REAL-TIME COMPUTATION OF ECONOMIC LOAD FOR HOPPER DREDGES

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Abstract: *Economic load* is the term used in dredging practice for the time during hopper dredge overflow pumping that further increase in load is not *economic*. As a dredge continues to pump, the rate of increase in hopper density declines. When the time to travel to the disposal site and return is balanced against the time required to take on additional load there is an optimal point when pumping should be stopped. This is a linear programming (LP) problem that has been solved in the past by making manual measurements of hopper volume and pumping time. Because of the time and labor required for the measurements and computations, the concept has not been widely implemented.

The Corps of Engineers Silent Inspector (SI) dredge monitoring system measures dredge performance and position in real-time. The SI has on-board analysis capability that computes the pumping, sailing, and dumping times along with the hopper load in Tons Dry Solids (TDS). TDS has been incorporated into the economic load solution as the load metric rather than in-situ sediment volume. An economic load analysis module for the SI has been developed and tested against previously recorded SI data from dredges operating in the Southwest Pass of the Mississippi river entrance. Preliminary results of the data analysis indicate that for cuts close to the disposal area, total load cycle times could be reduced by 30% with less than 10% reduction in load per cycle.

Details of the LP solution are presented along with an analysis of the effects of errors in TDS measurements. Tests of the system on operational dredges in Southwest Pass are planned for this year.

INTRODUCTION

This paper discusses the design and evaluation of a system for on-dredge, real-time, computation of the economic load for a hopper dredge operating with overflow. Rather than previous methods that use approximations based on bin density, this approach seeks to minimize the cost/time of the total Ton-miles for a load. The system generates a stop pumping advisory based on optimizing the time required to gain additional load vs. the time required to sail to the disposal area. The estimates are based on the distance to the disposal site and dredge performance measured in real-time.

The system builds on the capabilities provided by the Corps of Engineers Silent Inspector (SI) dredge monitoring system (Rosati 1998). Among other functions the Silent Inspector computes the Tons Dry Solids (TDS) contained in the hopper in real-time. TDS is an estimate of the weight of the sediment without water content. SI also determines the dredge activity (dredging, sailing, dumping,

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etc.). as well as position. SI computes the actual time from the dredge site to disposal area and uses this information along with updated real-time position to estimate the sailing-dumping time for the next load. The economic load is achieved when the increase in TDS has diminished to the point that time would be better spent traveling to the dump and returning to start another cycle. This point depends on the time required to sail to the disposal area for traffic and tide conditions, and the projected rate of increase of TDS. For a distant disposal area additional pumping time may be economical, while for a near-by disposal area it is better to dispose and start a new cycle. The operational goal is to maximize the daily production of the dredge in tons per day.

The basic data necessary to perform the optimization estimate are already acquired and computed by the SI. The system is implemented as an add-on analysis module. A graphics display updated in real-time allows the dredge operator or the Corps inspector to see the current and projected economic load times while dredging. The optimization algorithm is a form of linear programming that is based on modifications to the underlying algorithm used by the Corps of Engineers for manual analysis of economic load. The system was developed and tested using data recorded by SI from past dredging contracts at Southwest Pass, New Orleans District.

CURRENT PRACTICE

The concept of economic load for hopper dredges is well established. The current practice of the Corps of Engineers is documented in *Engineer Form 2590*[3] dated August, 1, 1955. The form specifies a manual spreadsheet computation based on monitoring the pumping time, total cycle time, and measurement of the total load. Total load measurements are specified as the volume of in-situ channel material computed by multiplying the volume of hopper material by a constant ratio of in-place density to absolute density. The draft Hopper Dredge Engineering Manual (EM1125 1994) provides guidance on obtaining these measurements in Appendix C. Coarse material or sand should be measured by sounding the hopper, while for fine material the integrated output of the production meter is suggested.

Form 2590 Computation

The Form 2590 spreadsheet computation has been redefined here using mathematical notation. We consider only the hopper volume since the in-place volume is assumed to differ by a constant factor. We define the following terms:

[3]Engineer Form 2590 *Economic Load Test* is available from http://www.usace.army.mil/inet/usace-docs/forms/e2590.pdf

t_p	pumping time
T_p	total pumping time
t_t	turning time
T_t	total turning time
T_L	total loading time
T_D	total disposal time
T_{cycle}	total cycle time
s_p	dredge speed while pumping
s_d	dredge speed while sailing to the disposal site
l_d	distance to disposal site
L	hopper load (cubic yards)

Given a time series of m samples of the load L and total pumping time T_p, we can define two rates that approximate the time derivatives of the load while pumping. The first is called the incremental load by *Form 2590.*

$$R_I = \Delta L / \Delta T_p \tag{1}$$

where

$$\Delta L = L_m - L_{m-1}$$

and

$$\Delta T_p = T_{pm} - T_{pm-1}$$

The total retained load for the duration of a total cycle is

$$R_L = L / T_{cycle} \tag{2}$$

where L and T are evaluated at each m. An estimated constant T_D is assumed when computing $T_{cycle} = T_L + T_t + T_D$. Therefore L and T_{cycle} are the values that should be obtained if at the corresponding m time, pumping is halted and sailing to the disposal site is begun. R_L can then be viewed as an the effective average rate for the retained load relative to the time for an entire cycle.

Form 2590 defines the *economic load* to occur at the pumping time when

$R_L = R_I$	economic load
$R_L < R_I$	under-pumping
$R_L > R_I$	over-pumping

Here we define a single economic load parameter E as

$$E = R_I - R_L \tag{3}$$

so that when $E = 0 = E_0$, the economic load has been obtained. When $E < 0$ the dredge is over-pumping.

Current practice recommends that the economic load test be performed at the beginning of dredging, and the economic load pumping time is then used for all subsequent cuts without repeating the test. If conditions change the test should be repeated.

Form 2590 Example

The *Form 2590* computations can be illustrated using sample data[4]. Table 1 show the data from 9 measurements that begin after the onset of overflow. The economic load occurs between measurements 3 and 4. The exact time is estimated by interpolation as $T_p = 44\ min$ pumping and $L = 2840\ yd^3$. Time less than 44 min is under-pumping and greater than 44 min is over-pumping.

m	time	T_p	t_t	T_L	T_d	T_{cycle}	L	R_L	R_I
1	1003	22	5	27	39	66	1850	28.0	84.1
2	1013	32	5	37	39	76	2430	32.0	58.0
3	1021	40	5	45	39	84	2780	33.1	43.8
4	1036	50	15	65	39	104	3050	29.3	27.0
5	1056	60	15	75	39	114	3290	28.9	24.0
6	1104	68	15	83	39	122	3470	28.4	22.5
7	1112	76	15	91	39	130	3630	27.9	20.0
8	1124	83	20	103	39	142	3730	26.3	14.3
9	1131	90	20	110	39	149	3770	25.3	05.7

Table 1: Data from hopper dredge *Wheeler* computed like *ENG Form 2590*

Figure 1 plots the evolution of R_I, R_L, and E as pumping time increases. The economic load point occurs when R_I crosses R_L. The difference between the two rates, E, passes through zero. The plot shows how the measurement intervals should be shorter as the economic load point is approached. With manual measurement and computation this may not be practical. The next section will explore the use of the automated measurements of the SI to provide better resolution of the economic load point, as well as a prediction for every load.

USING SILENT INSPECTOR DATA

The Silent Inspector (SI) is a system that continuously monitors dredge process variables. The system was developed to assist the Corps of Engineers in managing contract dredging. The Corps provides a specification as part of the dredging contract and the system is implemented by the contractor (Rosati and Prickett 2001).

The SI monitors the following basic variables that are computed by the dredge's process control computer and passed to the SI computer over a standard interface detailed in the SI specifications.

- Horizontal position
- Hopper status (open/closed)
- Tide level

[4]Data from Appendix C of the draft EM 1125 (1994).

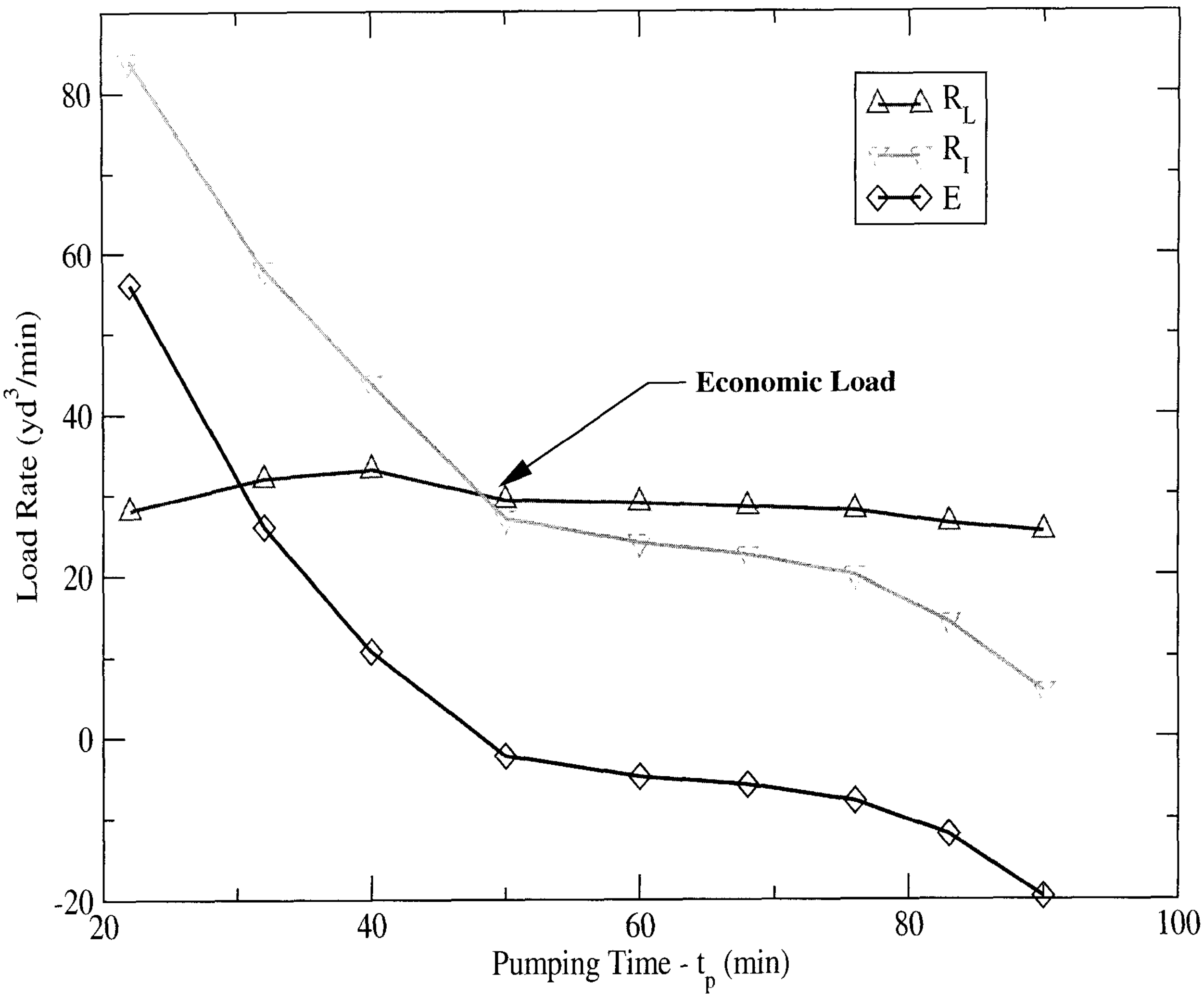

Figure 1: Form 2590 Economic load analysis from Table 1 data.

- Ship speed and heading
- Draft, displacement
- Hopper ullage and volume
- Draghead depth

Data quality assurance is a requirement of the SI specification. Each dredge must provide a detailed *Dredge Plant Instrumentation Plan* and pass a rigorous series of field tests designed to assure that data meet specifications.

To help assure data quality and assist on-board inspectors, the SI system analyzes data in real-time. All summary statistics required for standard inspector reports are computed as well as supplemental analyses to support performance evaluation, environmental, and safety requirements. For the discussion here, the important analyses are

- dredge state (ie. pumping, turning, sailing, dumping)
- track plot
- load summary statistics
- Tons Dry Solids (TDS)

Each of these is continuously computed and saved in an on-board relational database along with all of the raw data. Raw process variables are saved at 10sec intervals. TDS, dredge state, and track are recomputed at each 10sec interval.

Recognizing that all of the data necessary to compute the input variables for economic load were available in real-time, the New Orleans district has begun an investigation into the feasibility of using the SI to provide a **stop pump** advisory based on the current data for each load. Also recognizing the possible future incorporation of Ton-miles as a payment metric, the use of TDS rather than hopper volume is considered.

INCORPORATING TONS DRY SOLIDS

TDS is a production metric that estimates the total weight of the sediment in the hopper less the weight of all of the water content. TDS measurement for dredge production was developed and refined by the Netherlands *Rijkswaterstaat* (Ottevanger & van Rijn 1992). TDS implementation by the Corps in SI is described by Welp & Rosati (2000).

Automated TDS measurement requires the real-time measurement of the total volume of slurry in the hopper, V, and the weight of the ship M_s. Both are determined by level sensors. One set monitors the hopper slurry level. This level is converted to V using curves fitted to values from the hopper ullage chart. The other is the draft of the ship which is converted to M_s using the ship's displacement curves. M_s is measured for an empty hopper, and the mass of the hopper is computed by $M_h = M_{s_{loaded}} - M_{s_{empty}}$.

Summarizing the development of Rullens (1993), given the hopper volume and the hopper mass, the hopper slurry density $\rho_h = M_h/V$ can be estimated. Assuming the slurry is composed of sediment of density ρ_s and water of density ρ_w, the mass of only the sediment can be computed as

$$L_{TDS} = \frac{\rho_h - \rho_w}{\rho_s - \rho_w} \rho_s V \tag{4}$$

L_{TDS} is incorporated into the economic load computation by substituting it for volumetric hopper load L so that R_I and R_L are redefined as

$$R_I = \Delta L_{TDS} / \Delta T_p \tag{5}$$

where

$$\Delta L_{TDS} = L_{TDS_m} - L_{TDS_{m-1}}$$

The total retained load for the duration of a total cycle is

$$R_L = L_{TDS}/T_{cycle} \quad (6)$$

and the economic load parameter E is still computed using equation 3 using the TDS versions of R_I and R_L.

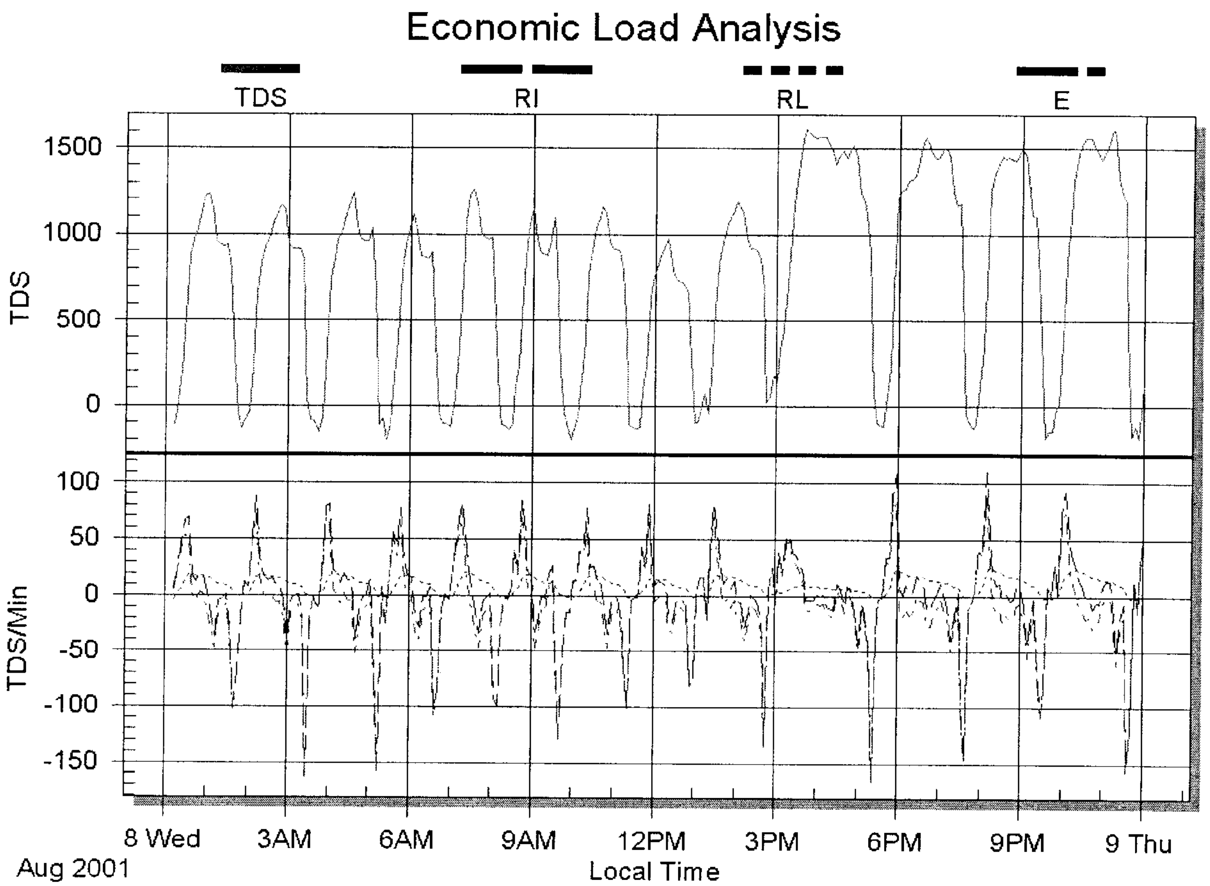

Figure 2: TDS, R_I, R_L, and E computed during a typical 24hr period of dredge cycles at Southwest Pass

REAL-TIME ANALYSIS

Previously recorded SI data from rental contract dredges operating in Southwest Pass of the Mississippi river were used to evaluate the feasibility of real-time computation of economic load using equation 3. An analysis module that computes E in real-time for each sample was added to the

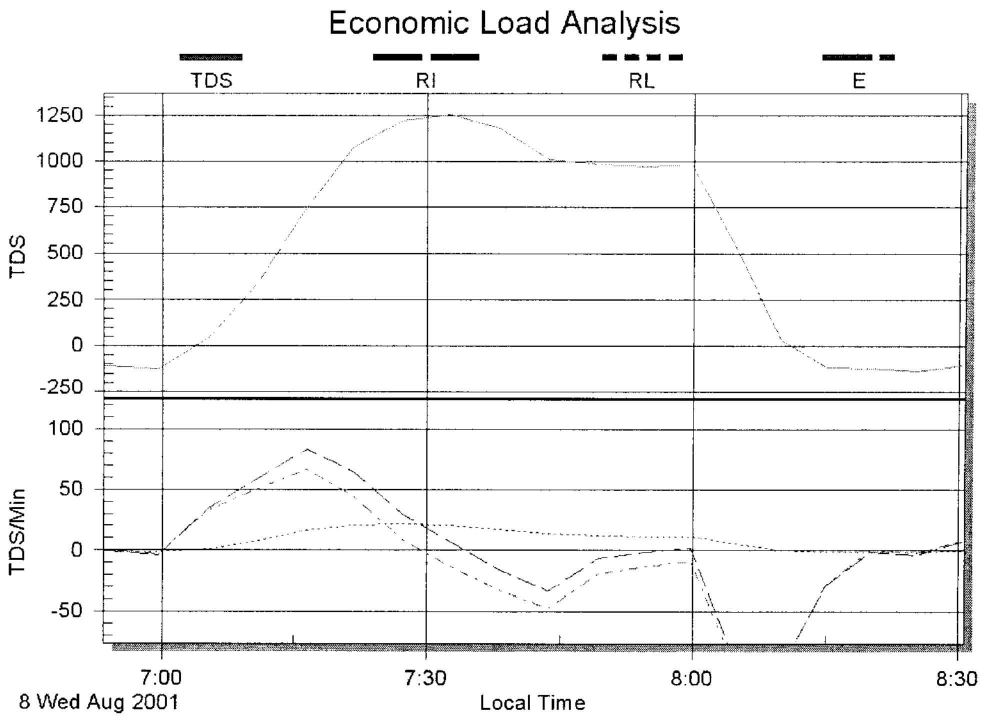

Figure 3: TDS, R_I, R_L, and E computed during a fine sediment dredge cut at Southwest Pass

SI on-dredge software. Figure 2 shows a plot of data recorded by the SI during a 24 hr period. The data are 10sec samples smoothed with a 300 sec moving window average. The smoothing is required to remove the variations due to the dynamics of the ship and the hopper slurry caused by wave action and maneuvering.

During this period, the TDS curves show two sets of cuts where the second set has 50% greater production than the first. However both sections require a T_D much less than T_L. This is a case where the use of an economic load criteria could be beneficial. The dredge is operating to maximize L but because of the short T_D this point occurs much later in the cycle than the economic load at E_0.

Figure 3 shows a view of a single cycle of dredging. The cut was in an area of fine sediment. The dredge was operated to maximize hopper density for the load. For this cycle T_{cycle} was approximately 1.5 hr while T_D was approximately 40 min or 44% of T_{cycle}. E_0 occurred at approximately 7:30 and was followed by 30 min of over-pumping. The peak load measured by TDS was 1.25 kT and coincided with E_0. It declined to 1.2 kT during overflow.

This result shows that automated real-time computation of E by SI is feasible for a typical overflow dredge operation. The results here suggest that it may be possible to improve total operational efficiency by using E_0 to trigger a **stop pumping** advisory. In this case cycle time could be reduced by 30% with no reduction in load.

Figure 4 shows another case where operation by economic load would depart significantly from current practice. In this case the dredge is operating in a cut with fine sand yielding high produc-

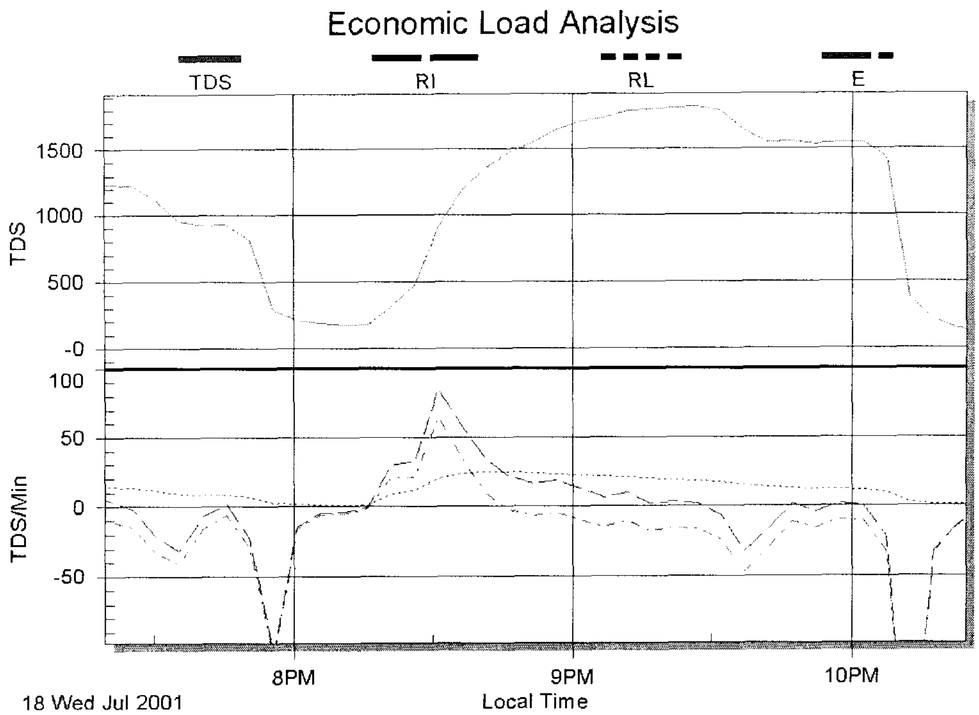

Figure 4: TDS, R_I, R_L, and E computed during a fine sand cut at Southwest Pass

tion. This cut is also close to the disposal site with $T_D \approx 35min$. E_0 occurs at approximately 8:50 at a TDS load of $L_{TDS} \approx 1.4kT$. However over-pumping continues another 50 min with the peak load reaching 1.9 kT before declining to 1.5 kT. This yields a $T_{cycle} \approx 2.25hr$ so that T_D is only 26% of T_{cycle} or half that of figure 3.

This case suggests that even in a cut yielding high production, the economic load may be better for a smaller load. In this case if pumping was stopped at E_0, the cycle time would have been reduced by 37% for a load reduction of 7%.

Effect of TDS errors

The SI implementation and quality assurance procedures have made substantial progress in improving the accuracy of routine automated TDS measurements. However with the current state-of-the-art in level sensing in the dynamic and hostile environment of a dredge at sea, there is still non-negligible error. Our current experience with SI capable dredges has shown that TDS errors should be less than 10% for a dredge instrumentation suite meeting specifications. Welp & Rosati (2000) provides details of the Corps TDS implementation and field experience. Scott (2000) presents an error sensitivity analysis of TDS measurement.

The TDS data shown in the figures illustrate typical errors. The plots in figures 2-4 show an $L_{TDS} \approx -100\ T$ after disposal when zero is expected. This can be caused by constant errors in the various terms of equation 4 and/or by vessel squat while underway.

Both figures 4 and 3 show a decline of TDS from the peak value after pumping stops. This seems unexpected but is the result of the lowering of hopper levels and loss of material due to continued run-off after pumping has stopped. The pump velocity sets up an increased static head in the hopper that must be run-off once the pump velocity goes to zero. This can also be affected by the downward adjustment of run-off weir levels. This represents real reduction in TDS and is not error.

Use of TDS as the load metric for economic load raises the question of the effect of errors on the economic load prediction. The observed TDS errors during quality assurance tests typically are bias errors. The economic load is related to the rate or the first order derivative of load so that errors do not translate directly to errors in E. We can model the effect of a bias error ϵ by substituting $L + \epsilon$ in the the computation of ΔL in equation 1.

$$\Delta L_\epsilon = (L_m + \epsilon) - (L_{m-1} + \epsilon) = \Delta L \tag{7}$$

observing that ϵ cancels. Then for equation 2 we have

$$R_{L\epsilon} = \frac{L + \epsilon}{T_{cycle}} = L/T_{cycle} + \epsilon/T_{cycle} \tag{8}$$

$$R_{L\epsilon} = R_L + \epsilon/T_{cycle} \tag{9}$$

so that R_L is in error by the TDS error divided by the cycle time. This translates directly to the error in

$$E_\epsilon = R_I - R_L + \epsilon/T_{cycle} \tag{10}$$

$$E_\epsilon = E + \epsilon/T_{cycle} \tag{11}$$

Evaluating this for an example case of $L_{TDS} = 1000T$ and a TDS bias error of 10%, $\epsilon = 100T$ and if $T_{cycle} = 100min$, then the error in E is $\epsilon/T_{cycle} = 1T/min$. This is an acceptable error for most operational requirements.

Predicting Disposal Time

The *Form 2590* manual computation assumes a constant disposal time T_D for each reach. A real-time system should determine T_D automatically. Better would be the ability to adjust the T_D prediction for each cut based on SI's knowledge of the ship position and distance to the disposal site.

The analysis of historical data shown here used a manually determined T_D. The field test implementation will evaluate an algorithm that predicts T_D for the next disposal by using T_D of the previous cut, the new cut distance difference , and the average ship speed. Future improvements may include adjustments for predicted tidal currents and typical ship traffic delays for the time of day.

CONCLUSIONS

The preliminary results of a real-time economic load analysis using TDS as the load metric are encouraging. The study has shown that all of the raw data for evaluation of the economic load are available in the SI data stream. The critical computations of dredge state and TDS have already been implemented and field proven. An economic load predictor based on a the procedure of *Eng Form 2590* adapted for TDS has been tested on data from operational dredges in Southwest Pass. The tests results show the potential for the reduction in dredge cycle times when the dredge is operating with overflow and is relatively close to the disposal site. For the example cases shown here cycle times could be reduced by 30% with reductions in load of less than 10%.

The next step in the study is to test the economic load predictor with a real-time **stop pumping** advisory during operational dredging. Tests are planned this season. Many factors affect the pumping time and disposal times so that the dredge cannot always execute the required maneuvers. Because of these and other real-world constraints, the improvements in efficiency may be less than indicated by the analysis here.

ACKNOWLEDGEMENTS

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