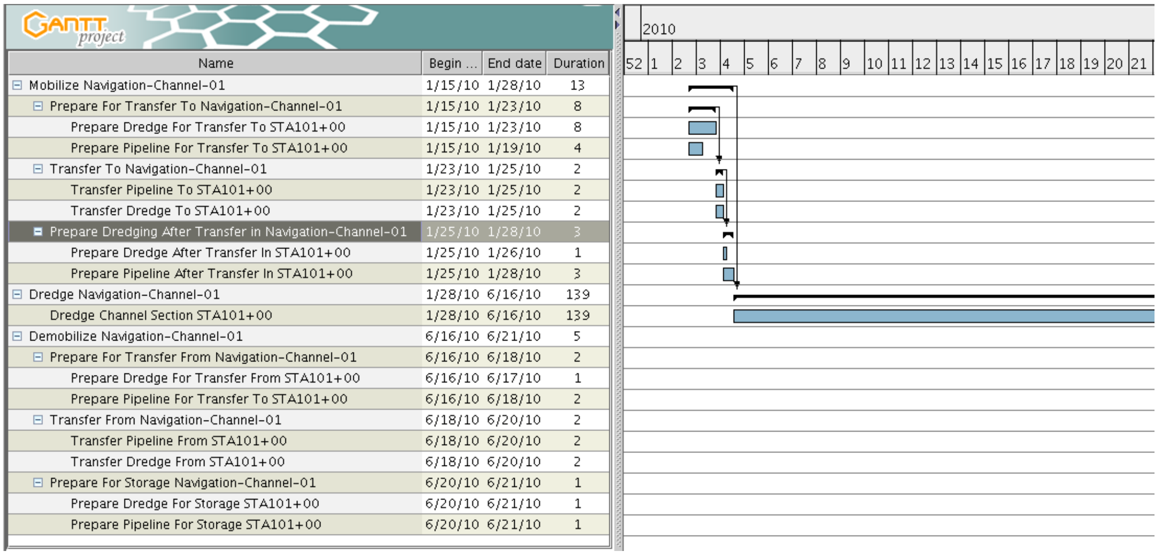
Name	Begin date	End date	Duration
⊟ Mobilize Navigation-Channel-01	1/15/10	1/28/10	13
⊟ Prepare For Transfer To Navigation-Channel-01	1/15/10	1/21/10	6
Prepare Dredge For Transfer To STA101+00	1/15/10	1/20/10	5
Prepare Pipeline For Transfer To STA101+00	1/15/10	1/21/10	6
⊟ Transfer To Navigation-Channel-01	1/21/10	1/23/10	2
Transfer Pipeline To STA101+00	1/21/10	1/23/10	2
Transfer Dredge To STA101+00	1/21/10	1/23/10	2
⊟ Prepare Dredging After Transfer in Navigation-Channel-01	1/23/10	1/28/10	5
Prepare Dredge After Transfer In STA101+00	1/23/10	1/24/10	1
Prepare Pipeline After Transfer In STA101+00	1/23/10	1/28/10	5
⊟ Dredge Navigation-Channel-01	1/28/10	6/15/10	138
Dredge Channel Section STA101+00	1/28/10	6/15/10	138
⊟ Demobilize Navigation-Channel-01	6/15/10	6/21/10	6
⊟ Prepare For Transfer From Navigation-Channel-01	6/15/10	6/18/10	3
Prepare Dredge For Transfer From STA101+00	6/15/10	6/16/10	1
Prepare Pipeline For Transfer To STA101+00	6/15/10	6/18/10	3
⊟ Transfer From Navigation-Channel-01	6/18/10	6/20/10	2
Transfer Pipeline From STA101+00	6/18/10	6/20/10	2
Transfer Dredge From STA101+00	6/18/10	6/20/10	2
⊟ Prepare For Storage Navigation-Channel-01	6/20/10	6/21/10	1
Prepare Dredge For Storage STA101+00	6/20/10	6/21/10	1
Prepare Pipeline For Storage STA101+00	6/20/10	6/21/10	1

Fig. 126. DKBES Gantt chart output for Dredge *A* on Project 3.



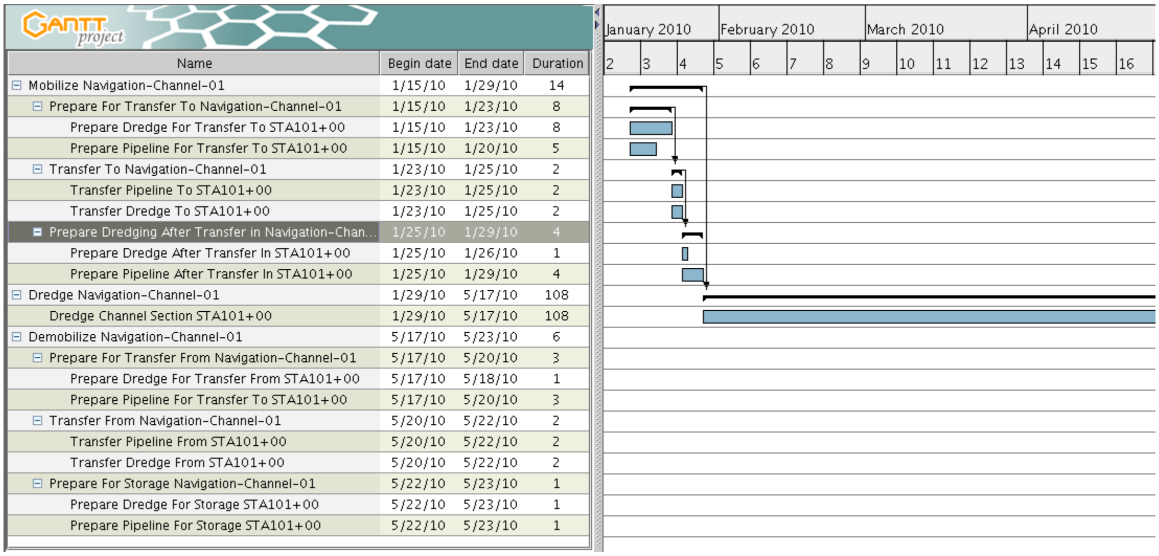
Name	Begin date	End date	Duration
⊟ Mobilize Navigation-Channel-01	1/15/10	1/29/10	12
⊟ Prepare For Transfer To Navigation...	1/15/10	1/24/10	8
Prepare Dredge For Transfer To...	1/15/10	1/24/10	8
Prepare Pipeline For Transfer To...	1/15/10	1/19/10	3
⊟ Transfer To Navigation-Channel-01	1/25/10	1/27/10	2
Transfer Pipeline To STA101+00	1/25/10	1/27/10	2
Transfer Dredge To STA101+00	1/25/10	1/27/10	2
⊟ Prepare Dredging After Transfer in ...	1/27/10	1/29/10	2
Prepare Dredge After Transfer I...	1/27/10	1/28/10	1
Prepare Pipeline After Transfer I...	1/27/10	1/29/10	2
⊟ Dredge Navigation-Channel-01	1/29/10	6/8/10	111
Dredge Channel Section STA101+00	1/29/10	6/8/10	111
⊟ Demobilize Navigation-Channel-01	6/8/10	6/13/10	5
⊟ Prepare For Transfer From Navigati...	6/8/10	6/10/10	2
Prepare Dredge For Transfer Fr...	6/8/10	6/9/10	1
Prepare Pipeline For Transfer To...	6/8/10	6/10/10	2
⊟ Transfer From Navigation-Channel-...	6/10/10	6/12/10	2
Transfer Pipeline From STA101...	6/10/10	6/12/10	2
Transfer Dredge From STA101+...	6/10/10	6/12/10	2
⊟ Prepare For Storage Navigation-Cha...	6/12/10	6/13/10	1
Prepare Dredge For Storage STA...	6/12/10	6/13/10	1
Prepare Pipeline For Storage ST...	6/12/10	6/13/10	1

Fig. 127. DKBES Gantt chart output for Dredge *B* on Project 4.



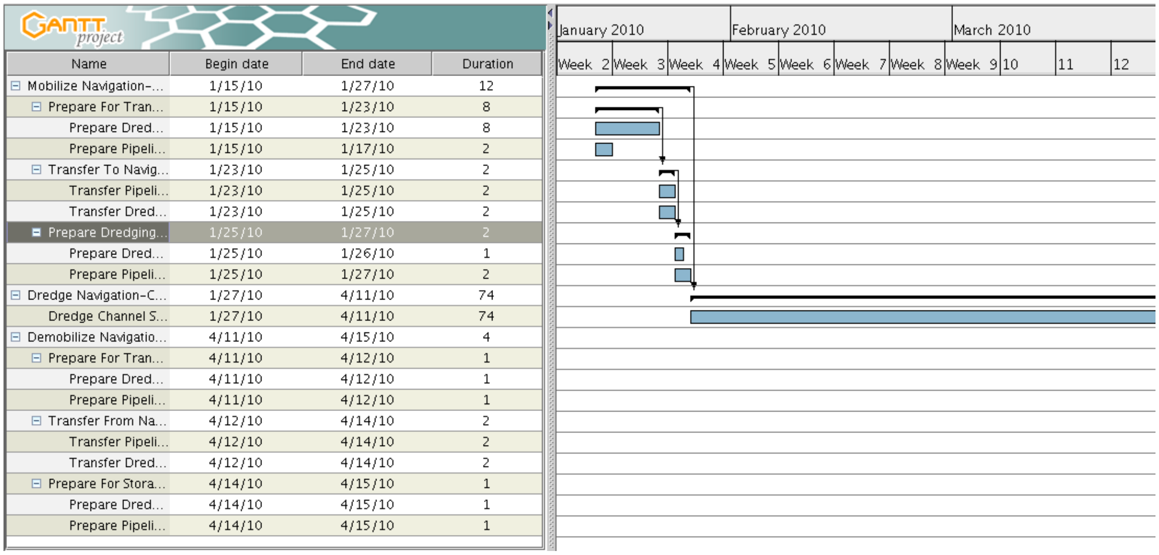
Name	Begin ...	End date	Duration
⊟ Mobilize Navigation-Channel-01	1/15/10	1/28/10	13
⊟ Prepare For Transfer To Navigation-Channel-01	1/15/10	1/23/10	8
Prepare Dredge For Transfer To STA101+00	1/15/10	1/23/10	8
Prepare Pipeline For Transfer To STA101+00	1/15/10	1/19/10	4
⊟ Transfer To Navigation-Channel-01	1/23/10	1/25/10	2
Transfer Pipeline To STA101+00	1/23/10	1/25/10	2
Transfer Dredge To STA101+00	1/23/10	1/25/10	2
⊟ Prepare Dredging After Transfer in Navigation-Channel-01	1/25/10	1/28/10	3
Prepare Dredge After Transfer In STA101+00	1/25/10	1/26/10	1
Prepare Pipeline After Transfer In STA101+00	1/25/10	1/28/10	3
⊟ Dredge Navigation-Channel-01	1/28/10	6/16/10	139
Dredge Channel Section STA101+00	1/28/10	6/16/10	139
⊟ Demobilize Navigation-Channel-01	6/16/10	6/21/10	5
⊟ Prepare For Transfer From Navigation-Channel-01	6/16/10	6/18/10	2
Prepare Dredge For Transfer From STA101+00	6/16/10	6/17/10	1
Prepare Pipeline For Transfer To STA101+00	6/16/10	6/18/10	2
⊟ Transfer From Navigation-Channel-01	6/18/10	6/20/10	2
Transfer Pipeline From STA101+00	6/18/10	6/20/10	2
Transfer Dredge From STA101+00	6/18/10	6/20/10	2
⊟ Prepare For Storage Navigation-Channel-01	6/20/10	6/21/10	1
Prepare Dredge For Storage STA101+00	6/20/10	6/21/10	1
Prepare Pipeline For Storage STA101+00	6/20/10	6/21/10	1

Fig. 128. DKBES Gantt chart output for Dredge *C* on Project 5.



Name	Begin date	End date	Duration
⊟ Mobilize Navigation-Channel-01	1/15/10	1/29/10	14
⊟ Prepare For Transfer To Navigation-Channel-01	1/15/10	1/23/10	8
Prepare Dredge For Transfer To STA101+00	1/15/10	1/23/10	8
Prepare Pipeline For Transfer To STA101+00	1/15/10	1/20/10	5
⊟ Transfer To Navigation-Channel-01	1/23/10	1/25/10	2
Transfer Pipeline To STA101+00	1/23/10	1/25/10	2
Transfer Dredge To STA101+00	1/23/10	1/25/10	2
⊟ Prepare Dredging After Transfer in Navigation-Chan...	1/25/10	1/29/10	4
Prepare Dredge After Transfer In STA101+00	1/25/10	1/26/10	1
Prepare Pipeline After Transfer In STA101+00	1/25/10	1/29/10	4
⊟ Dredge Navigation-Channel-01	1/29/10	5/17/10	108
Dredge Channel Section STA101+00	1/29/10	5/17/10	108
⊟ Demobilize Navigation-Channel-01	5/17/10	5/23/10	6
⊟ Prepare For Transfer From Navigation-Channel-01	5/17/10	5/20/10	3
Prepare Dredge For Transfer From STA101+00	5/17/10	5/18/10	1
Prepare Pipeline For Transfer To STA101+00	5/17/10	5/20/10	3
⊟ Transfer From Navigation-Channel-01	5/20/10	5/22/10	2
Transfer Pipeline From STA101+00	5/20/10	5/22/10	2
Transfer Dredge From STA101+00	5/20/10	5/22/10	2
⊟ Prepare For Storage Navigation-Channel-01	5/22/10	5/23/10	1
Prepare Dredge For Storage STA101+00	5/22/10	5/23/10	1
Prepare Pipeline For Storage STA101+00	5/22/10	5/23/10	1

Fig. 129. DKBES Gantt chart output for Dredge *B* on Project 6.



Name	Begin date	End date	Duration
⊟ Mobilize Navigation-...	1/15/10	1/27/10	12
⊟ Prepare For Tran...	1/15/10	1/23/10	8
Prepare Dred...	1/15/10	1/23/10	8
Prepare Pipeli...	1/15/10	1/17/10	2
⊟ Transfer To Navig...	1/23/10	1/25/10	2
Transfer Pipeli...	1/23/10	1/25/10	2
Transfer Dred...	1/23/10	1/25/10	2
⊟ Prepare Dredging...	1/25/10	1/27/10	2
Prepare Dred...	1/25/10	1/26/10	1
Prepare Pipeli...	1/25/10	1/27/10	2
⊟ Dredge Navigation-C...	1/27/10	4/11/10	74
Dredge Channel S...	1/27/10	4/11/10	74
⊟ Demobilize Navigatio...	4/11/10	4/15/10	4
⊟ Prepare For Tran...	4/11/10	4/12/10	1
Prepare Dred...	4/11/10	4/12/10	1
Prepare Pipeli...	4/11/10	4/12/10	1
⊟ Transfer From Na...	4/12/10	4/14/10	2
Transfer Pipeli...	4/12/10	4/14/10	2
Transfer Dred...	4/12/10	4/14/10	2
⊟ Prepare For Stora...	4/14/10	4/15/10	1
Prepare Dred...	4/14/10	4/15/10	1
Prepare Pipeli...	4/14/10	4/15/10	1

Fig. 130. DKBES Gantt chart output for Dredge *D* on Project 7.

B. Results and Discussion

Tables 52–58 show that the DKBES calculated mobilization and demobilization costs consistently below the spreadsheet program calculations. The DKBES uses a regression equation that calculates a shorter time to prepare pipeline for transfer, setup pipeline and store pipeline. The DKBES calculates a shorter time and subsequent lower cost for dredging the navigation channel based on higher calculated production rates from the Pipeline Analytical Program compared to the spreadsheet program from Chapter VI. Comparison of DKBES and spreadsheet program calculated dredging times to actual project dredging time showed that both programs consistently overestimate dredging time. Analytical results from Chapter V indicate that the Pipeline Analytical Program underestimates actual production. These results indicate that dredging cost relies heavily on time required to dredge which in turn requires accurate production rates.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The Dredging Knowledge–Base Expert–System (DKBES) study intended to draw comparison between an object–oriented knowledge–base expert–system and its counterpart spreadsheet program. This study further examined how the Pipeline Analytical Program used pump and pipeline hydraulics and slurry transport principles to determine production and power consumption compared to field data from dredge instrumentation and daily dredge reports.

Chapter IV compared Pipeline Analytical Program analysis to real–time field data from the Dredge *Goetz*. The Pipeline Analytical Program calculated a production rate 6.62% lower than the *Goetz* actually produced. The Pipeline Analytical Program calculated overall dry solids production of 191.6m^3 based on a continuous production rate of 139.1m^3/hr whereas the *Goetz* delivered a final dry solids production of 205.2m^3. Furthermore, the Pipeline Analytical Program calculated a constant dredged material delivered specific gravity, S_{md}, of 1.057 whereas the *Goetz* averaged 1.067. These figures suggest that the Pipeline Analytical Program underestimates the S_{md} using the Herbich (2000) empirical formula and as a result underestimates production.

Chapter V compared Pipeline Analytical Program analysis to daily dredge reports that contain the daily dredge *in–situ* production along with pipeline length, dredge depth, dredge advance, and time of pumping. The Pipeline Analytical Program returns analytical results in terms of both *in–situ* and dry solids production. In all but one case, the Pipeline Analytical Program underestimated the *in–situ* production between 27.5% and 57.1%. For the remaining case, the Pipeline Analytical Program overestimated production by 26.9%. For this data comparison, the Pipeline

Analytical Program accounted for the actual time spent pumping. These figures would suggest that the Pipeline Analytical Program underestimates the S_{md} when calculating production. More accurate and detailed studies to calculate delivered solids concentration based on dredge equipment and dredged material parameters would lend considerably into improving the pump and pipeline analysis.

Chapter VI compares the Pipeline Analytical Program to the spreadsheet program in terms of flow rate and production rate. The Pipeline Analytical Program consistently calculated a higher flow rate and production rate than the spreadsheet program. Chapter VII compared the DKBES and spreadsheet program in terms of the cost factors for a pipeline dredge project. In all cases, the DKBES calculated a higher production rate which translates to a shorter dredging time and lower dredging cost. The DKBES and spreadsheet program calculated different results for the mobilization and demobilization sub–activities. The DKBES and spreadsheet program use slightly different equipment and personnel lists for task–method cost calculation. These differences coupled with the user's ability to further change cost factors can allow users to generate inaccurate and inconsistent dredging costs if they are not cautious and aware of these actions.

Despite differences in the cost calculations of the spreadsheet program and the DKBES as well as the ability of the DKBES users to modify existing cost data, the object–oriented architecture allows users to readily and accessibly change equipment lists of tasks and empirical formula used to calculate duration without needing to modify the program itself. This modularity leads to an application that users and developers can refine and modify as their knowledge, understanding, and circumstances of the pipeline dredge project complexities change. Coupled with the Pipeline Analytical Program, the DKBES serves as a versatile and formidable program that can calculate the key performance metrics of a pipeline dredge project based on the fundamental components of a pipeline dredge project. This versatility and capability then offers users the means to solve their pipeline dredge project performance metrics efficiently and productively.

Recommendations for future work include expanding on the success of the comparison of Pipeline Analytical Program results to the *Goetz* dredge instrumentation data. Comparing a pipeline dredge instrumentation data from the project's start to finish will offer significant insights into how to improve the Pipeline Analytical Program ability to calculate the dredge's performance metrics. Conducting this research from dredging contracts within the U.S. Army Corps of Engineers, however, can encounter issues over proprietary information.

Presently, the Pipeline Analytical Program can analyze a dredge pump and pipeline system capability for a specific dredge project. Analysis of the *Goetz* pump and pipeline system underscores the capability of the Pipeline Analytical Program. The analytical results of the *Goetz* serves as a basis for a journal manuscript to the Journal of Pipeline Systems Engineering Principles and Practice.

The Pipeline Analytical Program capabilities of the DKBES coupled with the object–oriented architecture of its cost and planning functions provides a unique and versatile program for planning a pipeline dredging project. The ability to solve a dredge's performance metrics based on its physical and functional attributes without the need for meticulous human interaction allows users to quickly and readily develop a pipeline dredge project, view the resulting project scenario outcome and repeat the process based on any necessary modifications. Thus the DKBES can assist dredging engineering personnel carry out their responsibilities and mission requirements while doing so efficiently and effectively.

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APPENDIX A

TABLE OF NOMENCLATURE

Table 60. Table of Nomenclature for DKBES variables.

Symbol	**Description**	**Default Value**
D_d	Discharge pipe diameter (m)	
D_s	Suction pipe diameter (m)	
L_s	Suction length (m)	
Z_d	Digging depth (m)	
Z_b	Discharge elevation (m)	
Z_p	Pump elevation (m)	
L_d	Pipeline discharge length (m)	
m	Slurry friction gradient exponent	1.7
ϵ_s	Pipe relative roughness (mm)	0.05mm
μ_s	Pipe mechanical friction factor	0.66
ρ_w	Water density (kg/m^3)	1,000kg/m^3
γ_w	Water unit weight (N/m^3)	9,810N/m^3
μ_w	Water viscosity (Pa·s)	10^{-3}Pa·s
g	Gravitational acceleration (m/s^2)	9.81(m/s^2)
ρ_s	Solid particle density (kg/m^3)	2,650kg/m^3
ρ_f	Carrier fluid density (kg/m^3)	1,015kg/m^3
d_{50}	Median sediment grain diameter(mm)	

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
S_{md}	Specific gravity of delivered pipeline material	
S_f	Specific gravity of carrier fluid	1.015
S_s	Specific gravity of sediment solid particles	2.65
H_a	Atmospheric Pressure Head (mH_2O)	10.4mH_2O
H_v	Vapor Pressure Head (mH_2O)	0.18mH_2O
TDH_s	Total dynamic head of slurry material	
i_{ws}	friction gradient of water in suction pipeline	
i_{wd}	friction gradient of water in discharge pipeline	
i_{ms}	friction gradient of slurry in suction pipeline	
i_{md}	friction gradient of slurry in discharge pipeline	
f_{ws}	friction factor of water in suction pipeline	
f_{wd}	friction factor of water in discharge pipeline	
Re_s	Reynold's Number of suction pipeline flow	
Re_d	Reynold's Number of discharge pipeline flow	
V_s	Velocity of suction pipeline flow (m/s)	
V_d	Velocity of discharge pipeline flow (m/s)	
V_{50s}	Stratification velocity of suction pipeline flow (m/s)	
V_{50d}	Stratification velocity of discharge pipeline flow (m/s)	
w	Settling velocity factor of solid particle (m/s)	
v_{ts}	Settling velocity solid particle in water (m/s)	

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
v_{ts}^*	Dimensionless settling velocity solid particle	
d^*	Dimensionless particle diameter	
F_b	Bulking factor of dredged material	
c_{vd}	Volumetric solids concentration of delivered dredged material	
c_{vi}	Volumetric solids concentration of *in–situ* dredged material	
η_{bh}	Dredge bank height efficiency	
D_c	Dredge cutterhead diameter (m)	
η_d	Dredge efficiency	
Q	Volumetric flow rate (m^3/s)	
$\dot{M}$	Volumetric production rate (m^3/hr)	
V_{sm}	Stationary bed velocity of delivered pipeline material (m/s)	
k	Stationary bed velocity factor	
c_r	Volumetric solids concentration multiplier	
α	constant	
β	constant	
c_{rm}	constant	
$NPSHA$	Net positive suction head available	
$NPSHR$	Net positive suction head required	
RPM	Pump impeller rotations per minute	

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
ω	Pump impeller angular velocity	
D_i	Pump impeller diameter (m)	
F_d	Annual depreciation cost factor (\$/yr)	
F_m	Annual maintenance cost factor (\$/yr)	
F_r	Annual repair cost factor (\$/yr)	
F_i	Annual insurance cost factor (\$/yr)	
q	quantity	
C_c	Capitol cost (\$)	
N_d	Number of dredge days per year	
C_d	Daily depreciation cost (\$/day)	
C_{fl}	Daily fuel cost (\$/day)	
P_{ins}	Installed power of equipment	
f_l	Lubricating oil factor	0.1
f_c	Fuel consumption gradient for diesel engines	0.253L/(kW.hr)
t_{100}	percentage of time dredge operates at 100% capacity	75.0%
f_f	Diesel fuel cost rate	\$1.00/L
C_e	Daily cost rate for employees (\$/day)	
P_p	Employee pay–period	
S_e	Employee pay–rate	
N_m	Minimum number of employees	
N_{hs}	Number of hours per shift	12.0

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
N_{sd}	Number of shifts per day	1
β_{ot}	Overtime factor	14.3%
N_h	Holidays per year	13
N_v	Vacation days per year	10
β_{ss}	Social Security factor	2%
β_{wc}	Worker Compensation factor	45%
β_{su}	State unemployment factor	3.5%
β_{fu}	Federal unemployment factor	1.0%
β_{fr}	Fringe benefits factor	1%
T_{dc}	Time to dredge channel section (days)	
$\bar{T}_{dp}$	Average time dredge spends pumping (hrs/day)	16hrs/day
V_{mi}	*in–situ* volume of dredged material (m^3)	
P_{mi}	Production rate of *in–situ* dredged material (m^3/hr)	
T_{mpd}	Mobilization time to prepare dredge for transfer	
T_{mpp}	Mobilization time to prepare pipeline for transfer	
T_{mtp}	Mobilization time to transfer pipeline	
T_{mtd}	Mobilization time to transfer dredge	
T_{msp}	Mobilization time to setup pipeline	
T_{msd}	Mobilization time to setup dredge	
T_{dpd}	Demobilization time to prepare dredge for transfer	

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
T_{dpp}	Demobilization time to prepare pipeline for transfer	
T_{dtp}	Demobilization time to transfer pipeline	
T_{dtd}	Demobilization time to transfer dredge	
T_{dsp}	Demobilization time to store pipeline	
T_{dsd}	Demobilization time to store dredge	
T_{task}	Task duration (day)	
C_{sb}	Hourly standby rate of equipment ($/hr)	
N_{sb}	Number of equipment on standby	
C_{we}	Daily rate of working equipment ($/day)	
N_{we}	Number of working equipment	
C_p	Daily working rate of personnel ($/day)	
C_{sbs}	Daily subsistence rate for personnel ($/day)	
N_{pcc}	Number of personnel	
C_{spt}	Daily cost for supplies and tools ($/day)	
N_{nep}	Number of equipment not pumping related	
P_{pump}	Pipeline Analytical Program calculated pumping power (kW)	
N_{ep}	Number of pumping related equipment	
P_s	Pump suction pressure gauge	
P_d	Pump discharge pressure gauge	
Q_{dim}	Dimensionless flow rate	

Continued on next page

Table 60. Continued.

Symbol	**Description**	**Default Value**
TDH_{dim}	Dimensionless total dynamic head	
$RES_{TDH_{dim}}$	Residual total dynamic head	
Q_{eq}	Equivalent fluid flow rate	
V_{eq}	Equivalent fluid velocity	
TDH_w	Total dynamic head of water	
$NPSHR_{dim}$	Dimensionless net positive suction head	
t	time (sec)	
V_h	Stationary bed velocity factor (m/s)	
X_{PLP}	Performance metric of Pipeline Analytical Program	
X_{SS}	Performance metric of Spreadsheet Program	

VITA

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