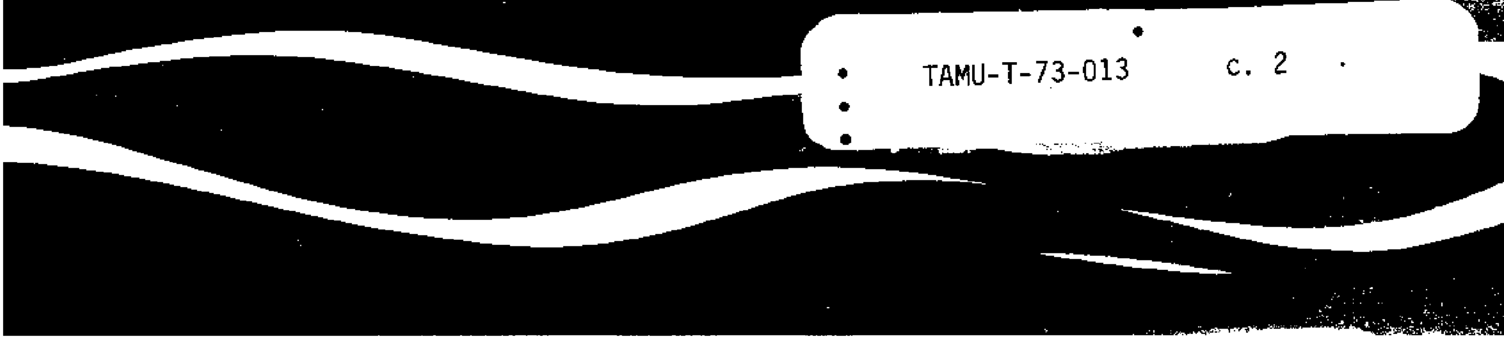

SYSTEMS ENGINEERING AND DREDGING —
THE FEEDBACK PROBLEM

Prepared by
DAVID R. BASCO
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Texas A&M University

Partially Supported by the Center for Dredging Studies

TAMU-SG-74-205 DECEMBER 1973

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ABSTRACT

A hydraulic cutterhead dredge which excavates soil at one point and disposes of it some distance away is an extremely complicated system. Much is unknown and remains to be discovered about its operation, consequently attempts to model the system are hampered by this lack of basic understanding of critical areas of the system. Soil, operation and other considerations vary considerably therefore actual, on-the-job, field dredging projects must be employed to gather information and overcome these gaps in dredging knowledge. Unfortunately, this feedback of information from real dredging projects is practically non-existent today.

This paper attempts to outline the important and critical links in the dredging system chain and to develop and discuss methods for overcoming those obstacles that inhibit or eliminate the feedback cycle. A computer model of a hydraulic dredging system is developed and used to examine the four major limitations on solids output, namely: horsepower, cavitation, line plugging and dislodgement limits. A full scale feedback program is also developed.

The feedback of knowledge gained on one project for use as input for future jobs and as basic knowledge is undoubtedly the industry's biggest problem today.

FOREWORD

This paper is essentially that submitted and presented at the "Vereinigung der Nassbaggerunternehmungen e.V." (German Dredging Association Conference) on December 5, 1973 at Hamburg, Germany.

The author wishes to thank Mr. Mark Puckett for his programming efforts, Mr. Randy Long for his graphical and computational efforts, and Mrs. Kristy Sablatura for typing the draft and final copies of the paper.

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF TABLES

SYSTEMS ENGINEERING AND DREDGING - THE FEEDBACK PROBLEM

by David R. Basco, Ph.D., P.E.[1]

I. Introduction

From an analysis of one's dredging system, the addition of a few process instruments, some judicial planning, and the use of high-speed digital computers, every hydraulic dredging job undertaken today can be readily turned into a research or "learning" project. This educational, feedback process about one's own equipment and system operation, under all types of soil and operating conditions is practically absent from today's dredging industry.

I have heard time and again that the wide variety of soil types and conditions routinely encountered on any dredging project preclude one from attempting to theoretically predict dredge performance. In addition, the variety of suction geometries and large number of unknowns only make such predictive attempts academic exercises. Also, attempts to use laboratory scale models under controlled soil and operating conditions are said to be unrealistic and not representative of true prototype conditions.

If the above is true, then how can we ever hope to learn about what really takes place during a hydraulic dredging operation? How can we ever hope to develop an understanding of the many unknowns involved so that a completely analytical model of the system can be constructed? How can we develop confidence in these models of our system if they are only based on laboratory scale results under uniform soil conditions?

---

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One answer to all these questions is the topic of this paper. We must work to turn each actual dredging job into a meaningful research project from which we extract information that can be readily used to learn more about the entire dredging system. In addition, this feedback of information is beneficial when:

(1) bidding the next job;

(2) evaluating changes during operation of a given job; and

(3) evaluating proposed changes in existing equipment.

Of course, the reasons for our present state (or lack) of knowledge regarding the capabilities of our dredging systems is a combination of many complex factors. Most spring from a shortage of financial resources to spend on complete tests of a dredge system. Once a job is obtained, the main objective is to keep the dredge in continuous operation at all costs, in order to complete the job as scheduled. It would be unrealistic to expect the dredge to be taken out of production and used for test purposes at this time - and rightfully so. Also, the additional instrumentation required is somewhat expensive and requires fairly sophisticated maintenance personnel to keep in proper working condition. Finally, even if all the variables of interest were recorded during some representative norms and extremes of the dredging cycle, the dredge contractor and his assistants are usually too busy with the daily tasks of keeping the system operating to begin to try to make some sense out of all the data collected. Or, the dredger simply lacks the necessary engineering knowledge and technical capabilities to make the required calculations. All the above reasons (and others) are obstacles to be overcome if the information feedback cycle is to be completed and if useful knowledge is to be gained from on-the-job dredging projects.

This paper attempts to outline the important and critical links in the dredging system chain and to develop and discuss methods for overcoming those obstacles that inhibit or eliminate the feedback cycle. The feedback of knowledge gained on one project for use as input for future jobs and as basic knowledge is undoubtedly the industry's biggest problem.

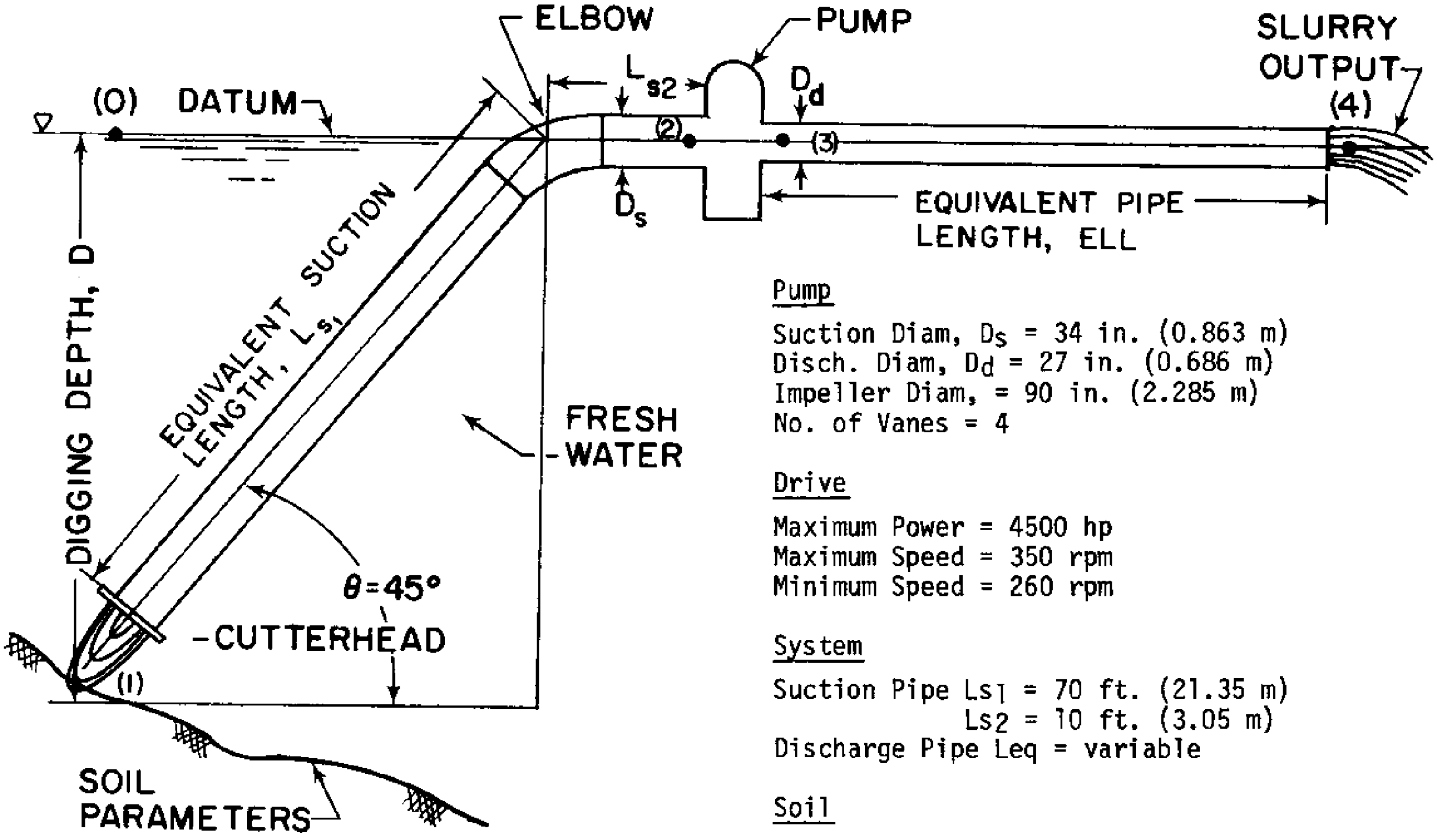
My discussion will be limited to the United States dredging industry and what I know about it. Perhaps, in some instances what I say will not apply to German dredgers. Your indulgence of my ignorance is requested in those instances.

II. Illustrative Example

In order to add realism to the discussion, a hypothetical, hydraulic cutterhead dredge system as shown in Fig. 1 will be referred to throughout the paper. For simplicity, the pump centerline is taken at the water level and the discharge pipe is also chosen at this datum. Centrifugal pump performance curves herein discussed have been developed from model tests of actual dredge pumps in the Hydrodynamics Laboratory of Texas A&M University. All other data, graphs, illustrations, etc. employed are also based on attempts to use the best knowledge available today.

III. Elements of Hydraulic Dredging Systems

A hydraulic cutterhead dredge as depicted in Fig. 1 is a complicated system. Of usual interest is knowledge of the maximum solids output per



Pump

Suction Diam, D_s = 34 in. (0.863 m)
Disch. Diam, D_d = 27 in. (0.686 m)
Impeller Diam, = 90 in. (2.285 m)
No. of Vanes = 4

Drive

Maximum Power = 4500 hp
Maximum Speed = 350 rpm
Minimum Speed = 260 rpm

System

Suction Pipe L_{s1} = 70 ft. (21.35 m)
L_{s2} = 10 ft. (3.05 m)
Discharge Pipe Leq = variable

Soil

Mean Diameter, d_{50} = 0.42 mm

Fig. 1 ILLUSTRATIVE EXAMPLE OF HYDRAULIC DREDGE SYSTEM

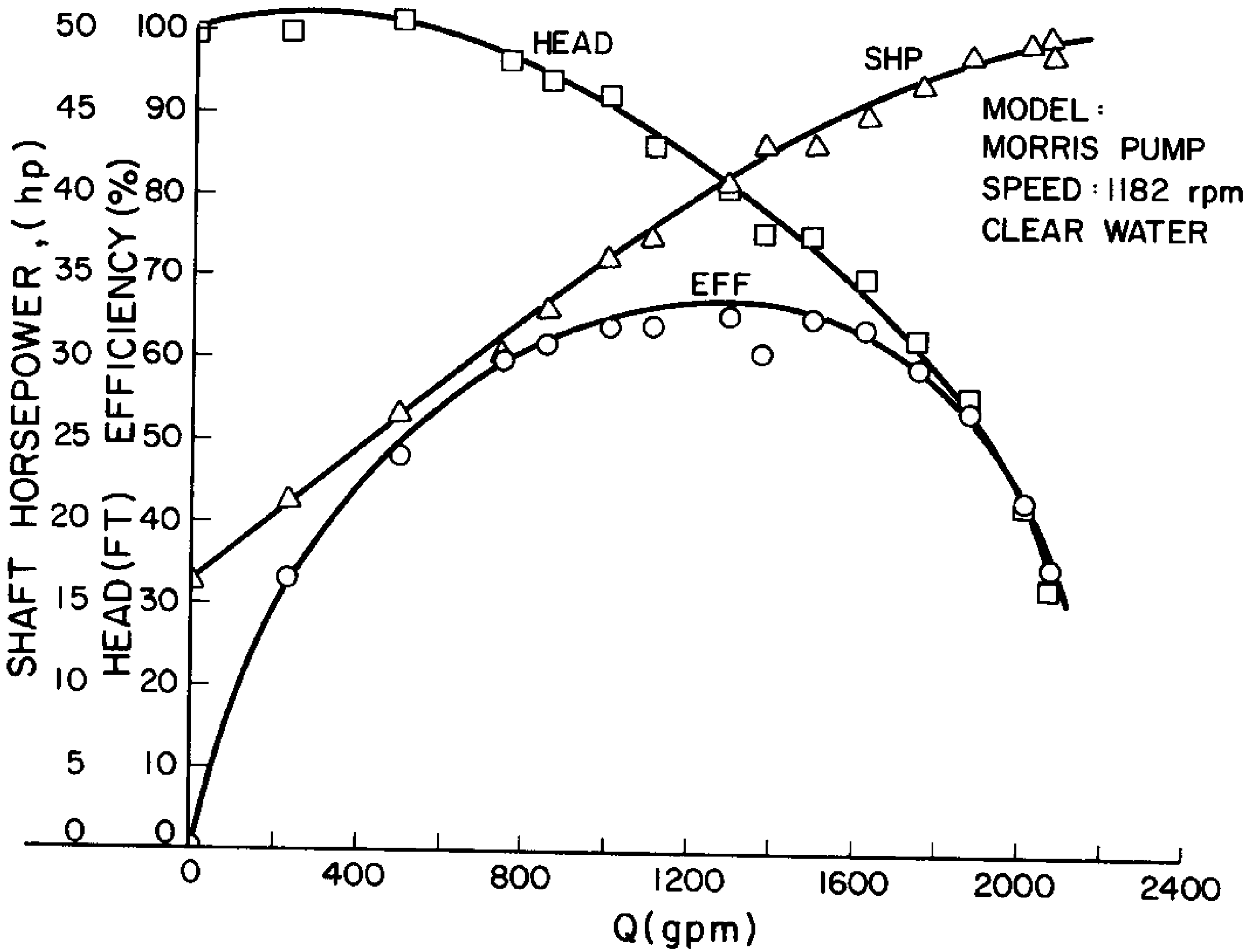


Fig. 2 MODEL DREDGE PUMP TESTS (TEXAS A&M UNIVERSITY)

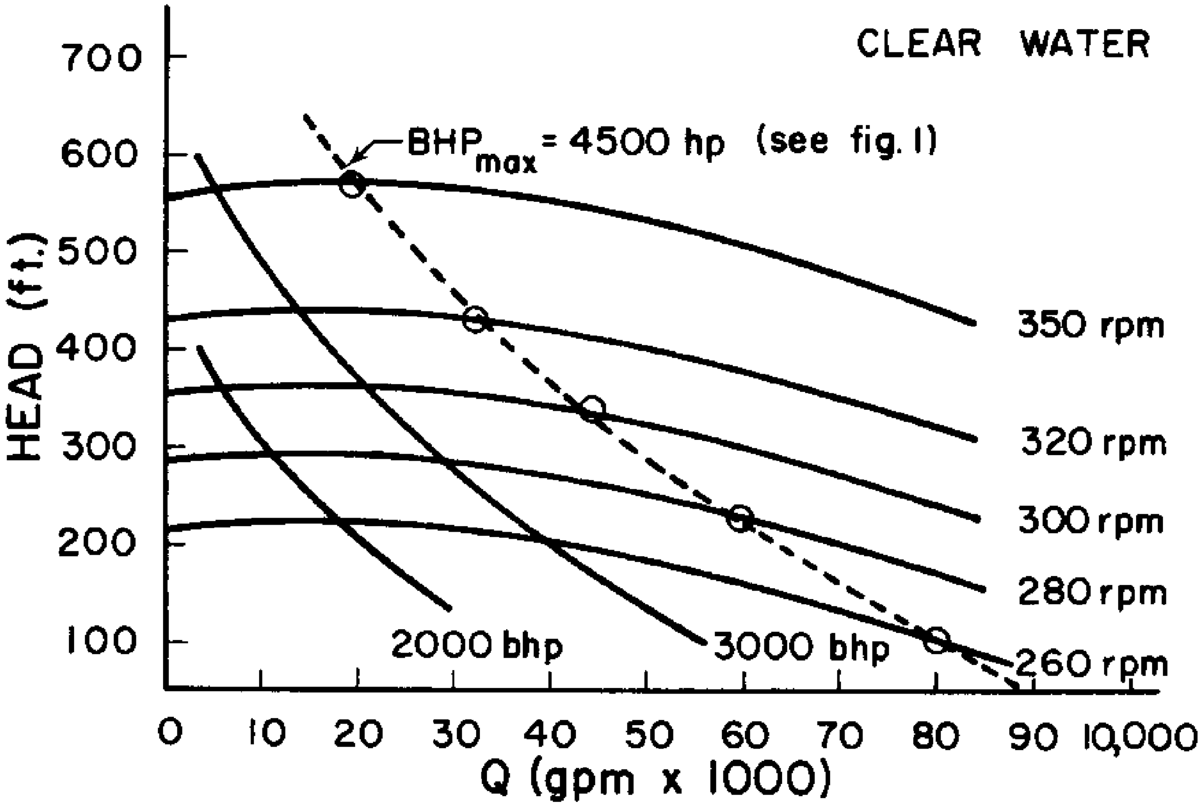


Fig. 3(a) SCALED-UP PROTOTYPE DREDGE PUMP CURVES

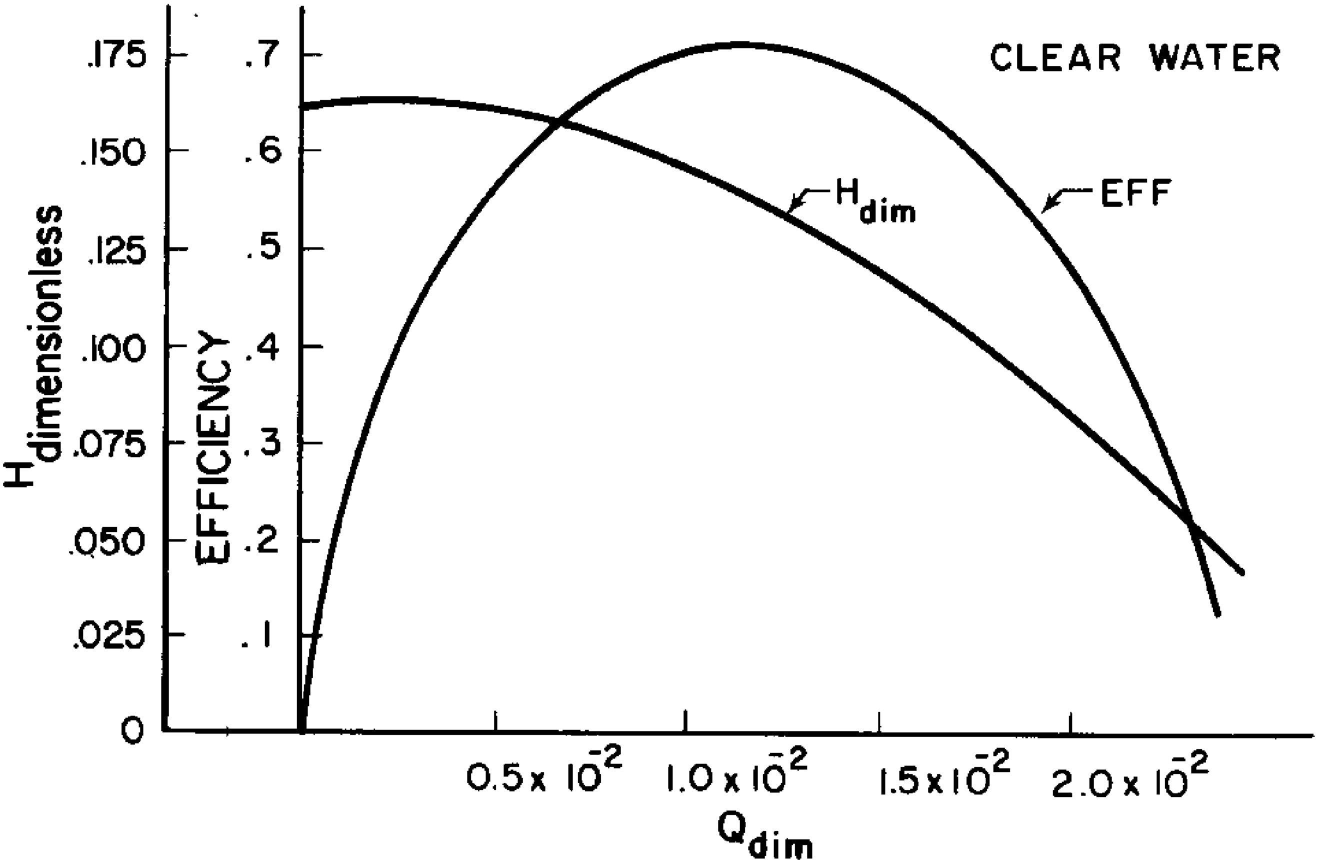


Fig. 3(b) DIMENSIONLESS DREDGE PUMP CURVES operating speeds can be readily established and output (in this case, clear water volume) is limited by the drive horsepower available. The various characteristic curves of Fig. 3(a) have been collapsed into a single dimensionless curve, Fig. 3(b) by the use of dynamic similitude relationships commonly called the "affinity laws". These "laws" only hold when cavitation is not present in the pump. The dimensionless head, H_{dim} is computed as gH/ω^2D^2 and dimensionless discharge, Q_{dim} is $Q/\omega D^3$, where:

ω = pump rotative speed, radians/sec
D = impeller diameter at discharge, feet
g = gravity constant, ft/sec^2

These dimensionless results for clear water can be readily employed in computer curve-fit programs to develop an equation for use with any similar pump operating on any speed in the non-cavitation regime. For example, the data shown in Figs. 2 and 3 produced the following equations for dredge pump head and efficiency as functions of flow rate:

$$H = (h_1+h_2Q_{dim} +h_3Q^2{}_{dim})\frac{\omega^2D^2}{g} \tag{1}$$

$$E = e_1+e_2Q_{dim}+e_3Q^2{}_{dim} \tag{2}$$

with the coefficients and variables as defined below

H = Dimensionless pump head
E = Pump efficiency
Q_{dim} = Dimensionless discharge
h_1 = 0.1620897 e_1 = 0.1042429

$h_2 = 0.683657$ $e_2 = 105.8745$

$h_3 = -239.4055$ $e_3 = -4421.454$

Slurry Effects

To be sure, the addition of solids to produce slurry flows through the pump complicates matters to some extent. In fact, all the influences of material concentration, size and distribution are not completely understood as of today. The type of pump as indicated by its specific speed is also thought to be important.

The pump will essentially reproduce its characteristic clear water head-capacity curve if the head is plotted in feet of mixture. However, the head and efficiency curves are slightly reduced due to the additional hydraulic losses caused by the presence of the solids in pump passages which waste their kinetic energy in the diffuser sections. Fig. 4(a) shows the results of tests of a model dredge pump conducted at Lehigh University by Herbich and Vallentine (2). The pump head expressed in feet of mixture and efficiency both drop off as the specific gravity of the mixture (volume concentration) increases. Stepanoff(3) studied the results of seven independent researchers throughout the world in 1965 and concluded that the efficiency when pumping solid-liquid mixtures is reduced as the ratio of the head reduction, i.e.

$$\frac{H_m}{H} = \frac{e_m}{e} \qquad (3)$$

where: H_m = head in feet of mixture,

e_m = efficiency when pumping a mixture,

H, e = same variables for clear water.

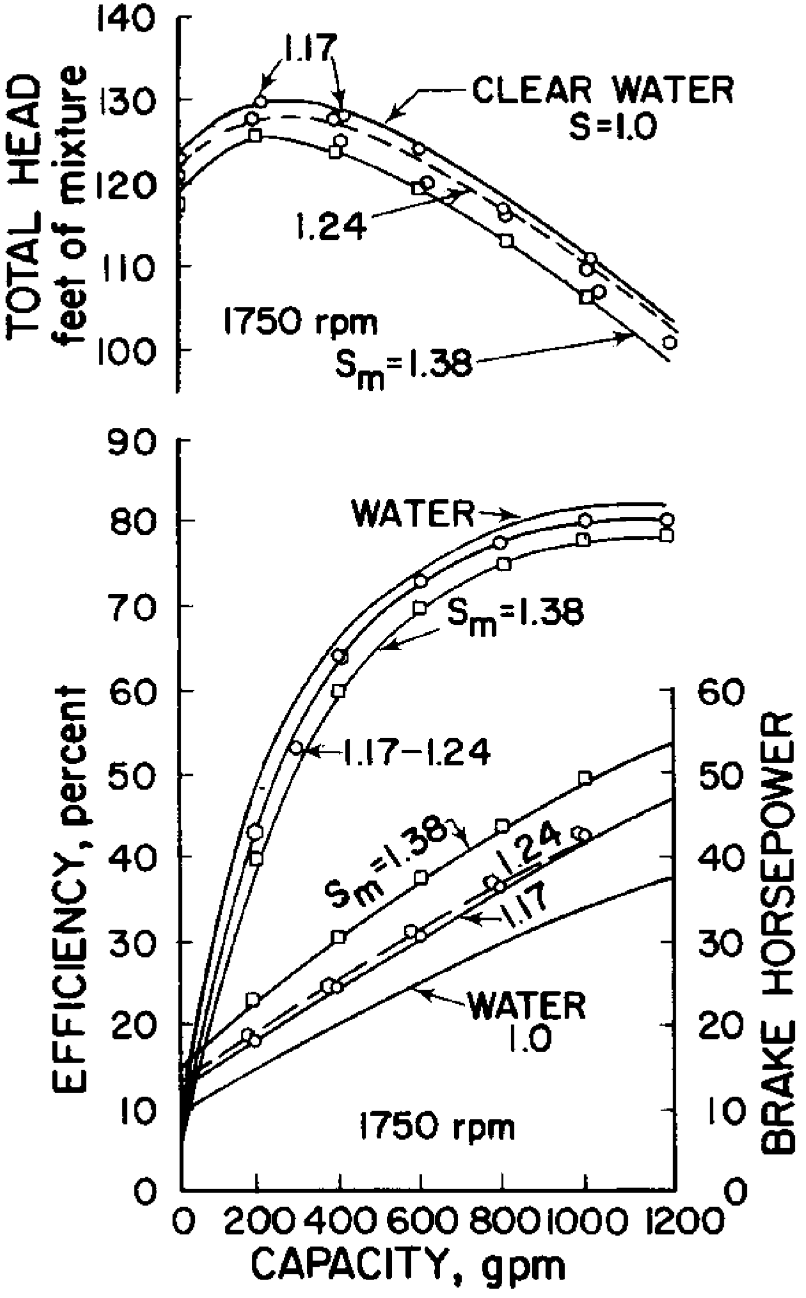


Fig. 4(a) EFFECTS OF DENSITY ON PERFORMANCE (REF. 2)

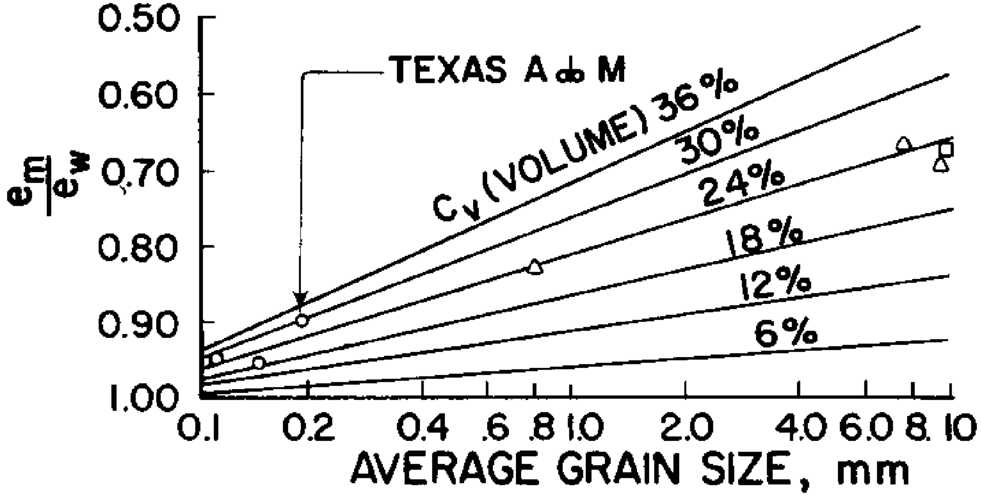


Fig. 4(b) RATIO OF EFFICIENCY MIXTURE TO EFFICIENCY WATER VERSUS GRAIN SIZE (COURTESY OF A. J. STEPANOFF - REF. 3)

The research efforts studied by Stepanoff covered a wide range of particle sizes and volume concentrations. From these results, he synthesized the plot also reproduced in Fig. 4(b) which enables one to estimate e_m/e for any volume concentration C_v and mean particle size of interest. These results can be collapsed into one equation for computer purposes and when coupled with the pump head equation above would permit the computation of the head developed in feet of mixture for any material size and concentration of interest. These results would then enable one to compute the shaft input power requirements when pumping slurry or even more simply from knowledge of the mixture specific gravity, S_m:

$$(BHP)_m = S_m \; (BHP)w \qquad (4)$$

A computer routine can then be developed to again compute the maximum pump flowrate Q_m and head developed H_m for all possible operating speeds as before, only in this case for slurries of a specified volume concentration (mixture specific gravity) and mean particle diameter. Again, the output is limited by the available drive horsepower as before in the clear water case. Fig. 5 illustrates these trends for both clear water and slurry solids output for the example pump data presented. The dotted lines show the effect of including the head and efficiency correction factors mentioned above for slurry flows. For the particular grain size material chosen, the plot clearly demonstrates the importance of the horsepower limitations on dredge pump output.

Recently, Wiedenroth (4) has also presented more evidence regarding the relationships between the head reduction for slurry pump flow and the volume concentration, particle size and type of pump as measured by its

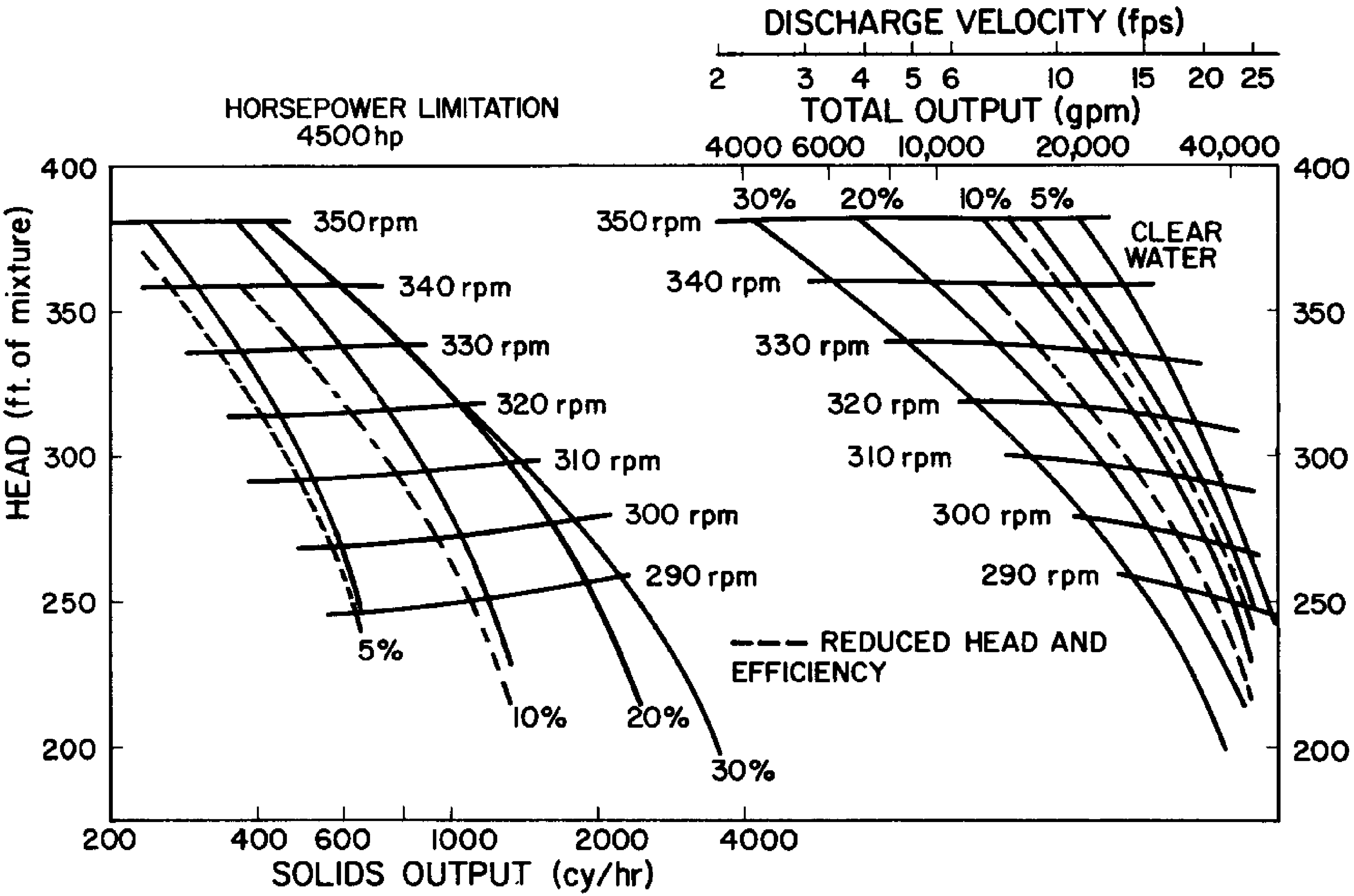

DISCHARGE VELOCITY (fps)
2
3
4
5
6
10
15
20
25
TOTAL OUTPUT (gpm)
4000
6000
10,000
20,000
40,000
HORSEPOWER LIMITATION
4500 hp
HEAD (ft. of mixture)
400
350
300
250
200
350 rpm
340 rpm
330 rpm
320 rpm
310 rpm
300 rpm
290 rpm
5%
10%
20%
30%
CLEAR WATER
REDUCED HEAD AND EFFICIENCY
SOLIDS OUTPUT (cy/hr)
200
400
600
1000
2000
4000

Fig. 5

specific speed. Using the combined results of his own work and others, he developed the following equation:

$$H_{dim} = 3.16 \times 10^{-4} \, C_v \, (R_e)_s^{\,1/3} \, (N_s)^{-2.46} \qquad (5)$$

where:

H_{dim} = a dimensionless head,

C_v = the volume concentration,

$(R_e)_s$ = the mean particle diameter Reynolds Number, and

N_s = the pump specific speed.

These results could also have been employed above instead of that expressed by Stepanoff (3). The two are obviously related and work is planned at the CDS to investigate these relationships and others. Field feedback information is also completely lacking in this important area.

The above discussion of dredge pump characteristic curves which culminates in determination of the horsepower limitations on output as illustrated in Fig. 5, clearly demonstrates the importance of one's knowledge of the actual (or estimated performance from homologous models) performance curves for dredge pumps. Unfortunately, current U. S. policy and practice in buying dredge pumps completely neglects the inclusion of certified pump test curves in the purchase specifications. Most dredge pumps have never been tested to determine their actual efficiency. Therefore, the first and primary prerequisite for solving the feedback problem is the complete testing and determination of the performance characteristics curves of the hydraulic dredge pumps in a particular system.

These curves (equations on computer) are then combined with the given pipeline configuration and system headloss computations to determine the maximum pumping distance (line length). This will be discussed in detail in a later section of this paper.

Dredge Pump Cavitation Curves

Equally as important as the characteristic curves are the pump cavitation curves or in other words, determination of the energy requirements on the suction side of the pump to prevent cavitation from influencing the pump performance. The curves are also neglected by the U. S. dredging industry when specifying the purchase of a dredge pump. They are, of course, required in determination of the maximum possible digging depth for a given dredge configuration, soil size and type, and transport concentration. Consequently, the cavitation limitation which results in maximum solids output for a given digging depth is the second limitation on system output that must be considered.

Clear Water

The cavitation curves of a particular pump can only be obtained by field or laboratory tests usually with clear water. The consequences of cavitation on the pump H-Q curve are illustrated in Fig. 6(a). At high cavitation intensities, the discharge rate is constant and the head drops to very low values. The pump sounds as if it were passing large rocks and boulders even though only clear water is used. Critical, "industrial" type cavitation values expressed as the net positive suction head above vapor pressure (NPSH) can be determined by experimental tests of the pump. NPSH is computed from the following equation and is the total absolute

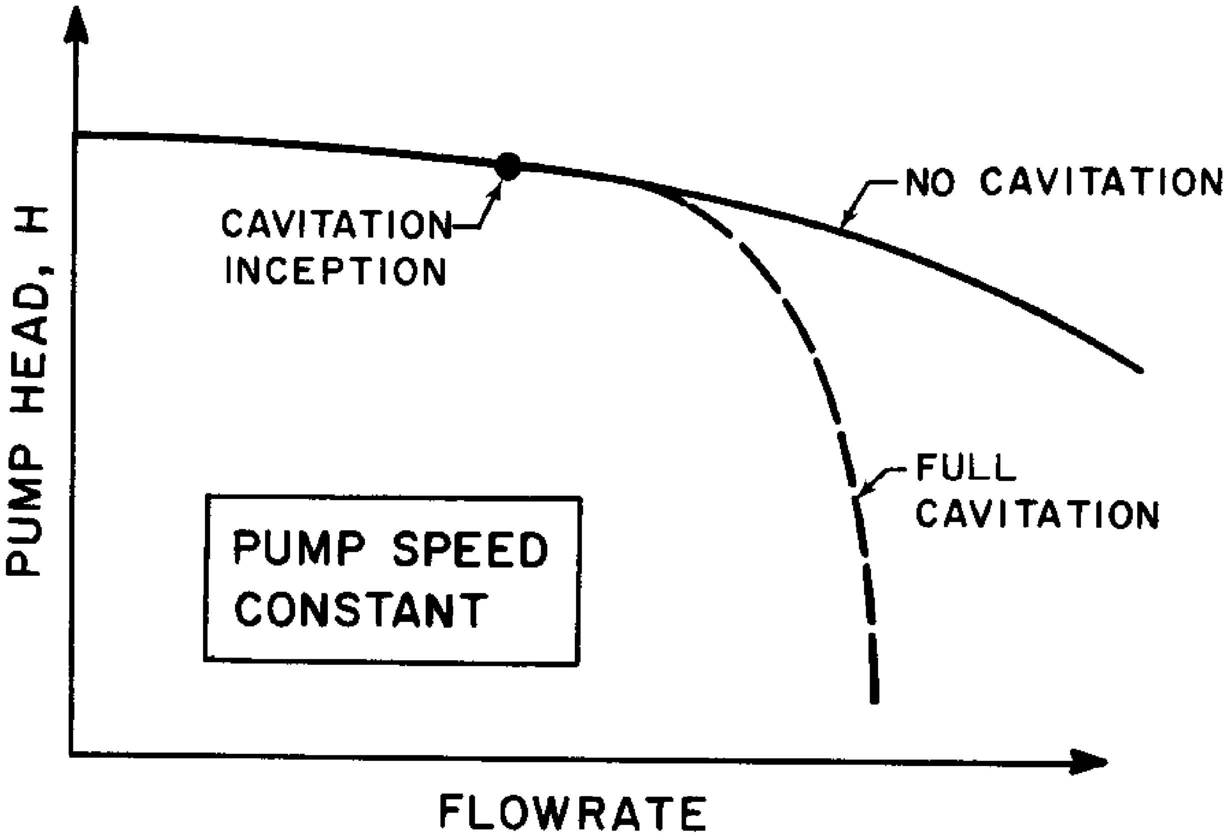


Fig. 6(a) EFFECT OF CAVITATION ON PERFORMANCE

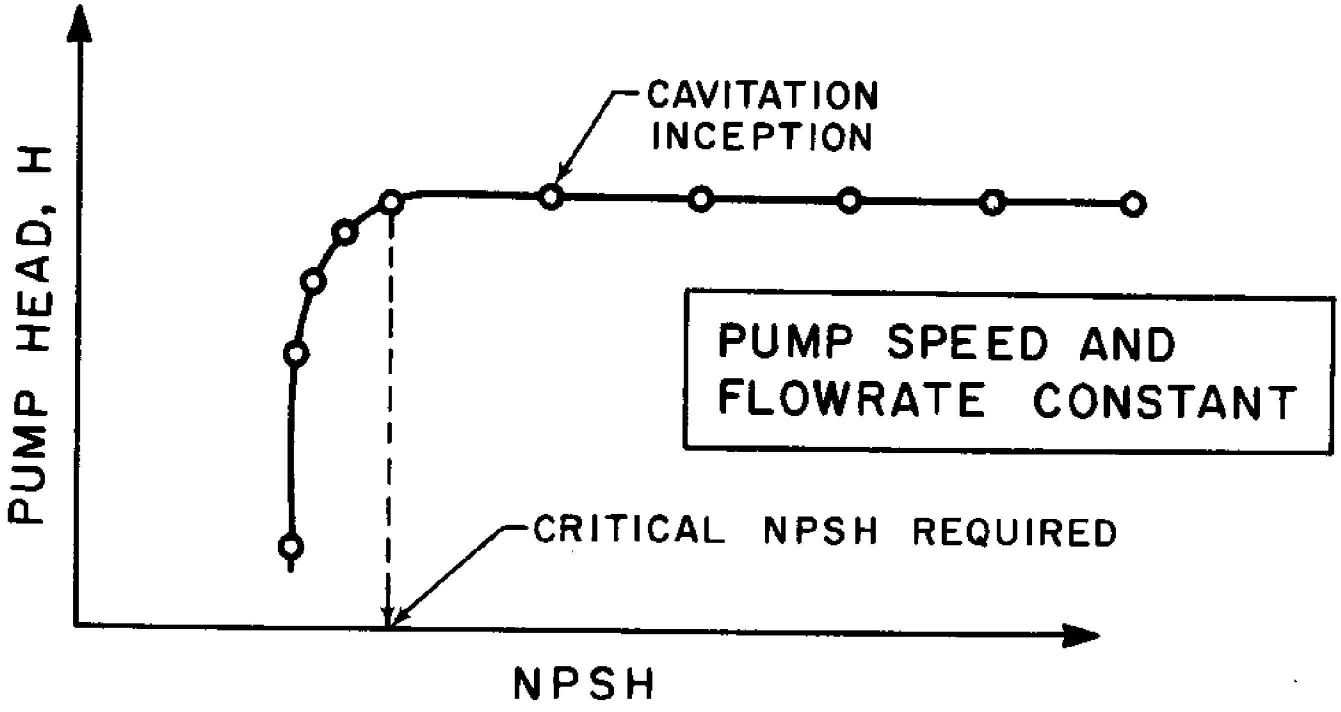


Fig. 6(b) TYPICAL CAVITATION TEST

amount of energy at the suction inlet expressed as head or foot-pounds per pound of liquid flowing.

$$NPSH = \frac{Pa}{\gamma} - \frac{Pvp}{\gamma} + (\frac{P}{\gamma} + \frac{V^2}{2g}) \qquad (6)$$

where: Pa = local barometric pressure,

Pvp = liquid vapor pressure,

γ = liquid unit weight,

P = pressure on suction side,

V = mean velocity at suction, and

NPSH = net positive suction head above vapor pressure.

The usual laboratory technique employed is to lower Pa until the pump head developed drops off. An enclosed head tank and vacuum pump are employed to regulate Pa. A given speed and flowrate are held constant during the test. The values of NPSH and H are plotted (Fig. 6(b)) and the value of NPSH "critical" to the proper performance of the pump is determined for this set of conditions. For low specific speed pumps (dredge pumps) the "break-off" in performance is usually not sharp and some predetermined drop in head (say 2%) is used as cut-off criteria. NPSH critical values are obtained for other flowrates and a critical cavitation curve developed. Fig. 7(a) and (b) illustrate some typical results, using a model dredge pump tested in the Texas A&M Laboratory. Critical NPSH is seen to increase with the flowrate. Higher operating speeds create increased velocities and require more NPSH to stifle cavitation. Dimensionless cavitation curves can therefore be developed to plot results for all speeds. Fig. 8 shows the results for the model pump of Fig. 1. The resulting equation developed from Fig. 8 for computer

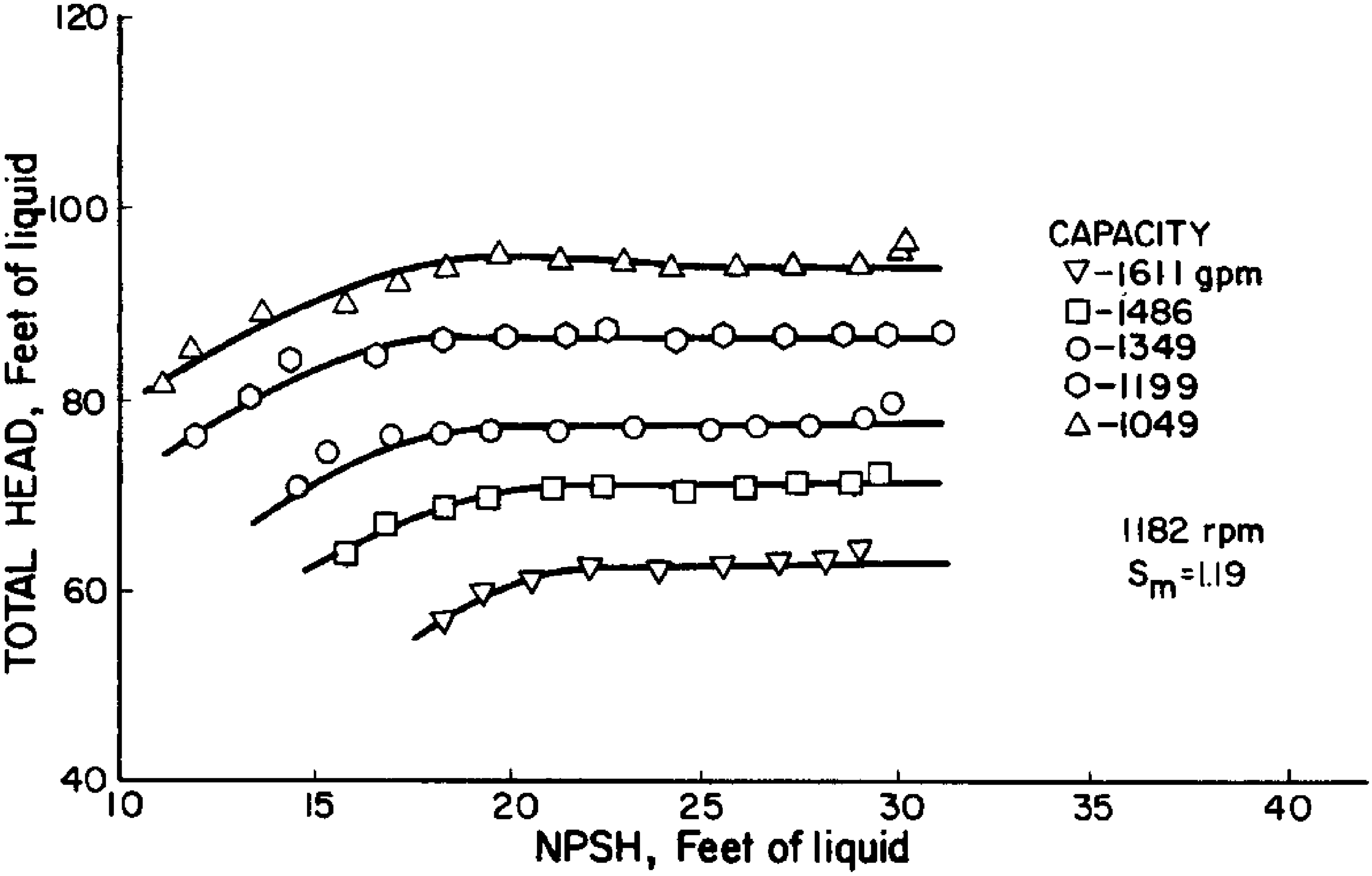


Fig. 7(a) NPSH CURVES AT FIVE FLOWRATES (TEXAS A&M)

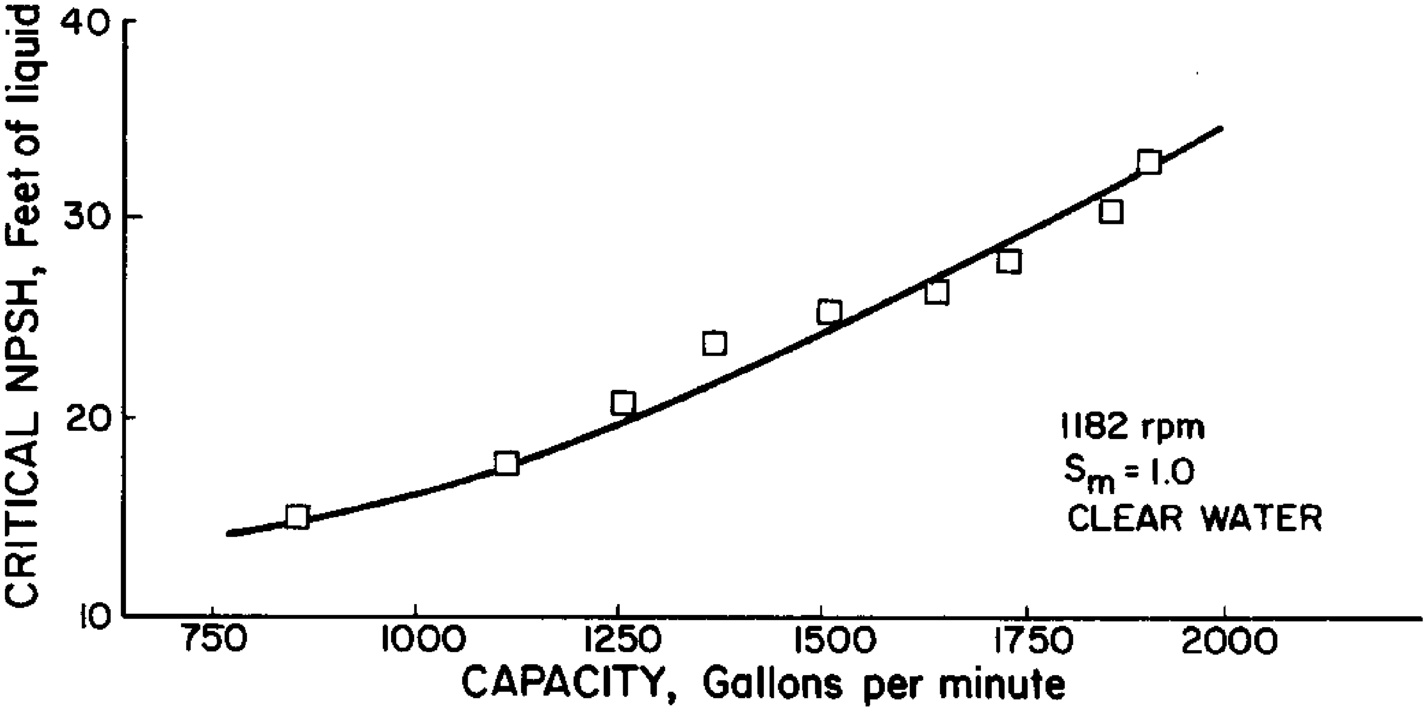
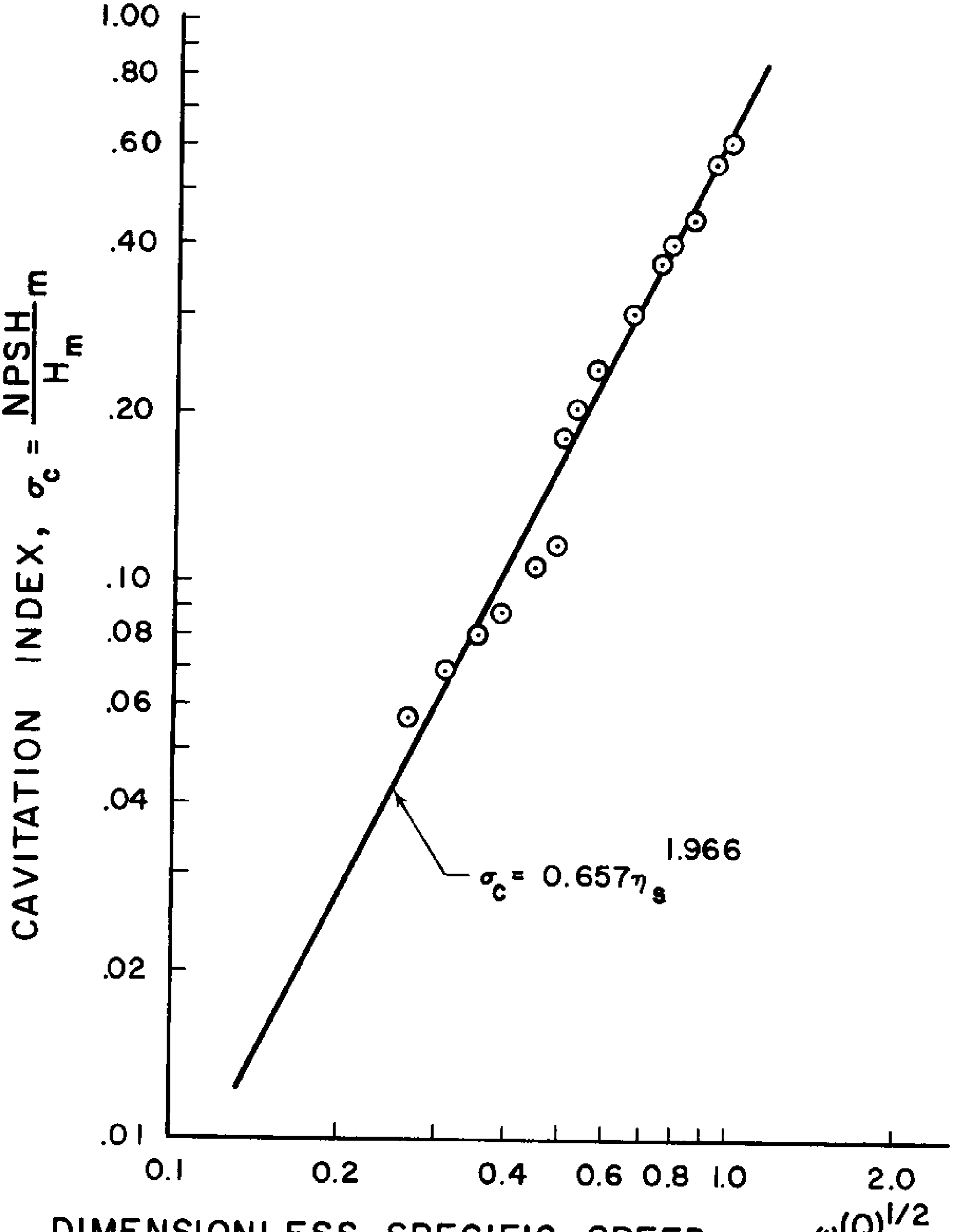


Fig. 7(b) TYPICAL NPSH "CRITICAL" CURVE (TEXAS A&M)



1.00
.80
.60
.40
.20
.10
.08
.06
.04
.02
.01
0.1
0.2
0.4
0.6
0.8
1.0
2.0
CAVITATION INDEX, $\sigma_c = \frac{NPSH_m}{H_m}$
DIMENSIONLESS SPECIFIC SPEED, $\eta_s = \frac{\omega(Q)^{1/2}}{(gH_m)^{3/4}}$
$\sigma_c = 0.657\eta_s^{1.966}$

Fig. 8

purposes is

$$\sigma_c = \frac{NPSH_m}{H_m} = 0.657\,\eta_s^{1.966} \qquad (7)$$

where:

σ_c = cavitation index

$NPSH_m$ = net positive suction head (ft. of mixture)

H_m = head (ft. of mixture)

η_s = dimensionless specific speed

Slurry Effects on NPSH

Very little information is available on the influence of solid particles in liquid-solid mixtures on cavitation effects in pumps. Tests at Lehigh (5) using silt-clay-water mixtures indicated slurries exhibited no difference in cavitation performance from clear water tests if the results are expressed in feet of mixture. Recent tests at Texas A&M (6,7) for larger sand particles (mean diameter 0.175 mm, 0.40 mm and 2.0 mm) also revealed no significant trend for densities from 1.0 to 1.4 (Fig. 9). Based on these results, it can tentatively be concluded that mixture density and size have little effect on the critical NPSH requirements for dredge pumps. Estimates of NPSH-required in feet of liquid for slurries can be made from clear water tests if the specific gravity of the mixture is known (Fig. 8).

To operate properly, the pump must be used in a system which provides enough energy (NPSH available) to keep the pump from cavitating. Hence, the suction system must be analyzed to determine the maximum digging depth in much the same fashion as the discharge system is analyzed to find the maximum pumping line length.

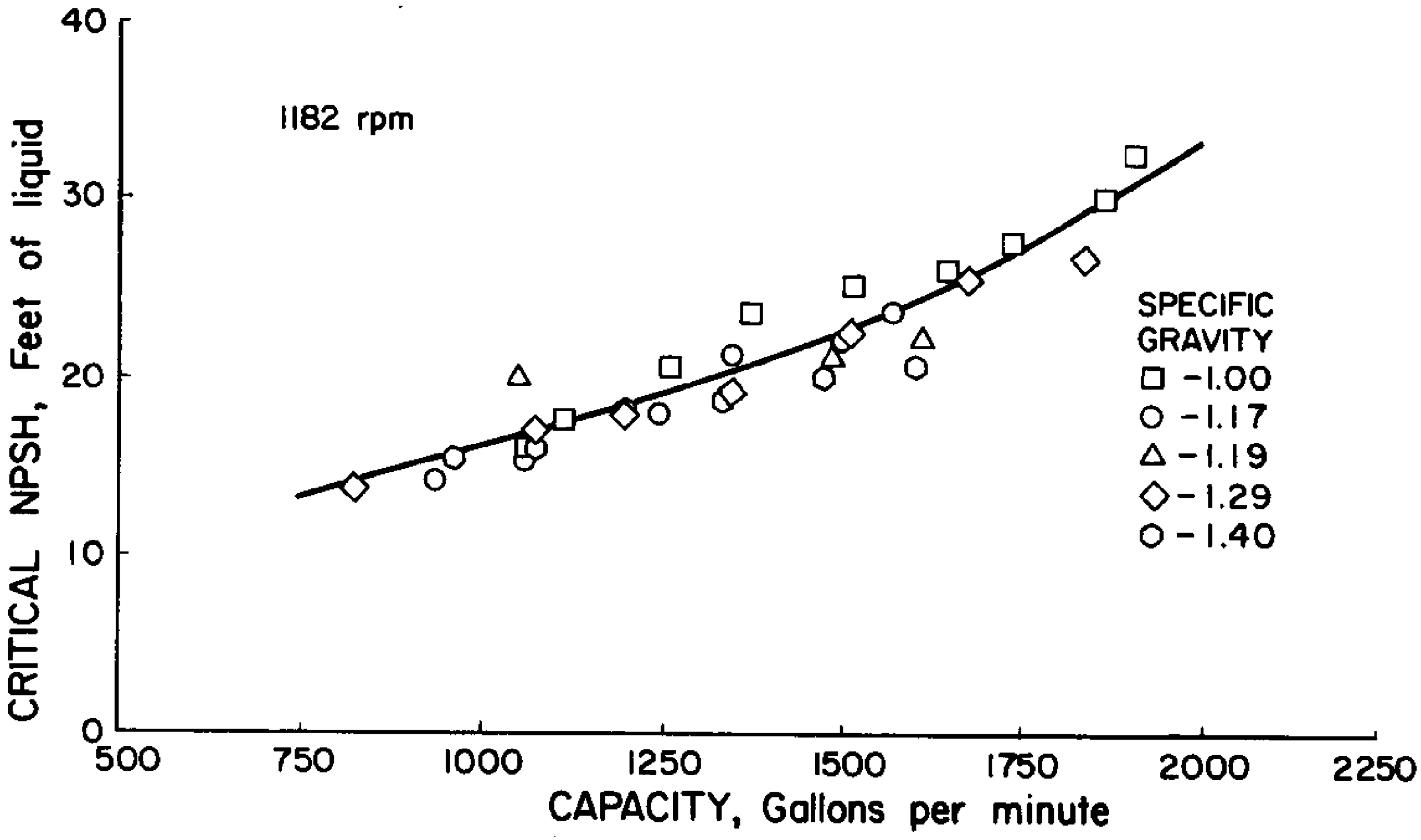


Fig. 9 EFFECT OF SPECIFIC GRAVITY ON NPSH CRITICAL (TEXAS A&M)

Dredge System Components and Analysis

If the basic work-energy equation in feet of mixture flowing is applied from point (0) to point (4) in Fig. 1, we would obtain

$$\frac{Vo^2}{2g} + \frac{Po}{\gamma} + Zo + Hp = \frac{V_4{}^2}{2g} + \frac{P_4}{\gamma} + Z_4 + H_{L_{1-2}} + H_{L_{3-4}} \qquad (8)$$

where the following terms are defined as:

$Vo^2/2g$ = reservoir velocity head, (approximately zero)

Po/γ = gauge pressure head at surface, (exactly zero)

Z_0, Z_4 = elevation heads at datum, (exactly zero)

Hp = total dynamic head developed by the pump,

$V_4{}^2/2g$ = discharge velocity head, (not zero but minor)

P_4/γ = gauge pressure head at pipe exit, (exactly zero)

$H_{L_{1-2}}$ = head loss in suction pipe system,

$H_{L_{3-4}}$ = head loss in discharge pipe system.

Note that in general minor elevation changes of pump and discharge pipe termination point could easily be included if required.

Using the above simplifications, the work-energy equation becomes

$$Hp = V_4{}^2/2g + H_{L_{1-2}} + H_{L_{3-4}} \qquad (9)$$

which means that the net total head developed by the pump must be used to overcome suction and discharge system pipe friction and developed minor losses and in providing the discharge velocity head.

Head Losses Due to Straight Pipe Friction

Clear Water

Current U. S. engineering practice employs the use of the Darcy-Weisbach equation

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad (10)$$

to compute the head loss due to friction h_f in a straight circular pipe, where:

f = friction factor = fcn (Re, k/D), from Moody Diagram,

L = pipe length,

D = pipe diameter,

$Re = VD/\nu$ = pipe Reynolds No.,

ν = kinematic viscosity, and

k = absolute pipe roughness.

Colebrook (8) developed the following equation from experimental results for the pipe friction factor, f, for any pipe flow of known roughness, k, and Reynolds No., Re.

$$1/\sqrt{f} - 2 \log D/k = 1.14 - 2 \log \left[1 + \frac{9.28}{Re(k/D)\sqrt{f}}\right] \qquad (11)$$

A trial and error solution is required and can be readily adapted for computer solution. The above two equations permit the computation of the pipe head loss for clear water for a given pipe size and roughness, flowrate, and pipe length.

Slurry

The head loss for water and solids (slurry) is larger than the head loss for clear water. Equations have been developed by empirical means to permit computation of the slurry head loss in pipes. Graf (9) recently presented an excellent summary of the current state of knowledge in this area as of 1971. The equation employed depends upon the particular flow regime present in the pipe. Fig. 10 depicts the various flow regimes (defined below) and transition velocities for a 27 inch pipe.

1. Pseudohomogeneous Flow - Solid particles with a settling velocity above 0.002 to 0.005 ft/sec which never settle out and become fully suspended in the liquid and are essentially uniformly distributed over the entire pipe cross section.
2. Heterogeneous Flow (no deposit) - Flow in which the concentration varies with depth over the pipe cross section but no particles can remain on the bed.
3. Heterogeneous Flow - With a Moving Bed - Heterogeneous flow with particles settling to the bottom but continuing to move down the pipe.
4. Flow with a Stationary Bed - Slurry flow continues to take place; however, some particles settle out and remain stationary as a deposit on the bottom.

The head loss equations that best represent flow in each regime along with the expressions describing the velocity that separates each regime are tabulated in Table II below after Graf (9).

Equations (13) and (14) in Table II require knowledge of the particle settling velocity, v_{ss} which must be obtained by experiment. Fig. 12 duplicates the results of many experiments with irregular shaped sand grains commonly dredged (9). The settling velocities fall into three distinct regions:

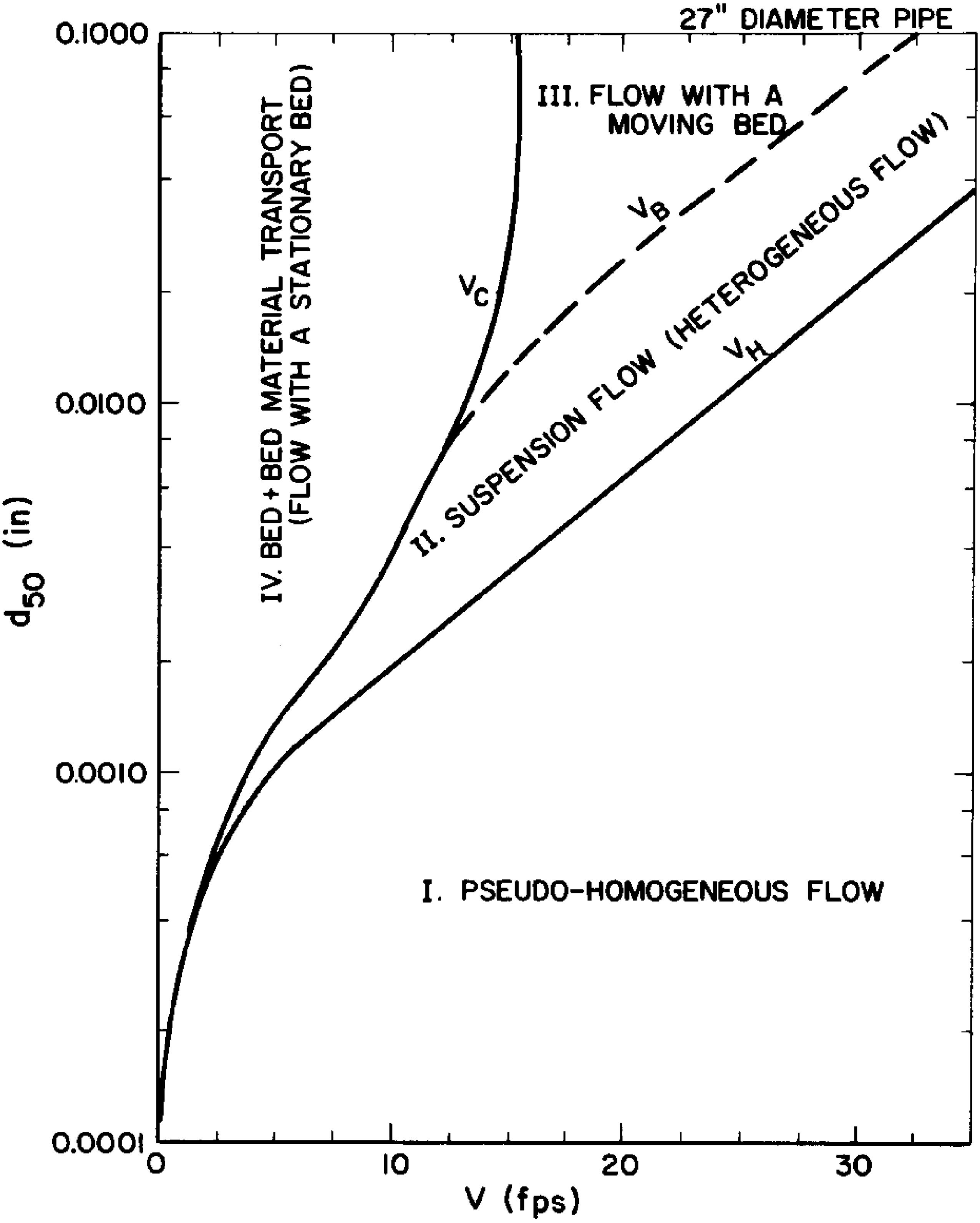

27" DIAMETER PIPE
0.1000
0.0100
0.0010
0.0001
0
10
20
30
V (fps)
d_{50} (in)
IV. BED + BED MATERIAL TRANSPORT (FLOW WITH A STATIONARY BED)
III. FLOW WITH A MOVING BED
II. SUSPENSION FLOW (HETEROGENEOUS FLOW)
I. PSEUDO-HOMOGENEOUS FLOW
V_C
V_B
V_H

Fig. 10

TABLE II

EQUATIONS TO COMPUTE SLURRY FLOW HEAD LOSS IN STRAIGHT, CIRCULAR PIPES

Regime	Head Loss and Boundary Velocity Equation	Author [See Graf (9)]
I Pseudohomogeneous Flow, $V > V_H$	$\bar{\Phi} = (S_s-1)$ (12)	Graf
V_H	$V_H = \sqrt[3]{1800 g v_{ss} D}$ (13)	Newitt et al.
II & III Heterogeneous Flow, $V_c < V < V_H$	$\bar{\Phi} = 1100\ (S_s-1)\frac{v_{ss} gD}{V\ \ V^2}$ (14)	Newitt et al.
V_c	$V_c = F_L \sqrt{2gD(S_s-1)}$ (15) $F_L = f(d,c)$ See Fig. 11	Durand
IV Flow with Stationary Deposit	$\frac{CVR_h}{\sqrt{S_s-1}\ gd^3} = 10.39\ \left[\frac{(S_s-1)d}{SR_h}\right]^{-2.52}$ (16) $\frac{V}{\sqrt{4\ R_n g}} = \frac{V_c}{\sqrt{Dg}}$ (17)	Graf-Acaroglu

where $\bar{\Phi} = \frac{(\Delta h/\Delta L)_m - (\Delta h/\Delta L)_1}{C\ (\Delta h/\Delta l)_1}$ = dimensionless head loss coeff. (18)

$(\Delta h/\Delta L)_m$ = head loss per unit distance for mixture expressed in feet of clear water

$(\Delta h/\Delta L)_1$ = head loss per unit distance for clear water (see above Darcy-Weisbach Eqn)

C = volume concentration of solids.

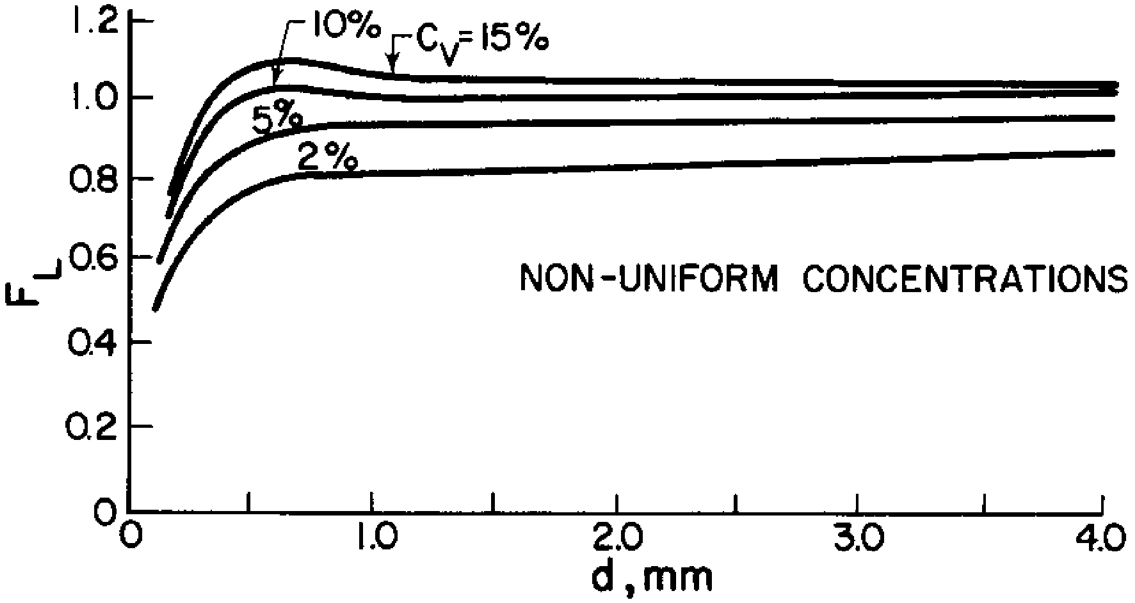


Fig. 11 F VALUE -VS- PARTICLE DIAMETER, FOR VARIOUS CONCENTRATIONS (REF. 9)

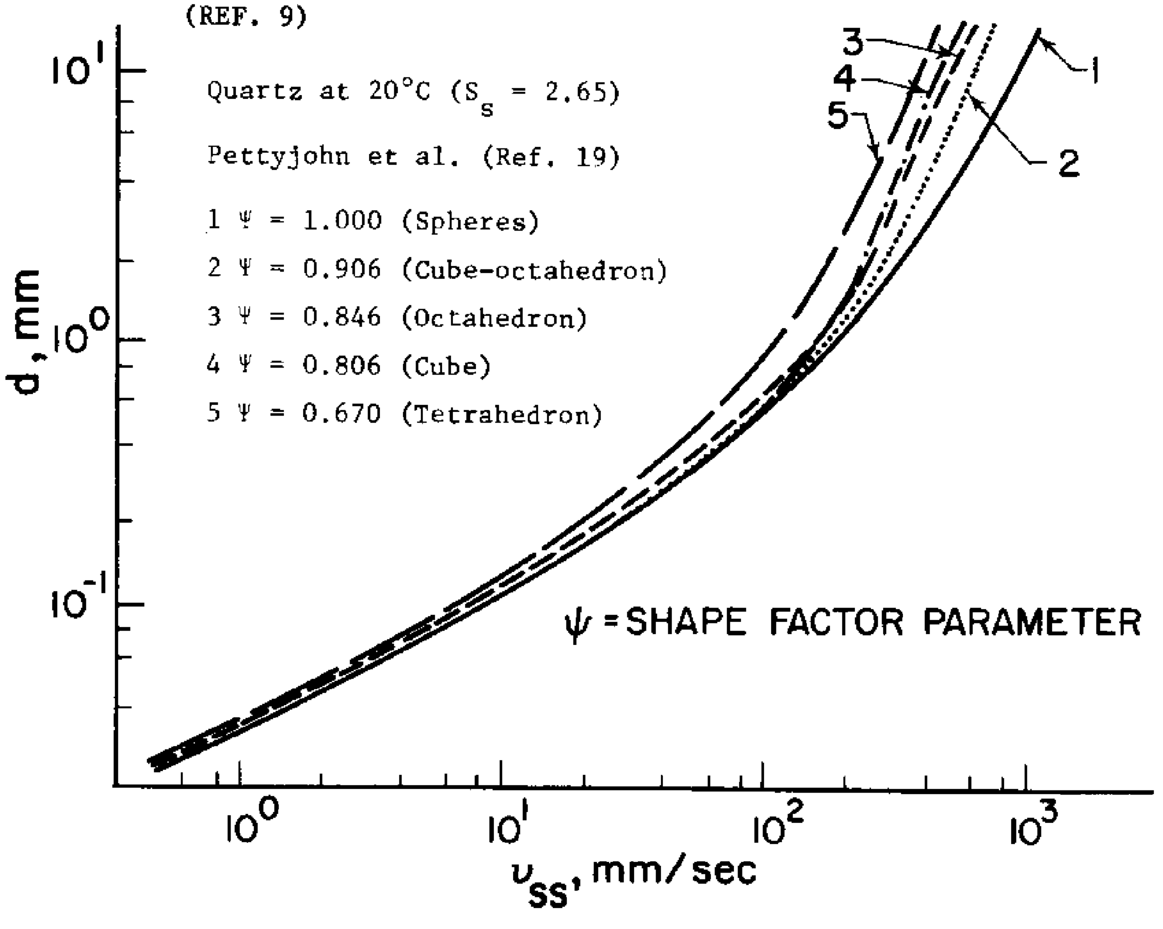


Fig. 12 SETTLING VELOCITY -VS- PARTICLE DIAMETER, VARIOUS EQUATIONS (REF. 9)

1. Laminar Flow $d < 0.006$ in. (0.074mm)

$$v_{ss} = [g d_{50}^2/18\nu]\ (S_s-1) \qquad (19)$$

2. Transition Regime 0.006 in. $< d < 0.06$ in. (0.074mm-2.0mm)

3. Turbulent Settling $d > 0.06$ in. (2.0mm)

$$v_{ss} = 87\ \sqrt{d(S_s-1)} \qquad (20)$$

In addition, the critical transition velocity, V_c between heterogeneous flow and flow with a stationary deposit requires the use of a special plot for F_L (Fig. 11) which was developed by Durand (10) and discussed in detail by Graf (9).

All terms in Table II and Figs. 11 and 12 are defined below:

Ss = specific gravity of solids,

v_{ss} = particle settling velocity,

D = pipe diameter,

d = mean d_{50} particle diameter,

V = velocity

V_H = transition velocity, homo. to heterogeneous

V_C = transition velocity, heter. to deposit with stationary bed

R_h = hydraulic radius, A/P defined as the ratio of the cross sectional area in which the flow takes place to the wetted perimeter

S = slope of energy grade line = $(\Delta h/\Delta L)_m$

hence
$$V/\sqrt{4gRh} = V_c/\sqrt{gD} \qquad (21)$$

As an example, a sand-water mixture flows through a horizontal steel pipe with a 27 inch diameter. The granulometric curve of the sand analysis indicates that it is a fairly uniform material with a size of d_{50} = 0.42 mm. (0.017 inches, no. 40 sieve is transition from medium to fine sand). Of interest is the computation of the head loss per unit pipe length of the slurry mixture for volumetric transport concentrations up to Cv = 30 percent and for mixture velocities up to V = 35 ft per second. The resulting numerical values are tabulated in Table III and subsequently plotted in Fig. 13. For each flow regime, the different head loss relations as listed in Table II have been employed. The computations are greatly facilitated by use of a high-speed digital computer. Similar curves are required for the 34 inch diameter suction pipe. Of primary interest is the point of minimum head loss at the critical velocity region.

Other "Minor" System Head Losses

Between points (1) and (4) in Fig. 1, i.e., throughout the dredge system, there exist a number of features which contribute additional head losses. These are listed in Table IV along with representative ranges of loss coefficient, or equivalent pipe lengths and reference to their source. These coefficients are based on clear water tests. Additional tests are required to investigate the influence of slurry mixtures on the estimates shown and to determine actual values for those dredging components actually employed (rubber suction sleeves, stern swivels, etc.). Field tests would prove more valuable in these instances. The equivalent pipe length, L_{equiv} is the length of straight pipe that would produce an equivalent head loss of the component considered.

TABLE III

HEAD LOSS PER UNIT LENGTH FOR DIFFERENT VELOCITIES AND CONCENTRATIONS

C,% V, fps	0	2	5	10	20	30	Regime
1		.1163	.2019	.3017	.4344	.5103	
2		.0664	.1152	.1721	.2479	.2912	
3		.0478	.0830	.1240	.1785	.2097	
4		.0379	.0657	.0982	.1414	.1661	
5		.0316	.0549	.0820	.1180	.1387	$V_c > V$
6		.0273	.0473	.0707	.1019	.1196	
7		.0241	.0418	.0624	.0899	.1056	Flow with stationary bed
8		.0216	.0375	.0560	.0807	.0948	
9		.0196	.0341	.0509	.0734	.0861	
10		.0180	.0313	.0468	.0674	.0791	
11		.0167	.0290	.0433	.0624	.0732	
12		.0150	.0270	.0404	.0581	.0683	
13		.0170	.0253	.0378	.0545	.0640	
14		.0190	.0229	.0356	.0513	.0603	
15		.0212	.0249	.0310	.0485	.0570	
V_c		11.40	13.33	14.80	15.94	15.94	V_c
16		.0235	.0270	.0328	.0444	.0559	
17		.0264	.0297	.0350	.0462	.0572	
18		.0292	.0324	.0371	.0480	.0584	
19		.0320	.0351	.0398	.0498	.0597	
20		.0350	.0378	.0424	.0517	.0609	$V_c < V < V_H$
21		.0385	.0413	.0456	.0546	.0634	
22		.0421	.0447	.0489	.0575	.0659	Heterogeneous Flow
23		.0456	.0482	.0521	.0604	.0684	
24		.0493	.0516	.0555	.0632	.0709	
25		.0535	.0558	.0595	.0609	.0744	
26		.0578	.0599	.0635	.0707	.0779	
27		.0621	.0641	.0675	.0744	.0813	
28		.0663	.0683	.0716	.0782	.0848	
V_H		28.09	28.09	28.09	28.09	28.09	V_H
29		.0690	.0723	.0778	.0889	.0999	
30		.0738	.0773	.0832	.0950	.1068	
31		.0787	.0825	.0888	.1013	.1139	$V > V_h$
32		.0838	.0878	.0945	.1079	.1212	
33		.0890	.0933	.1003	.1146	.1288	
34		.0944	.0989	.1065	.1215	.1366	
35		.1000	.1047	.1127	.1287	.1446	

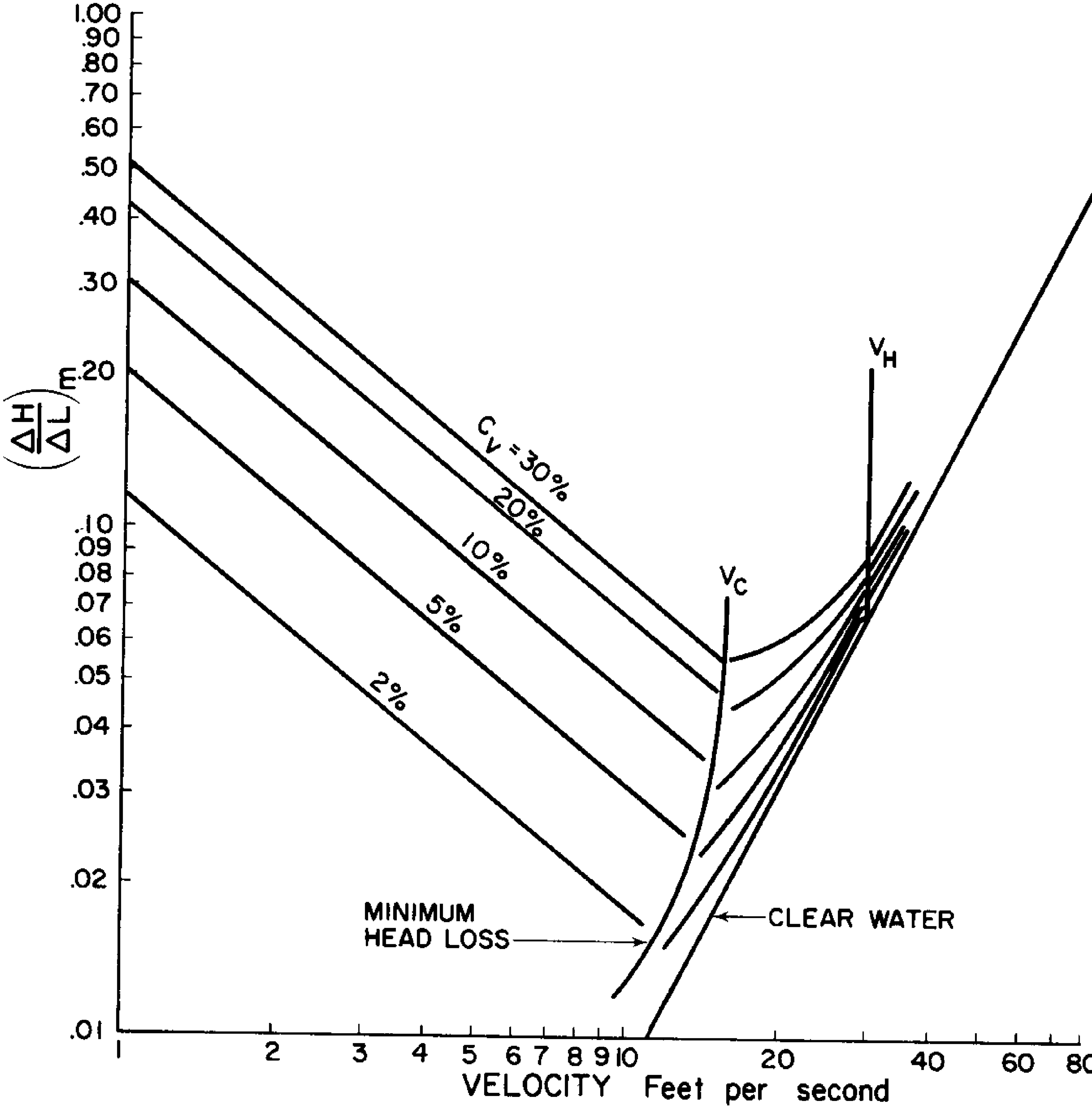


Fig. 13 SLURRY HEAD LOSS PER UNIT LENGTH (27 in. pipe)

TABLE IV

"MINOR" SYSTEM LOSS COEFFICIENTS FOR DREDGING

System Component	$K_L = \frac{h_L}{V^2/2g}$	$\frac{L_{equiv}}{D}$	Reference (Remarks)
Suction Entrance*			
Cutter with flare opening			Unknown
Plain-end suction	1.0		Crane (13)
Rounded suction	0.05		Crane (13)
Dragheads	varies		WES Rept. (11)
Nozzle	5.5		Salzman (12)
Oval	1.0		Salzman (12)
Funnel	0.10		Salzman (12)
Pear	0.02		Salzman (12)
Elbows			
Long radius-suction	0.60	20	Crane (also depends on pipe diam.) (13)
45° elbows	0.4	15	
90° elbows	0.9	35	
Stern Swivel	1.0	40	Estimated
Ball Joints			
Straight	0.1	5	
Medium cocked	0.4-0.6	20-30	Rose (14)
Fully cocked (17°)	1.1	50	
Wedge Joints			Unknown
End Section	1.0		

* Dependent on distance from suction opening to bottom; suction angle, etc. (12)

NPSH Available in the Dredging System

The amount of Net Positive Suction Head, NPSH, available in the dredging system must always be greater than that required by the pump in order to prevent cavitation damage and excessive performance reduction. It can be computed by simply applying the energy equation in feet of slurry mixture flowing and absolute terms from the suction inlet to the suction side of the pump (i.e., from point 1 to point 2 in Fig. 1). Using the example in Fig. 1, the energy equation becomes

$$\frac{P_1}{\gamma m} + \frac{V_1^2}{2g} + \frac{Z_1}{Sm} = \frac{P_2}{\gamma m} + \frac{V_2^2}{2g} + Z_2 + h_{L_{1-2}} \qquad (22)$$

But in absolute energy terms above vapor pressure

$$P_1/\gamma m = Pa/\gamma m - Pvp/\gamma m + D/Sm \qquad (23)$$

where D is the digging depth. Taking the datum at point 1 and substituting Eq. (23) into (22) we obtain after some rearranging

$$P_2/\gamma m + V_2^2/2g = Pa/\gamma m - Pvp/\gamma m + D/Sm - Z_2 - h_{L_{1-2}} \qquad (24)$$

The sum of $P_2/\gamma m$ and $V_2^2/2g$ is the total NPSH available at the suction entrance in feet of slurry to the pump, and since $Z_2 = D$ in this simple example, we obtain

$$NPSH_{avail} = Pa/\gamma m - Pvp/\gamma m - D + D/S_m - h_{L_{1-2}} \qquad (25)$$

Obviously, the critical factors reducing the amount of $NPSH_{avail}$ to stifle cavitation are the digging depth, D, the mixture concentration or specific gravity, S_m, and the head losses on the suction side of the pump. In fact, increased digging depths also require longer suction pipe lengths which cause increased friction losses and greater head loss.

IV. Limitations of Hydraulic Dredging Systems

A considerable amount of detailed information has been reviewed in the previous section in order to develop the building blocks required for a complete understanding of the four basic limitations on performance of hydraulic dredging systems. These limitations are discussed separately below.

Horsepower Limitation (Output -vs- Line Length)

The maximum head developed by the pump for various slurry concentrations is limited by the horsepower available as shown in Fig. 5. These results can be combined with Eq. (9) and the head loss equations of Table II to relate dredge output to equivalent total line length, ELL. In other words, the total head loss per equivalent unit length of pipe as a result of straight pipe friction and other system losses is computed from the equations in Table II and Table IV for slurries of various concentrations. These values are then used to compute the actual head loss for various typical expected pumping distances. Using Fig. 5 and Eq. (9) in combination, the output is then determined which can be pumped over this equivalent line length. The results when plotted as shown in Fig. 14 are very similar to Fig. 5 except ELL has replaced the pump head H. Note also that for each slurry concentration considered, an optimum condition is obtained corresponding to the peak of each concentration curve which results in the maximum possible solids output for the maximum possible line length (pump distance). This optimum point, of course, corresponds directly to the minimum head loss point as noted in Fig. 13.

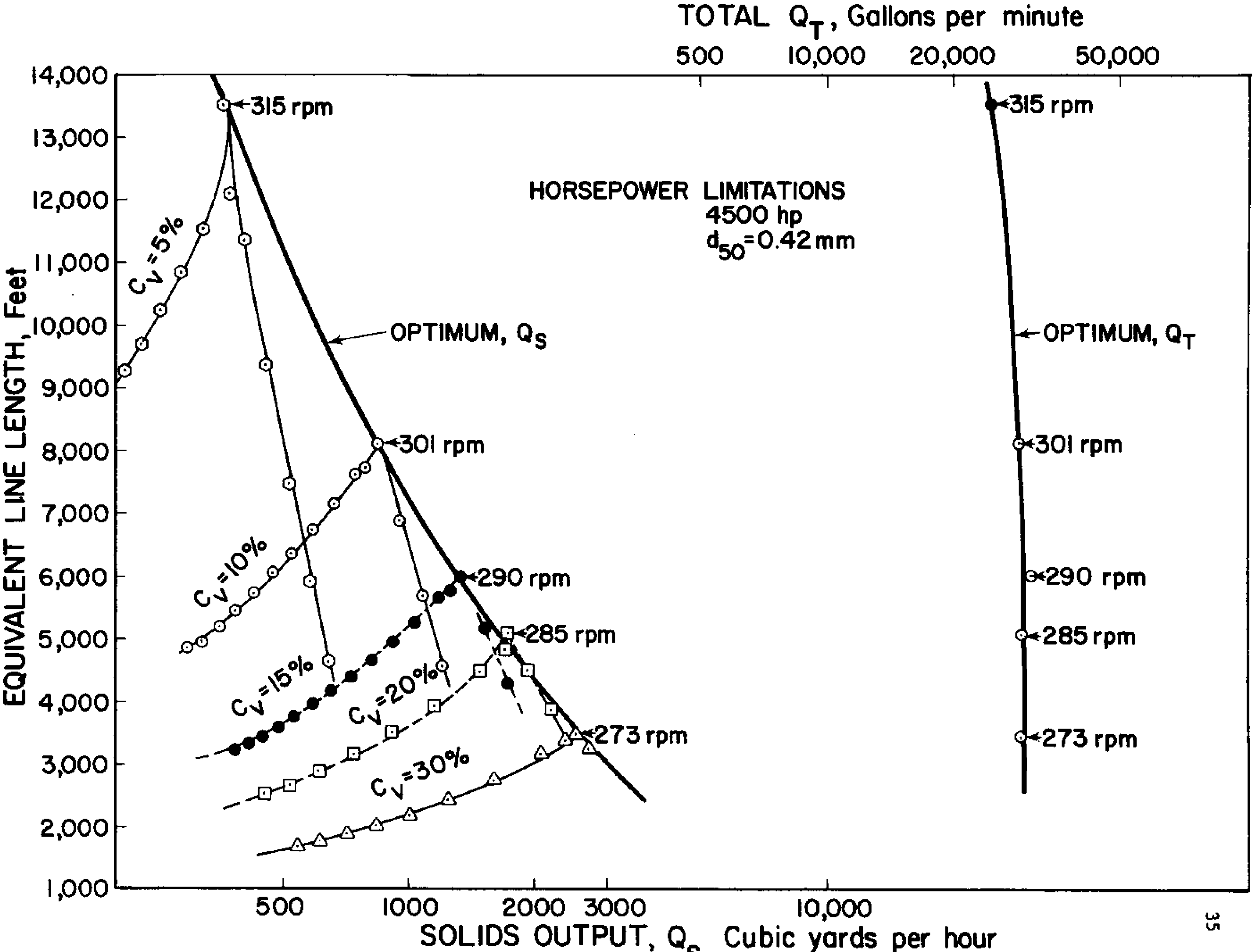


Fig. 14 DREDGE OUTPUT LIMITED BY DRIVE HORSEPOWER AVAILABLE

The envelope curve connecting up these optimum operation points therefore becomes the maximum output curve as governed by the horsepower limitation of the drive system for the dredge pump. It can be noted in Fig. 14 that as the line length increases, more pump head is required to overcome pipe friction and therefore the pump speed must increase. In addition the volume concentration pumped must be reduced to lower the slurry head loss per unit foot to overcome the required pressure drop in the longer line lengths. Consequently, less solids output is produced when pumping long distances even though the total volumetric flowrate, Q drops off only slightly.

The envelope curve of results shown in Fig. 14 was first discussed by Turner (15) who plotted the output and line length in reverse order. The results are limited to a given soil size, dredging system, and drive horsepower.

Again, use of digital computers greatly facilitate the trial and error computations that are required.

Cavitation Limitation (Output -vs- Maximum Digging Depth)

Since the $NPSH_{avail}$ must be greater than or equal to that required for proper pump performance, and the digging depth primarily determines that available for various slurry concentrations as seen in Eq. (25), then the maximum digging depths to produce the maximum dredge output can be calculated in a similar fashion to the line length versus output plots in Fig. 14. The computation would proceed as follows. From Fig. 14, the total slurry output in gallons per minute would be determined for the various operating speeds and slurry concentrations limited by the available drive horsepower. From this information and the NPSH requirements as indicated in Fig. 8, the required NPSH would be determined. Setting this value equal to the NPSH available in Eq. (25) and using the local vapor pressure and atmospheric pressures; the required slurry concentration (Sm); and computing the head losses using the equations and methods previously discussed in Tables II and IV, the maximum allowable digging depth can be determined by trial and error. Even though the optimum speed decreases as maximum output increases the maximum digging depth will decrease with increasing output due to the relatively greater increases in volume concentration transported.

For the example considered in Fig. 1, these computations have been made on the computer and are tabulated in Table V and plotted in Fig. 15. Again, because of the complexities of the computations, the results are greatly speeded up by previous programming of a computer. The significance of the results shown in Fig. 15 are simple. The maximum slurry output is limited by the maximum digging depths shown. For greater digging depths, the output (solids concentration) must be reduced to prevent cavitation in the pump. Or, as seen in Figs. 6(a) and (b), the pump output performance as measured by head developed or flow delivered drops off rapidly when the NPSH required (or equivalent maximum digging depth) limits are exceeded.

The combined results of both the horsepower and cavitation limitations are shown in Fig. 16 for selected digging depth intervals. When digging at a given depth, maximum output is limited (for the range of pumping distance indicated) to a constant value which then decreases due

TABLE V EXAMPLE PROBLEM RESULTS: HORSEPOWER & CAVITATION LIMITATIONS

Pump Speed N	Q Maximum				Velocity		Pump Head Developed H	Pump Eff. Eff.	Maximum Digging Depth D	Equivalent Line Length ELL
	Solids Only		Total Slurry		Suction V_s 34"	Disch. V_d 27"				
	C_v	Q_s	Q_t							
RPM	%	Cu Yds/Hr	Cu Yds/Hr	GPM	Ft/sec	Ft/sec	Feet of Mixture	%	Feet	Feet
325.	2.5	151.	6047.	20359.	7.19	11.40	324.1	38.8	----	18297.
315.	5.0	353.	7066.	23790.	8.41	13.33	298.0	43.1	----	12010.
307.	7.5	589.	7848.	26425.	9.33	14.80	278.2	46.0	----	9158.
301.	10.0	785.	7848.	26425.	9.33	14.80	262.7	45.8	68.6	7715.
296.	12.5	1057.	8453.	28462.	10.05	15.94	249.4	47.7	42.9	6508.
290.	15.0	1268.	8453.	28462.	10.05	15.94	236.1	47.5	32.9	5732.
287.	17.5	1479.	8453.	28462.	10.05	15.94	226.7	47.1	25.4	5177.
283.	20.0	1691.	8453.	28462.	10.05	15.94	217.6	46.7	19.8	4712.
282.	22.5	1902.	8453.	28462.	10.05	15.94	211.9	46.0	15.2	4379.
279.	25.0	2113.	8453.	28462.	10.05	15.94	203.7	45.6	11.8	4037.
276.	27.5	2325.	8453.	28462.	10.05	15.94	195.6	45.1	9.1	3734.
273.	30.0	2536.	8453.	28462.	10.05	15.94	188.3	44.6	6.8	3472.

Slurry Flow

d_{50} = 0.42 mm

HP_{max} = 4500 hp

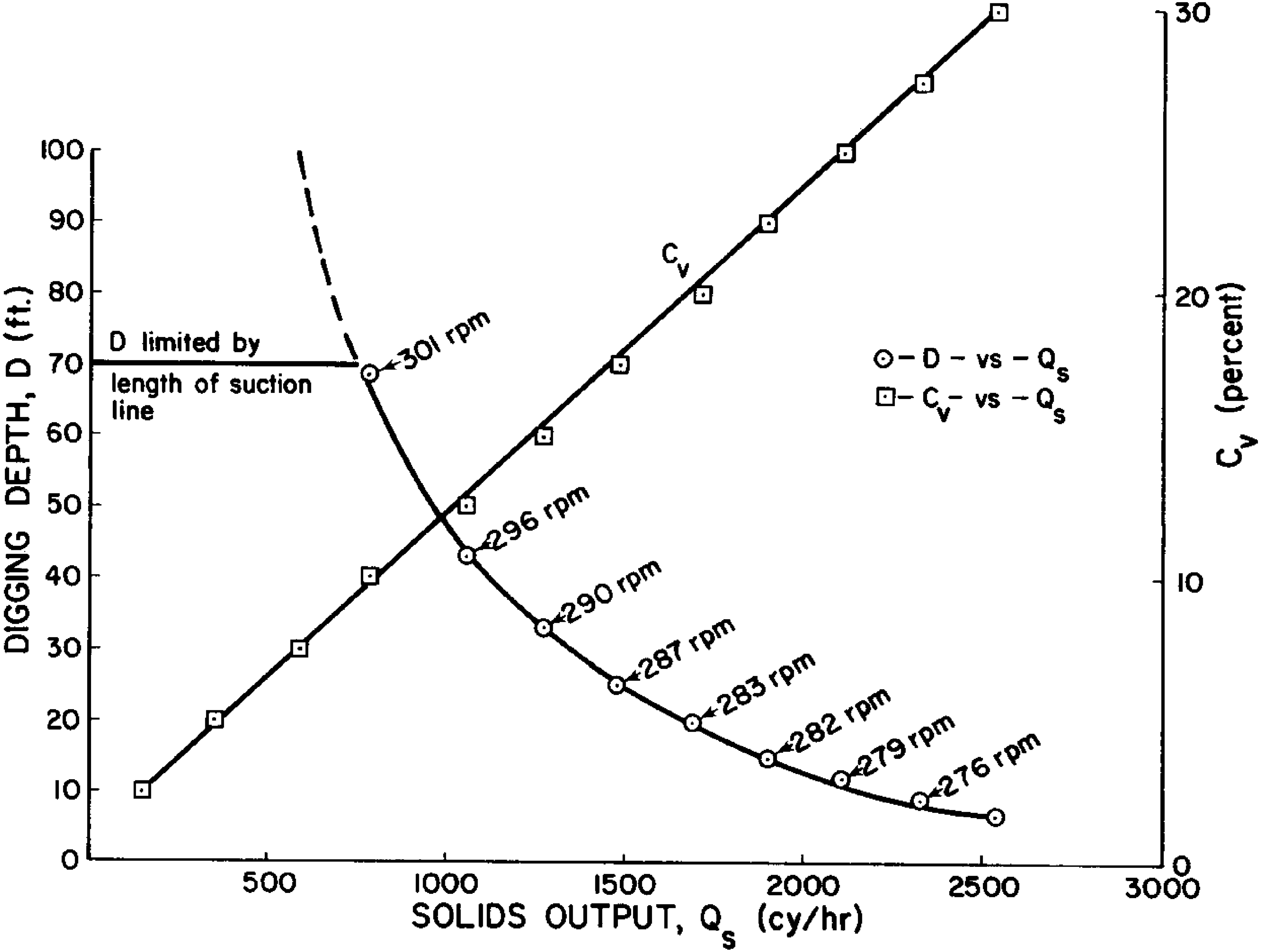


Fig. 15 CAVITATION LIMITATION (MAXIMUM SOLIDS OUTPUT -VS- DIGGING DEPTH)

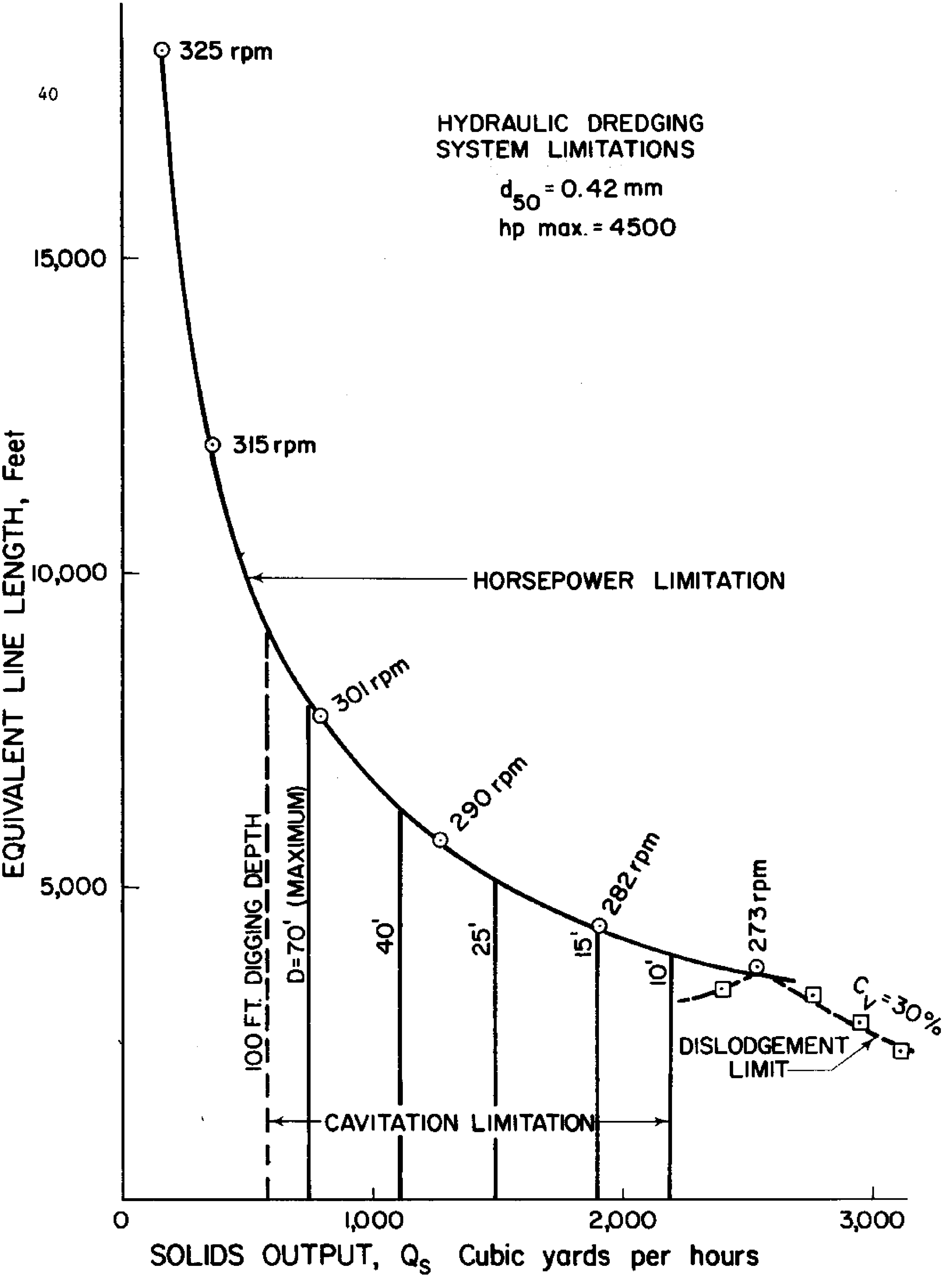


Fig. 16 HYDRAULIC DREDGING SYSTEM LIMITATIONS

to the horsepower limitation for longer line lengths.

Critical Plugging Velocity and Concentration Limitations

The third limiting condition for solids output occurs at relatively longer line lengths where because of horsepower limitations, the flow-rate (velocity) must be decreased. Of necessity, a decrease in solids concentration must also take place (Fig. 14). If the line velocity is allowed to drop too low or if the concentration becomes excessive, line plugging will result.

In most dredging systems the suction pipe is larger than the discharge for cavitation reasons, therefore line plugging should take place first on the suction side due to the slower velocities on this side of the system. However, since the suction pipe is always at some angle from the vertical, the settled solids generally will slide down the pipe, hence the discharge pipe may govern after all.

Little is known of this limiting condition and the variables that result in plugged lines. Field results are required although even laboratory data is lacking on this critical area as shown in Fig. 13.

Cutterhead Design and Dredge Operation

Finally, the maximum output of a dredge system is controlled by the limitations on dislodgement efficiency of the suction intake (cutterhead) design and the efficiency of dredge operation. In other words, the outputs shown in Fig. 14 will never be achieved if the indicated solids concentrations are never obtained.

Cutterhead Variables

Some cutterhead factors of concern are listed in Table I. The geometry of a particular cutter design (size, shape, number of blades or type of cutting edge, and attack angle) are all important to varying degrees of importance. If the design not only lossens the material for liquid transport, but also guides much of it into the suction opening, then the dislodgement rate will be sufficient to meet the optimum needs of the entire system. The rotational speed of the cutting device also obviously plays an important role.

Closely related also is the manner in which the dredge is operated.

Dredge Operation

Except in those instances when the material consistently flows toward a stationary suction inlet, the dredge must be continually moved by mechanical means in order to maintain solids transport in the system. During some period of the normal dredging cycle for a cutterhead dredge operating from pivot spuds and swing winches, the flow in the system is clear water. Thus, the average solids output per unit of time is the integrated area under the transport volume versus time curve as shown schematically in Fig. 17(a). This plot can be obtained from instantaneous recordings of both the total volumetric flowrate pumped and the mass desnity (ρ) or specific gravity of the slurry mixture throughout the entire dredge cycle. A schematic representation of what these curves may look like is shown in Fig. 17(b) for the cutter swinging through its various arcs of Fig. 17(c). The shape of the curves are only qualitatively known at this time. The "peak" slurry Sm is esti-

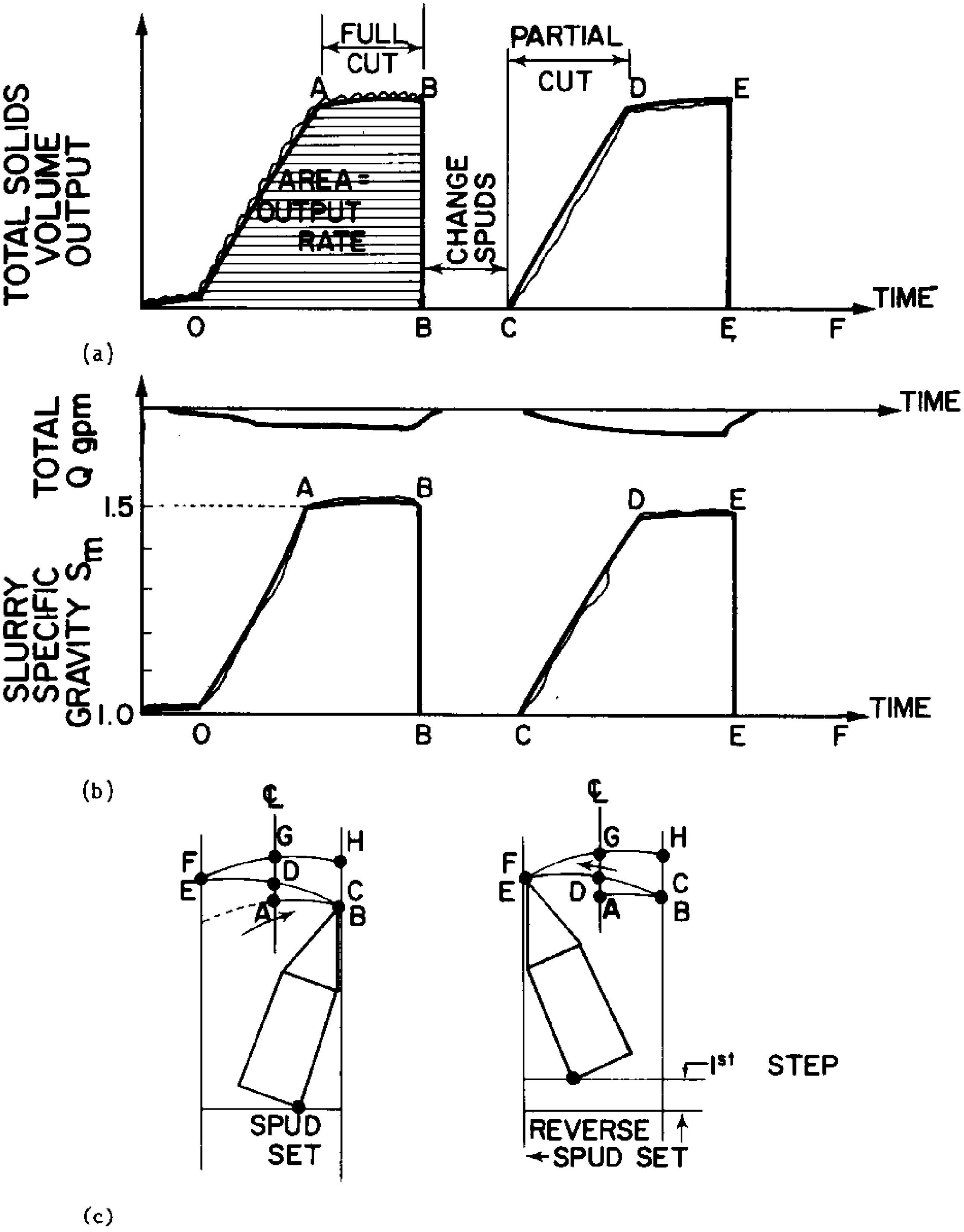


Fig. 17 DREDGING EFFICIENCY CURVES - SCHEMATIC

mated at about 1.5-1.55 based on some tests performed by Ellicott Machine Corporation and mentioned by Turner (16). Obviously, the length of time in which only clear water is pumped and zero solids are transported also greatly influences the average output per unit time rate of dredging. Thus, the rate of swing in the cut by the swing winches, the rate of progression forward (time for spud change); the height of the dredged bank and depth of cut all play an important role in the determination of the dredging efficiency curves shown in Fig. 17(a) or (b).

There is actually no way to practically duplicate a "normal" dredging cycle in the laboratory. This information (as shown in Fig. 17(b)) must be obtained from actual job records in the field. It must be obtained under all types of soil and digging conditions; with various types of cutterheads employed; and with different crews and dredge tenders operating the equipment. Average results must be obtained for "easy", "normal", and "tough" dredging conditions and situations.

This basic, fundamental information which becomes the key to the fourth limitation of dredge output, namely, the dislodgement limitation, is one of the biggest unknown areas in dredging today. It is here that the feedback problem is most critical.

To illustrate this point, let me cite an example of how management of one dredging contractual firm in the U. S. approached a problem in the operation of his dredging system. (I can safely say the situation is typical of many operations in the U. S. today).

The contractor was interested in the relocation of a booster pump further downline and increasing the main dredge pump speed to improve the overall output of the system. He measured the pump discharge pressures, main pump speed, and estimated the system velocity with a "measuring-stick" at the discharge end. The average solids output in cubic yards per hour was estimated for a number of days by determining the volume of material removed in the cut and dividing by the length of dredging time. This practice is standard in the United States. These values of average solids output and flowrate were then employed to determine volume concentration Cv, slurry specific gravity, Sm, which in turn were used to estimate characteristics about the improved system performance at higher pump operating speeds. No pump test performance curves were available so an efficiency of 70% was estimated in calculations of the maximum horsepower required. The concept of a dredging cycle and efficiency curves such as that in Fig. 17(b) in which the system limiting events (Sm = 1.5 maximum) govern the maximum output was not considered in the above case. The lack of intelligent feedback of critical information from previous jobs or in this case, the actual job at hand, and the lack of understanding of one's own dredging system resulted in a total misunderstanding and compounding of errors regarding the consequences of their estimations. Unfortunately, this situation exists throughout the industry today. The feedback of intelligent information from daily dredging projects must begin to overcome our shortcomings in the four vital areas of output limitation on dredge performance summarized below.

1. Horsepower Limitation (Maximum line length)
2. Cavitation Limitation (Maximum digging length)
3. Critical Velocity and Concentration Limitation (Prevent line plugging)

4. Dislodgement Limitation (Optimize solids concentration)

The fourth limitation for the example system has been assumed to be a maximum slurry Sm of 1.5 (C_v= 30%) which is also shown in Fig. 16 for completeness. It must be noted, however, that the rate of speed advance or winch swing rate could be such that a much lower dislodgement rate would occur which could result in a considerable reduction in solids output under short line length conditions.

A computer program has been written at the Center for Dredging Studies of Texas A&M University to perform all the computations outlined above. The computer listing is presented in the Appendix I of this paper. For a given dredge system and soil size, plots similar to Fig. 16 can be developed. We are also currently developing the computer plot subroutines to allow the automatic plotting of the output curves as shown in Fig. 16.

V. Instrumentation and Measurement Requirements

Modern day dredges have many instruments which monitor the performance of the steam-turbine diesel drives or other drive systems that provide power for the dredge and dredge pumps. They are usually continually watched and controlled by a well trained crew (Navy experience) to evaluate their performance and note any shortcomings in the drive system.

Almost unbelievingly, however, most dredges have no instrumentation that continually records the direct production (solids output) of the system. The dredger is paid for the amount of solids delivered over a given unit of time and yet he usually has no idea of what production rate is occurring at any given time throughout the daily dredging routine.

This situation is roughly analogous to a paper mill where expensive equipment is used to make fine grade paper but no instrumentation exists throughout the rolling mills to permit learning whether fine writing paper or brown butcher paper is being made until a piece is cut off the final roll for analysis. I have also seen other cases where the required process monitoring equipment has been installed but soon became inoperative because of lack of maintenance or skilled electronics personnel available to keep it running.

On many U. S. hydraulic cutterhead dredges, the following list of instruments are usually provided to monitor slurry output:

1. Pressure Gauges, suction and discharge of dredge pump,
2. Pump speed,
3. Cutterhead speed, and
4. Digging depth.

In addition, measurements of discharge velocity by the velocity stick are occasionally made for special projects but are not routine. System pipe lengths, number of ball joints in the discharge, and other details of the piping system are usually kept track of and some soil gradation analyses are usually reviewed before the project begins. This information together with a daily report of the in situ volume of material removed during the previous day's dredging is generally all a contractor has to make decisions about his equipment and project of interest. It is also all that is available as feedback information from a particular job that enables the dredger to learn the capabilities of his equipment for future undertakings. It is the primary thesis of this paper that this limited amount of feedback information is inadequate to enable the dredger to make intelligent, technical decisions about the true and limited capabilities of his equipment and system. In fact, that age old axiom that too little knowledge is dangerous could be applied here. Too often in the past, the feedback dredgers received from one job has gotten him into trouble on another job which appeared superficially to be very similar.

In addition to the above instrumentation, most hydraulic dredges require the installation of an additional two, basic process instruments which together measure and record continuously the total mass flowrate of slurry during every second of dredge operation. This information is the key that is vitally missing from most dredge feedback programs in existence today. With it, most of the difficulties and shortcomings in the construction of a mathematical model of a given dredge system (as previously discussed) would be overcome and a truly accurate predictive tool would be developed. The additional instruments required measure total volumetric flowrate, Q, and mass density, ρ_m (specific gravity, Sm) of the transported slurry.

Volumetric Flowrate

Although many devices exist, two seem particularly appropriate for dredging applications. The simplest is the adaptation of a regular 90° elbow into a pressure differential (inner- and outer radii) gauge which can be calibrated with known values of slurry present to read the total rate of flow of slurry in the discharge pipe.

The second is an electromagnetic flowmeter. The mixture cuts through an electrically propagated magnetic field which induces a voltage proportional to the mixture velocity. It has no moving or wearing parts in the pipe (installed vertically) and is readily adaptable to electronic calibration, and continuous data recording on graph paper or paper tape. Knowledge of total Q at all times during the dredging cycle (Figs. 16 and 17) is essential to the feedback process.

Mass Density

Again, two devices appear to be most practical for dredging application of the many that exist. The simplest makes use of the pressure differences in both the rising section and downcomer section of a vertical pipe loop (Graf, 9). The system of equations developed can be used to solve directly for solids concentration, C_v. Then specific gravity is determined from the relationship

$$C_v = \frac{Sm-Sw}{Ss-Sw}$$

where, C_v = fraction of solids by volume

Sm = mixture specific gravity

Ss = solids specific gravity (2.65 for sand)

Sw = liquid specific gravity (1.03 for seawater)

The second device is called a nuclear density meter. A radioactive source radiates through a slurry flow and by proper calibration, the mixture density is related to the amount of radiation getting through the mixture to a receiving cell. This device creates no flow disturbance and the output signal also is easily amplified and recorded for later computation purposes. Stability and sensitivity do pose some problems, however. Recent advances using Geiger-Mueller tubes as the radiation detector eliminate detector drift and greatly increase the system stability and reliability (17). Knowledge of Sm(Cv) at each instant of the dredging cycle (Figs. 16 and 17) is also critical to the feedback process.

Undoubtedly, the greatest problem with the use of these devices on a dredge is their proper calibration and maintenance to insure their reliability. Too often, in the past, those dredgers who purchased these devices were quickly disillusioned when something went wrong and the equipment supplier was unable or unwilling to supply the required technical expertise to keep the instruments in proper working order. If the dredger could not find and keep a capable electronics technician to service these instruments, then they were of no productive good and became expensive, wasteful toys on the dredge. This has happened numerous times both on private and federal government dredges in the U. S.

A few industrial concerns in the U. S. have recognized this problem, however, and have stepped in with a plan to overcome these shortcomings on dredges. They not only sell (or lease) the necessary process instruments and recorders (electromagnetic flowmeter and nucleonic densitometer), but they also assume complete system responsibility for the installation, continual operation, calibration, and maintenance of all required primary measurement and recording equipment. Consequently, they insure their customers at least 95% reliability of use of these instruments during actual dredging operations and provide the results (Q and Sm, etc.) to the dredger in a format of his choosing for later analysis.

Of course, cost of this equipment and service is also of concern. If one considers it a luxury accessory to be added on when convenient (i.e., the money is available) then the costs can usually be falsely justified as being too expensive. However, if these process measuring devices are considered as necessities, without which the dredge tool is rendered ineffective, and are included in the initial design, remodeling, or updating costs of the equipment, then they are well worth the expense. In fact, they'll probably pay for themselves many times over the first year alone. Close analysis will reveal many instruments on a dredge power plant that are by nature essential. For all the feedback reasons mentioned in this paper, no dredge should ever be allowed to start digging without continual, instantaneous feedback of how much solids are being continuously dredged.

Compared with daily operating expenses and other dredging costs, the actual cost of these process instruments and services is really inexpensive. For example, a recent quotation received from a U. S. firm for a 33" dredge was $40,000 for the determination of the net solids transferred during dredging. This price included the cost of the electromagnetic flow meter and nucleonic densitometer, appropriate readout equipment along with installation and field services. After the first three months of free service and upkeep, the yearly upkeep costs were to be 8% of the equipment costs renewable for three years after purchase. This arrangement was included solely for the purpose of assuring the dredging industry of the supplier's strong desire to overcome previous problems regarding the use of these measuring devices.

Lease and other options-to-buy plans are also made available.

By taking the measurement problem off the shoulders of the industry and contractors in this fashion, the dredger can concentrate on using the resulting information as vital feedback information about his system.

A few other additional instruments could be added to enable more information to be obtained from each dredging project.

Cutterhead Lateral Speed

A recorder to measure and relate the speed with which the swing winches are taken in to move the dredge laterally through the cut would aid in determining the dredging efficiency. This information could also be roughly obtained from Fig. 17.

In situ Soil-Density Meter

Recently (Dec. 1972) a device has been described for rapid, in-the-field measurement of the soil density without disturbing the deposit (18). The device incorporates a two-probe gauge which houses a nuclear source and a radiation detector in much the same fashion as the device to measure the density of flow in the discharge pipe. This information would be of value in improving knowledge of the soil properties being dredged for later correlation with dislodgement and cutterhead efficiency determinations.

Slurry Deposit Indicator

It would be very valuable during dredging to know exactly when solids begin to settle out and remain stationary on the bottom of the discharge pipe. One possibility is to incorporate a temperature sensitive, flush mounted heating-probe on the bottom of the discharge pipe near the dredge. For a given amount of heat to the probe, the temperature it attains will depend on the slurry velocity, and concentration of solids present which can be noted by prior calibration. When solids deposit on the probe, the heat will not be lost to the fluid and the temperature increases sharply. Of interest only are conditions under which the relatively sharp temperature increases occur or are removed from a recording of the temperature plot. The feasibility of the device is being considered for further study at the CDS laboratory. Knowledge of this occurrence is necessary to compare field data of critical deposit velocities with the equations previously discussed and as a quick indicator of when conditions approach those when pipe plugging may result.

In total, the devices discussed above are not at all unrealistic and would all aid greatly in understanding what takes place during normal dredging cycles on a dredging project.

VI. Data Collection and Analysis System

Because of the complicated nature of a dredging system as evidenced by the large number of variables involved (Table I) and because of the time varying nature of the slurry output variables of interest, large amounts of data can be quickly generated and will become totally useless unless a carefully designed program for collecting and analyzing the data is initiated.

The type of data gathered can be broken down into three categories:

Type A - System Constants
Type B - Variables changing slowly with time
Type C - Variables continually changing during any dredging cycle

In Table VI, examples of most of the kinds of data to be collected in each category are listed. Each type lends itself better to a certain method of collection, handling and storage for later analysis by computer techniques.

A computerized data collection and handling system is shown schematically represented in Fig. 18. The computer program is written generally to handle any type of similar system. Physical constants, pump equations, transport equations, etc., are included as integral parts of the basic program. The initial input data card includes all the constants that are given for the particular dredge of interest (Type A Data Category). This flexibility in programming would for example enable one to study the effects of different suction pipe sizes, lengths, etc., on resulting output curves, if desired.

Data under category B would be recorded periodically by dredge crew members as the need arose during actual dredging operations. In some cases, hourly recordings may be required. The key to this data collection is the use of specially designed paper format for the data which in

TABLE VI DATA CATEGORIES AND EXAMPLES

A	B	C
System Constants	Possible Variables (Changing Slowly with Time)	Variables (Changing Continuously with Time)
Readily entered into computer program as initial constants, eqns., or on input data cards. a. Suction and discharge pipe diameters b. Type of cutterhead employed c. Length of suction pipe d. Maximum drive horsepower e. Impeller diameter f. Pump centerline distance below water surface g. Pump characteristic curves h. Water specific gravity i. Etc.	a. Date, time of data taken b. Length of dredge pipe c. Number of ball joints 1. Fully cocked 2. Straight 3. Other d. Terminal elevation head e. Digging depth f. Soil Parameters 1. d_{50} size 2. gradation curve 3. in situ soil density; shear strength, etc g. Number of elbows h. Time of critical velocity i. Depth of bank cut j. Water temperature k. Atmospheric pressure l. Dredged volume	a. Date, time of initial calibration and start of test. b. Time step for interrogation c. Qm -vs- time d. ρm (Sm) -vs- time e. Cutterhead 1. Swing rate 2. Rotation speed f. Pump 1. Suction, discharge pressures 2. Speed g. Deposit meter temperature h. Etc.

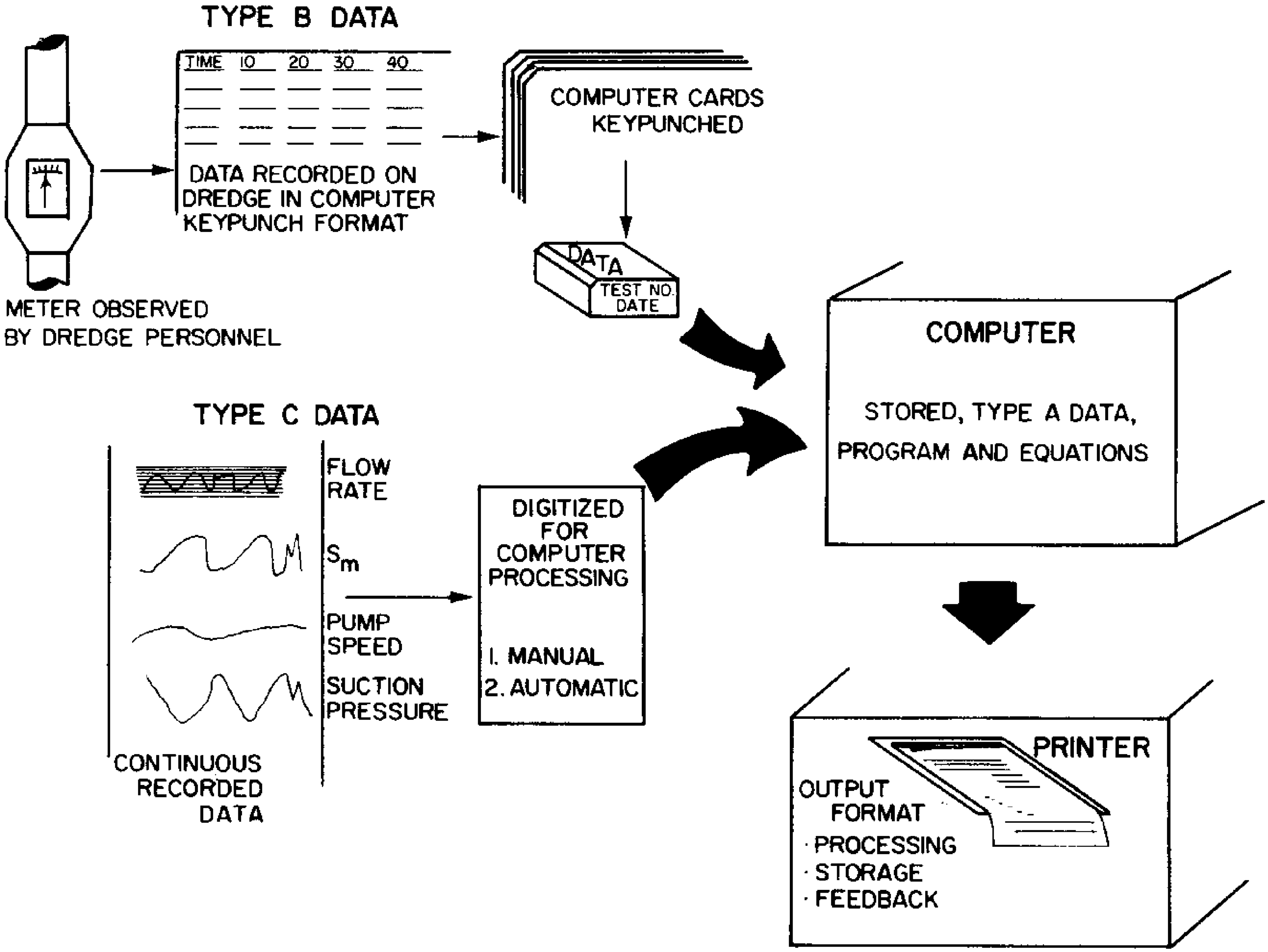


Fig. 18 TEST DATA COLLECTION AND COMPUTATION SYSTEM

turn can be used directly by computer keypunch personnel for data take-off and sorting for computer application. Incidentally, this should be used already in any case for the limited amount of data presently collected on daily dredging report sheets and logs. This information is intended as feedback for management but too often ends up collecting dust in the files because too much information is collected of a meaningless nature. Because of the costs involved and limited format space, the task of providing computer output often results in some critical decisions regarding what information is essential for feedback purposes. The key correlating factor relating all this data should be the precise time it was recorded. Hence, the date, hour and minute become the index or test number for each bit of data recorded.

The most difficult data to handle effectively is that of category C which because of its volume requires continuous recording by analog methods (tape, graphical output, etc.). Then for use in the computer, the data must be digitized, calibrated properly and again keypunched for processing. It is recommended that initially, manual methods be utilized for this process to insure confidence in the data and to become familiar with the data trends during the dredging cycle. The time step interval for data take-off can also be adjusted readily to coincide with critical changes in the data trends and with index or test numbers mentioned above for comparison and computer usage. Automated digitizing equipment is available for later more sophisticated usage as the need arises.

It is also recommended that initially one dredge cycle (Fig. 17) be studied in detail until all facets of its relationship to all other variables be thoroughly understood. Dredging under actual production circumstances is preferred to that specially set-up for testing purposes.

The team of personnel performing this work can be technical employees of the particular dredging concern (if available), dredge consultants, or university personnel with dredging experience. It is important, however, that they be allowed to concentrate their sole attention to this one task until such time that the procedures become so routine that they can be turned over to other, technical personnel. They should not be involved with the daily tasks of keeping the dredge in operation for production purposes. A computer program will be required to handle all the various forms of input data.

A wide variety of output formats of the results is possible. Many should be investigated until those most suitable for management and technical decisions are determined. Computed plotted results are also readily possible in most instances.

Finally, the group responsible for improving the feedback capability of a dredging system must be held fully accountable for their efforts. In this way, the reasons for all problems and failures will come to light and be eventually overcome. Gradually one will learn more and more about the capabilities and limitations of a particular dredging system. Finally, the actual savings in dredging costs will more than make up for the time and money invested in the feedback undertaking.

VII. Data Feedback and Results

Two classes of valuable feedback information will be generated by a program as outlined above. In one case, the information will be of a basic, fundamental nature of general interest and applicability to all people interested in knowing more about hydraulic dredging. Secondly, the information learned will only be of interest for the particular dredging system and operating personnel from which it was obtained.

Basic Information on Hydraulic Dredging

As mentioned above, probably the least understood part of hydraulic dredging centers around determinations of the dislodgement rate and all the variables that affect this factor such as material dredged, personnel, cutterhead design, swing rates, cut depths, etc. Data collected in a concise and systematic manner as suggested can begin to be used to build correlations with the variables involved. The maximum dislodgement rate can be defined. This information can be employed to develop typical dredging efficiency curves (Fig. 17) under all types of dredging conditions. Of course, the actual cutterhead geometry will be an important factor in the generalization.

In addition, the effects of particle size, gradation, concentration, etc., on the pump head reduction (Fig. 4(b) or Eq. 5); wear rates on the pump; and NPSH required critical values can be added to that information determined in the laboratory.

Also, the effectiveness of Durand's equations (and others, Table II) for head loss determinations can be studied. In particular, if a plug in the line occurs, conditions can be traced such that the critical velocity and concentration formulas for solids deposition in the line can be evaluated for practical application to dredging.

Finally, additional loss coefficient determinations can be made to supplement the meager amount of data available (Table IV, mainly based on clear water tests) and to add additional information for cutterhead intakes, stern swivels, suction sleeves, and other appurtenances typical for dredging systems. All that is required is additional pressure drop measurements across these devices under known flowrate and slurry density conditions.

Overall, all those factors where our general technical knowledge is deficient can be improved by using real field test information. The result will be better, more accurate, and field verifiable mathematical models of all similar systems for predictive purposes. Parameter studies of these math models will then isolate those few key variables of relative importance when compared to all factors involved. And, where available, physical laboratory tests of dredge systems will have actual field information to evaluate and interpretate the model results.

Individual System Information

A great deal of knowledge will only apply to the actual dredge system from which it was obtained. But since most dredges become "lifetime" machines which are rebuilt, remodeled, and revised many times, the information can be applied as long as the dredge is in working condition.

The primary use of the feedback information will be for ways in which the solids output per unit operation time can be improved. This improvement will take many forms. In most cases, those occurrences and operation procedures which waste production effort will be immediately noticed and ways devised to eliminate or reduce their impact. For example, the changing of spuds and repositioning the dredge both take time and no solids transport occurs during this operation. Slow procedures will be immediately noticed and possibly fast acting speed controls added to decrease this delay in the dredging efficiency curve (Fig. 17). Operation and choice of correct cutterhead design will be more scientific and less costly trial and error will be required.

Decrease in pump performance due to wear rates will be easily detected and more predictable. Standby replacement units will decrease low efficiency during operation with worn equipment.

The effect on the entire system output curves (Fig. 16) as a result of the addition of a new improved piece of equipment can be computed before purchase to evaluate the economic rate of return on the investment. For example, a larger horsepower prime mover can be evaluated as to its impact on performance resulting from the horsepower limitation previously discussed. Or one pump manufacturer's new dredge pump design may be evaluated in the system which it will actually operate.

The addition of various types of suction booster pumps to overcome the cavitation limitation can also be evaluated on the dredge model. The advantages and disadvantages of a suction jet booster system versus a submerged booster pump in the suction line can be completely reviewed regarding their individual effects on all limitations of the entire system. For example, the jet booster requires the addition of a clear water, high pressure supply which adds to the total flowrate resulting in the horsepower limitation being reached sooner for smaller concentrations of solids transported. The actual magnitudes of this effect can be determined from the verified mathematical model of the dredge system.

Another use will be in the precise determination of the optimum number and location of additional booster pumps under long line pumping conditions. The most advantageous time for their addition will also be known.

An additional important use will be in the training and evaluation of dredge operating personnel. Ways will become clear to both management and dredge operators for keeping dredge production at or near optimum solids output for all types of dredging conditions encountered. The situations that worked on the last job will be forgotten in light of new evidence of the present job and many old rules-of-thumb will be disregarded because of their limited applicability under a wide variety of dredging circumstances.

Finally, between jobs, the total results of the last job can be completely evaluated and the information stored for future use. That future use will be for bidding on future jobs. The contractor or equipment supplier who factually knows what his system can and cannot do under a wide variety of dredging situations has the competitive edge. He knows when and how to cut corners and what factors are most critical in meeting the requirements or specifications of the next job bid. It appears to be only a matter of time before some organization will fully realize the total implications of what a feedback program as outlined herein will accomplish when applied to his dredging system.

VIII. Summary and Conclusions

Fig. 19 summarizes a complete feedback program as outlined in this paper. The various blocks shown were discussed in detail previously. The results provide badly needed management information which is

1. Factual,
2. On time,
3. Concise,
4. Impartial, unbiased,
5. Proven on own equipment,
6. Useful for present day, short term and long range decisions and planning purposes.

Most of the problems associated with the instigation of such a program as mentioned at the beginning of this paper have been overcome. It is not necessary to take the dredge out of production to run complete tests on its performance. In fact, actual project conditions are required to provide the wide variety of information needed. The new instrumentation required is not that costly or complicated and previous maintenance and upkeep problems are overcome by the suppliers agreement to furnish complete system responsibility for years afterwards, if desired. If the technical know-how to implement such a program is unavailable in a dredge organization, it can probably be found using consultants or university personnel with dredging expertise. Data reduction and analysis can become overbearing if not for the time and labor-saving advantages of high-speed computers. All that is required is some prior planning to handle the data generated. Finally, shortsightedness and money can be

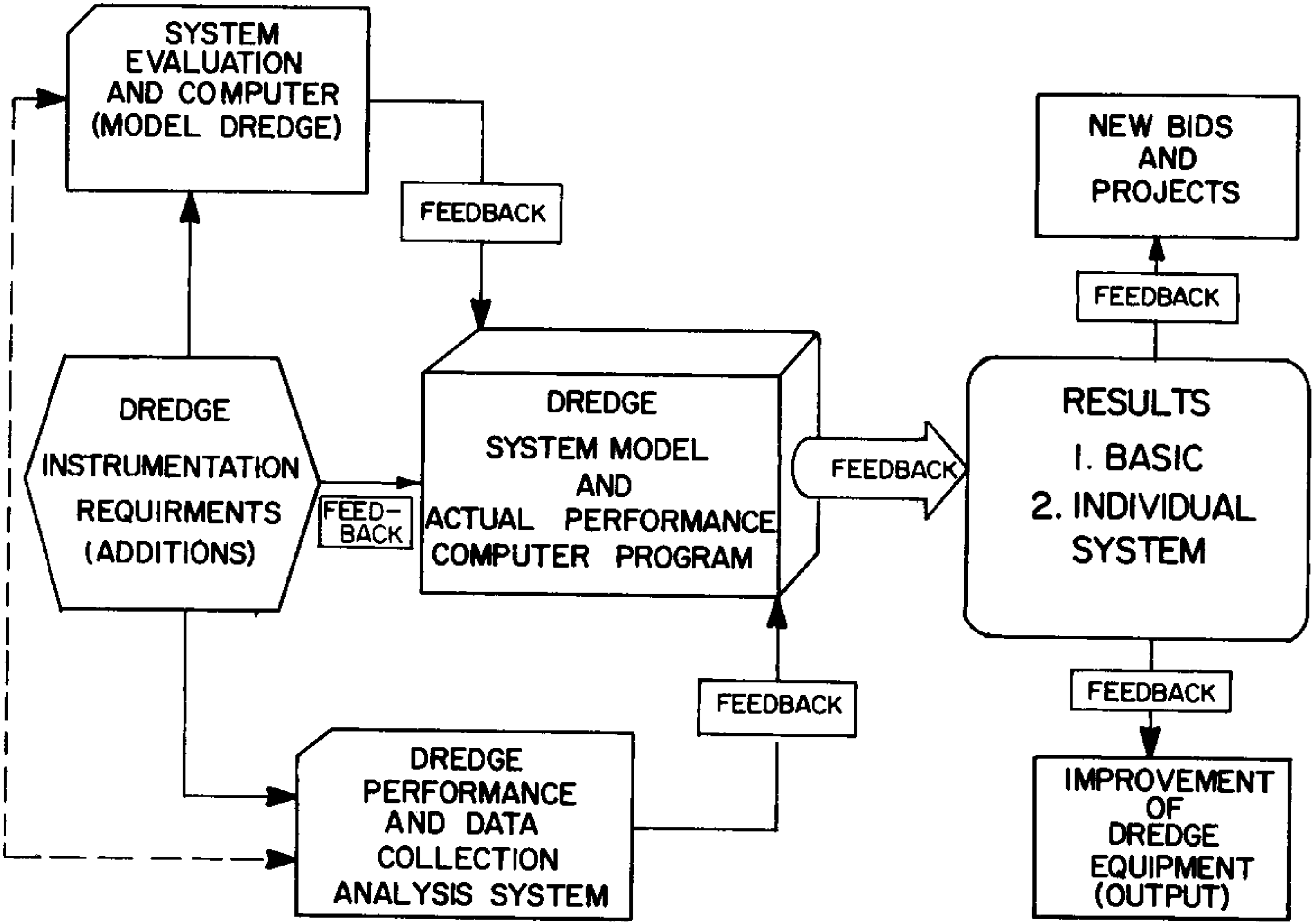


Fig. 19 DREDGE SYSTEM EVALUATION AND FEEDBACK PROGRAM

major hurdles to overcome. Vision is required to "see" the long-term advantages of such an undertaking. A commitment must be made and the organization must be willing to risk something to gain a whole lot more. Such an improvement program should be made cost accountable for its efforts. This means individual developments must show how they could repay their investment costs over some short return period. For example, the cost of the new required process monitoring instruments and maintenance program could probably be repaid quickly by the elimination of the daily need to post survey the dredge area to determine the volume of material (solids, voids [air and water]) dredged for payment purposes. Payment could be for solids delivered which is continually totalized by a meter on the dredge. This would be similar to the water or gas meters that provide continuous totals of volumes used in your house.

Finally, the basic, fundamental knowledge gained about all aspects of hydraulic dredge operation will be very valuable to the progress of the entire industry. Hopefully, those organizations will be willing to share the basic information obtained of a general nature with the entire industry.

Conclusions

1. Feedback from day-to-day dredging projects is fundamental, lacking or non-existent, and the biggest problem facing the industry today if it hopes to pull up its technology to levels consistent with the 20th Century (rockets, space travel, etc.).

2. The problems to be faced in providing feedback of both a fun-

damental nature and specific type are not insurmountable. All that is required is

a. an analysis of one's dredging system,

b. the addition of a few process instruments,

c. some judicial planning,

d. the use of high speed computers, and

e. a commitment to undertake the effort and expense.

3. Such a feedback development program can be made cost accountable by which the improvements in output can be shown to be more than worth the added expense.

4. Efforts should begin immediately to begin such programs by a wide range of the dredging community. The knowledge gained of a general, basic nature, should be shared with all concerned for the betterment of the total industry. Knowledge of a specific nature for a particular system can be kept proprietary and will also eventually contribute to progress of the dredging industry as a whole.

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REFERENCES

1. Moody, L.F.; "The Propeller Type Turbine", Trans. A.S.C.E. Vol. 89, pp. 625-690, 1926.

2. Herbich, J.B. and Vallentine; "Characteristics of a Model Dredge Pump", Lehigh University Report No. 33 for U. S. Army Engineers, Sept., 1961.

3. Stepanoff, A.J.; Pumps and Blowers - Two-Phase Flow, John Wiley and Sons, Inc. New York, 1965.

4. Wiedenroth, W.; "An Examination of the Problems Associated With the Transportation of Sand-Water Mixtures in Pipelines and Centrifugal Pumps", Proceedings WODCON II, Rotterdam, 1968.

5. Mariani, V.R. and Herbich, J. B.; "Effect of Viscosity of Solid-Liquid Mixture on Pump Cavitation", Lehigh University Report No. 297, Jan., 1966.

6. Basco, D.R.; "Particle Size and Density Effects on Cavitation Performance of Dredge Pumps", Proceedings, Third Dredging Seminar, CDS Report No. 148, Texas A&M University, August, 1971.

7. Chandler, P.; Kindel, C.; and Herbich, J.B.; "Status Report on Cavitation of Dredge Pumps", Center for Dredging Studies Report No. 147, Texas A&M University, July, 1971.

8. Colebrook, C.F.; "Turbulent Flow in Pipes with Particular Reference to the Transition Region Between Smooth and Rough Pipe Laws", Journal Inst. Civil Engineers, London, p. 133, Feb., 1939.

9. Graf, W.H.; Hydraulics of Sediment Transport, McGraw-Hill Book Co., New York, 1971.

10. Durand, R., and Condolios, E., "Experimental Investigation on the Transport of Solids in Pipes", LeJournéls d'Hydraulique, Société Hydrotechnique de France, Grenoble, June, 1952.

11. "Model Study of Hopper Dredge Dragheads", U. S. Army Engineer Waterways Experiment Station, TR No. 2-755, Jan., 1967.

12. Salzmann, V.H., "Hydraulische und Bodentechnische Vorgänge beim Grundsaugen", Mitteilungen des Franzius - Instituts für Grund - und Wasserbau der Technischen Universität Hannover, Heft **31**, 1968, pp. 1-80.

13. "Flow of Fluids through Valves, Fittings, and Pipe", Crane Co., Technical Paper No. 409, Chicago, May, 1942.

14. Rose, R., verbal communication, Mobile Pulley and Iron Wks, Mobile, March, 1973.

15. Turner, T.M., "The Basic Dredge Laws", Proceedings, WODCON III, Singapore, 1970, pp. 413-424.

16. Turner, T.M., "Dredging Systems and the Basic Dredge Laws", Short Course Notes, CDS, Texas A&M University, August, 1972.

17. Cressman, D.E., personnel communication, Industrial Nucleonics Corp., Columbus Ohio, March, 1973.

18. Poloncsik, S.; Langdon, W.M.; Nedued, T.K.; and Fochtman, E.G.; "In-Place Measurement of Shoal Density", Journal Water Pollution Control Federation, Vol. 44, No. 12., Dec., 1972, pp. 2334-2341.

19. Pettyjohn, E.S., and E.F. Christiansen, "Effect of Particle Shape on Free-Settling Rates of Isometric Particles", Chemical Engineering Program, Vol. 44, No. 2, 1948.

APPENDIX I

Computer listing of Hydraulic Dredge System Program

```
//TA114    JOB (T321-,2-A--,*10,002,99),' PUCKETT           '         '
C ************************************************************************
C
C                              OUTPUT VS. LINE LENGTH
C                                       WITH
C                        HORSEPOWER AND SUCTION LIMITATIONS
C
C ************************************************************************
C
C
C ******************** EXPLANATION OF VARIABLES ***************************
C
C      ACCCHK = ALLOWABLE PER CENT ERROR IN 'BHP' CALCULATIONS
C      BHPMAX = MAXIMUM HORSEPOWER OF PRIME MOVER
C      CSUBV  = CONCENTRATION OF SOLIDS BY VOLUME
C      D50    = AVERAGE GRAIN SIZE (MILLIMETERS)
C      DDEPTH = DIGGING DEPTH
C      DISDIA = DISCHARGE PIPE DIAMETER IN INCHES
C      EFF    = PUMP EFFICIENCY
C      ELEVP  = ELEVATION OF PUMP WITH RESPECT TO WATER SURFACE
C      G      = ACCELERATION OF GRAVITY (32.174 FT/SEC**2)
C      HEAD   = TOTAL DYNAMIC HEAD DEVELOPED BY PUMP
C      IMPDIA = IMPELLER DIAMETER IN INCHES
C      K      = K-FACTOR IN HEAD LOSS TERM
C      L1     = LENGTH FROM CUTTERHEAD TO WATER SURFACE
C      L2     = LENGTH FROM WATER SURFACE TO SUCTION SIDE OF PUMP
C      LENGTH = LENGTH OF SUCTION PIPELINE FROM CUTTERHEAD TO PUMP
C      LLEQIV = EQUIVALENT LINE LENGTH
C      OMEGA  = PUMP SPEED IN RADIANS PER SECOND
C      PA PVP = ATMOSPHERIC PRESSURE MINUS VAPOR PRESSURE OF WATER
C      PI     = 3.141593
C      Q      = TOTAL OUTPUT (GPM)
C      QSOLID = OUTPUT OF SOLIDS (CY/HR)
C      QSTART = 'EDUCATED GUESS' FOR INITIAL FLOWRATE
C      RPMMAX = MAXIMUM PUMP SPEED
C      RPMMIN = MINIMUM PUMP SPEED
C      RPMINC = DESIRED INCREMENTS OF PUMP SPEED
C      SPGRM  = SPECIFIC GRAVITY OF SLURRY
C      SPGPS  = SPECIFIC GRAVITY OF SOLIDS - (USUALLY = 2.65)
C      SUCDIA = SUCTION PIPE DIAMETER IN INCHES
C      TITLE  = ANY DESIRED HEADING FOR OUTPUT PAGE
C      VELDIS = FLUID VELOCITY IN DISCHARGE PIPE
C      VELSUC = FLUID VELOCITY IN SUCTION PIPE
C      HA1,FA1,NA1, ETC. ARE COEFFICIENTS OF THE VARIOUS DIMENSIONLESS
C        CURVES WHICH ARE USED
C
C ************************************************************************
C
C
C ****************** REQUIRED INPUT AND DATA FORMAT ***********************
C
C      1ST CARD - TITLE - ANY ALPHANUMERIC CHARACTERS IN A 20A4 FORMAT
C      2ND CARD - BHPMAX, IMPDIA, SUCDIA, DISDIA, L1, L2, ELEVP, AND
C                 RPMMAX IN AN 8F10.0 FORMAT
C      3RD CARD - RPMMAX, RPMINC, QSTART, AND D50 IN A 4F10.0 FORMAT
C      THE NEXT CARD OR GROUP OF CARDS (UNLIMITED NUMBER) SHOULD
C        CONTAIN ONE VALUE OF CONCENTRATION BY VOLUME IN A F10.3 FORMAT
C      THE LAST CARD SHOULD BE A '/*' CARD TO TERMINATE THE PROGRAM
C
C ************************************************************************
```

```
      IMPLICIT REAL(A-I,K-Z)
      INTEGER TITLE(20),KEY
      COMMON /GRAIN/D50,D50FT,CSUBV,SPGRS
      COMMON /CONST/PI,G
      COMMON /VALUES/PA PVP,K
      COMMON /PROPTY/DSQR,DCUBE,BHPMAX,RPMMAX,SPGRM,RATIOE,ACCCHK
      COMMON /COEFFI/HA1,HA2,HA3,EA1,EA2,EA3,NA1,NA2
      READ(5,1000) TITLE,BHPMAX,IMPDIA,SUCDIA,DISDIA,L1,L2,ELEVP,RPMMIN,
     1RPMMAX,RPMINC,QSTART,D50
      IMPDFT=IMPDIA/12.
      DSQR=IMPDFT**2
      DCUBE=IMPDFT**3
      SUCDFT=SUCDIA/12.
      DISDFT=DISDIA/12.
      AREAS=PI*(SUCDFT**2)/4.
      AREAD=PI*(DISDFT**2)/4.
      D50FT=D50/304.8
      ACCCHK=0.0001*BHPMAX
      LENGTH=L1+L2
      WRITE(6,100) TITLE,BHPMAX,RPMMAX,RPMMIN,IMPDIA,SUCDIA,DISDIA,D50
   26 READ(5,1001,END=10) CSUBV
      KEY=0
      SPGRM=CSUBV*(SPGRS-1.)+1.
      RATIOE=1.00-(CSUBV/0.06*0.049)-(ALOG10(D50)*CSUBV/0.06*0.039)
      VCRITD=FL(D50,CSUBV)*SQRT(2.*G*DISDFT*(SPGRS-1.))
      QCRITD=VCRITD*AREAD*449.
      VCRITS=FL(D50,CSUBV)*SQRT(2.*G*SUCDFT*(SPGRS-1.))
      QCRITS=VCRITS*AREAS*449.
   27 WRITE(6,102) SPGRM,CSUBV
      RPM=RPMMAX
   18 Q=QSTART
   17 OMEGA=RPM/9.549
   15 QDIM=Q/(449.*OMEGA*DCUBE)
      HDIM=HA1+HA2*QDIM+HA3*QDIM**2
      HEAD=(HDIM*OMEGA**2*DSQR/G)*RATIOE
      EFF=(EA1+EA2*QDIM+EA3*QDIM**2)*RATIOE
      BHP=Q*HEAD*SPGRM/(3960.*EFF)
      IF(ABS(BHP-BHPMAX)-ACCCHK) 14,14,21
   21 Q=BHPMAX*3960.*EFF/(HEAD*SPGRM)
      GO TO 15
   14 NSUBS=OMEGA*(Q/449.)**0.5/(G*HEAD)**0.75
      SIGMAC=NA1*NSUBS**NA2
      NPSHAV=SIGMAC*HEAD
      VELSUC=Q/(449.*AREAS)
      CALL FRIFAC (VELSUC,SUCDFT,F)
      CALL REGIME (VELSUC,SUCDFT,F,S)
      HSUBLM=LENGTH*S+(K*VELSUC**2/(2.*G))
      IF(SPGRM-1.)1,1,2
    1 DDEPTH=1000.
      GO TO 22
    2 DDEPTH=((PA PVP+ELEVP-HSUBLM)/SPGRM-NPSHAV)/(1.-1./SPGRM)
      IF(DDEPTH.LT.0.0.AND.KEY.EQ.0) GO TO 8
      IF(DDEPTH.LT.0.0.AND.KEY.EQ.1.OR.KEY.EQ.-1)DDEPTH=1000.
   22 QSOLID=Q*CSUBV*0.297
      VELDIS=Q/(449.*AREAD)
      CALL FRIFAC (VELDIS,DISDFT,F)
      CALL REGIME (VELDIS,DISDFT,F,S)
      LLEQIV=HEAD/S
      RPM=OMEGA*9.549
      IF(DDEPTH.EQ.1000.) GO TO 3
```

```
      IF(DDEPTH-L1)3,3,4
    4 WRITE(6,106)RPM,HEAD,EFF,Q,VELDIS,QSOLID,LLEQIV
      GO TO 6
    3 WRITE(6,101)RPM,HEAD,EFF,DDEPTH,Q,VELDIS,QSOLID,LLEQIV
    6 IF(KEY) 26,8,7
    5 WRITE(6,103)
      KEY=1
      CALL QCHEFF (QCRITD,OMEGA,Q,HEAD,EFF)
      WRITE(6,104)
      GO TO 14
    7 KEY=-1
      CALL QCHEFF (QCRITS,OMEGA,Q,HEAD,EFF)
      WRITE(6,105)
      GO TO 14
    8 IF(RPM-RPMMIN)5,5,9
    9 Q=Q+(RPMINC/20.)*Q
      RPM=RPM-RPMINC
      GO TO 17
   10 WRITE(6,107)
      WRITE(6,108)
  100 FORMAT('1'///////////////////////////27X,'***** PUMP OUTPUT VS. LINE
     1 LENGTH WITH SUCTION AND HORSEPOWER LIMITATIONS *****'///32X,20A4/
     2//6X,'MAXIMUN',8X,'MAXIMUM PUMP',7X,'MINIMUM PUMP',8X,'IMPELLER',8
     3X,'SUCTION PIPE',6X,'DISCHARGE PIPE',6X,'AVERAGE GRAIN'/5X,'HORSEP
     4OWER',7X,'SPEED (RPM)',8X,'SPEED (RPM)',6X,'DIAMETER (IN.)',4X,
     5'DIAMETER (IN.)',4X,'DIAMETER (IN.)',8X,'SIZE (MM)'
     6// 6X,F6.0,13X,F4.0,15X,F4.0,14X,F4.0,15X,F3.0,15X,F3.0,15X,F5.2)
  101 FORMAT('0',5X,F4.0,10X,F5.1,11X,F5.3,10X,F5.1,10X,F6.0,12X,F5.2,13
     1X,F5.0,11X,F6.0)
  102 FORMAT('1',1X,'SLURRY SPECIFIC GRAVITY = ',F5.3//2X,'CONCENTRATION
     1 OF SOLIDS BY VOLUME = ',F5.3///3X,'PUMP SPEED',8X,'HEAD',9X,
     2'EFFICIENCY',3X,'DIGGING DEPTH',3X,'TOTAL OUTPUT',3X,'AVERAGE DISC
     3HARGE',3X,'SOLIDS OUTPUT',3X,'EQUIVALENT LINE',/
     45X,'(RPM)',5X,'(FT. OF MIXTURE)',20X,'(FT.)',10X,'(GPM)',7X,
     5'VELOCITY (FT/SEC)',6X,'(CY/HR)',6X,'LENGTH (FT.)')
  103 FORMAT('0',31X,'**************************** CRITICAL VALUES *******
     1*********************')
  104 FORMAT('0',3X,'DISCHARGE')
  105 FORMAT('0',3X,'SUCTION')
  106 FORMAT('0',5X,F4.0,10X,F5.1,11X,F5.3,10X,'$$$$$',10X,F6.0,12X,F5.2
     1,13X,F5.0,11X,F6.0)
  107 FORMAT(/////56X,'***** END OF PROBLEM *****')
  108 FORMAT('1')
 1000 FORMAT(20A4/8F10.0/4F10.0)
 1001 FORMAT(F10.3)
      STOP
      END

      BLOCK DATA
      IMPLICIT REAL (A-I,K-Z)
      COMMON /GRAIN/D50,D50FT,CSUBV,SPGRS
      COMMON /CONST/PI,G
      COMMON /VALUES/PA PVP,K
      COMMON /PROPTY/DSQR,DCUBE,BHPMAX,RPMMAX,SPGRM,RATIOE,ACCCHK
      COMMON /COEFFI/HA1,HA2,HA3,EA1,EA2,EA3,NA1,NA2
      DATA PI,G/3.141593,32.174/
      DATA SPGRS/2.65/
      DATA PA PVP/33./,K/1.4/
      DATA HA1,HA2,HA3/.1620897,.683657,-239.4055/,
     1     EA1,EA2,EA3/.1042429,105.8745,-4421.454/,
```

```
     2      NA1,NA2/.6574733,1.965857/
      END

      SUBROUTINE QCHEFF (QCRIT,OMEGA,Q,HEAD,EFF)
      IMPLICIT REAL (A-I,K-Z)
      COMMON /COEFFI/HA1,HA2,HA3,EA1,EA2,EA3,NA1,NA2
      COMMON /PROPTY/DSQR,DCUBE,BHPMAX,RPMMAX,SPGRM,RATIOF,ACCCHK
      COMMON /CONST/PI,G
      OMEGA=RPMMAX/9.549
      Q=QCRIT
      DOMEGA=OMEGA/10.
    1 OMEGA=OMEGA-DOMEGA
      QDIM=Q/(449.*OMEGA*DCUBE)
      HDIM=HA1+HA2*QDIM+HA3*QDIM**2
      HEAD=(HDIM*OMEGA**2*DSQR/G)*RATIOF
      EFF=(EA1+EA2*QDIM+EA3*QDIM**2)*RATIOF
      BHP=Q*HEAD*SPGRM/(3960.*EFF)
      IF(ABS(BHP-BHPMAX)-ACCCHK)2,2,3
    3 IF(BHP-BHPMAX)4,2,1
    4 OMEGA=OMEGA+DOMEGA
      DOMEGA=DOMEGA/10.
      GO TO 1
    2 RETURN
      END

      SUBROUTINE REGIME (V,D,F,S)
      IMPLICIT REAL (A-I,K-Z)
      COMMON /GRAIN/D50,D50FT,C,SG
      COMMON /CONST/PI,G
      HOVERL=F*V**2/(D*2.*G)
      IF(C) 2,2,6
    6 VH=(1800.*G*VSS(D50,SG,G)*D)**(1./3.)
      VC=FL(D50,C)*SQRT(2.*G*D*(SG-1.))
      IF(V-VH) 1,1,2
    1 IF(V-VC) 4,4,3
    2 PHI=SG-1.
    5 S=HOVERL*(PHI*C+1.)
      RETURN
    3 PHI=1100.*(SG-1.)*VSS(D50,SG,G)*G*D/V**3
      GO TO 5
    4 RH=(V*SQRT(D*G)/VC)**2/(4.*G)
      S=(SG-1.)*D50FT/RH*(C*V*RH/(10.39*SQRT((SG-1.)*G*D50FT**3)))**(1./
     12.52)
      RETURN
      END

      SUBROUTINE FRIFAC (V,D,FNEW)
      IMPLICIT REAL(A-I,K-Z)
      DATA KSUBS/0.00015/,KVISCO/1.06E-05/
      REYNO=V*D/KVISCO
      F=0.015
      X2=2.*ALOG10(KSUBS/D)
    3 X1=2.*ALOG10(1.+9.35*D/KSUBS/(REYNO*SQRT(F)))
      FNEW=(1.14-X1-X2)**(-2)
      DIFF=ABS(FNEW-F)
      IF(DIFF-0.0001) 1,1,2
    2 F=FNEW
      GO TO 3
    1 RETURN
      END
```

```
      FUNCTION VSS (D,SG,G)
      IMPLICIT REAL (A-I,K-Z)
      DATA KVISCO/1.06E-05/
      DATA D1,D2,D3/122.5192,.8792887,.3379573/
      IF(D-0.074) 1,1,2
    1 VSS=(G*(D/304.8)**2/(18.*KVISCO))*(SG-1.)
      RETURN
    2 VSS=D1*D**(D2*(1.-D3*ALOG10(D)))/304.8
      RETURN
      END

      FUNCTION FL (D,C)
      IMPLICIT REAL (A-I,K-Z)
      DATA F21,F22,F23,F24,F25/-.0062374,-1.356054,1.968543,.2224506,
     1     -.0187021/,F51,F52,F53,F54,F55/-.0032526,-1.668764,2.340979,
     2     .2899664,-.0268365/,F101,F102,F103,F104,F105,F106/.0094699,
     3     1.777178,-1.523239,.9819833, -.2540082,.0234211/,F151,F152,
     4     F153,F154,F155,F156,F157/-.0010988,2.026733,-2.282632,
     5     1.935678,-.7528045,.1408272,-.0102302/
      IF(C-0.125) 2,1,1
    2 IF(C-0.075) 3,4,4
    3 IF(C-0.035) 6,5,5
    1 FL=F151+F152*SQRT(D)+F153*D**2+F154*D**3+F155*D**4+F156*D**5+F157*
     1D**6
      RETURN
    4 FL=F101+F102*SQRT(D)+F103*D**2+F104*D**3+F105*D**4+F106*D**5
      RETURN
    5 FL=F51+F52*D+F53*SQRT(D)+F54*D**2+F55*D**3
      RETURN
    6 FL=F21+F22*D+F23*SQRT(D)+F24*D**2+F25*D**3
      RETURN
      END

//*DATA
```

SYSTEMS ENGINEERING AND DREDGING-
THE FEEDBACK PROBLEM

for
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