EVALUATION OF DREDGING PERFORMANCE IN A TRAILING SUCTION HOPPER DREDGER

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ABSTRACT

The performance and operational efficiency of a trailing suction hopper dredger currently heavily depend on the experience and insight of the operators on board of the ship. While dredging companies are interested in the continuous evaluation and improvement of the dredging performance, no sound evaluation methods have been proposed yet. In this paper, a systematic methodology is developed to evaluate the dredging performance based on data measured onboard. Four performance indices are proposed: *Added tons of dry solids*, *Dry solids production rate*, *Sand storage ratio* and *TDS mass ratio*. These indices facilitate performance evaluation from the production and time efficiency point of view. A dredging cycle is first evaluated as a whole to get an overall indication of the performance. Furthermore, in order to get more insight in what causes such a performance, the dredging cycle is divided into three phases: 1) initial filling of the hopper without overflow, 2) constant-volume phase with overflow, and 3) constant-tonnage phase with overflow automatically controlled by lowering the overflow pipe. The performance indices are then employed to evaluate the three phases separately. The proposed methodology can be used as a tool for an off-line analysis and also as a part of an on-board decision-support or advisory system. In this way, the operators can continuously evaluate the dredging performance and consequently adapt their control strategy if necessary.

INTRODUCTION

A trailing suction hopper dredger consists of a large number of interconnected subsystems such as the diesel engine, pump, pipeline, drag head, overflow pipes and hopper, as shown in Fig. 1. During dredging, the mixture of sand and water is excavated from the sea bottom by the drag head and transported to the hopper through the pipe by means of the pump. The sand settles at the bottom of the hopper. When the hopper is filled up to the overflow pipe, the low density mixture at the top of the hopper content overflows through this pipe, and consequently the density of the hopper content increases. The loading of the hopper than usually continues until the overflow losses become so high that it is no longer economical to continue dredging. The sand which stays in the hopper is regarded as the dredging production. The efficiency of excavation by the drag head and the efficiency of the sand sedimentation in the hopper both influence the dredging performance.

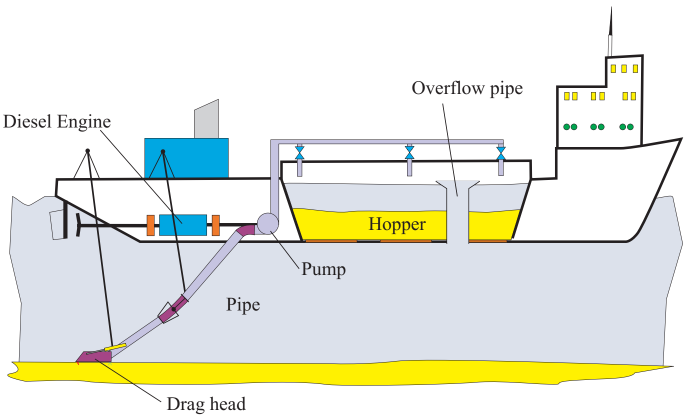

Figure 1. A schematic drawing of a trailing suction hopper dredger.

Two crew members usually operate the ship: one is responsible for maneuvering the ship and determines the ship's speed and the other one controls the excavation and storage process. In practice, the dredging process is influenced by the operators' control strategy and by disturbances (dredging depth, soil characteristics, sea bed condition). The presence of disturbances requires that the operators constantly adjust their control actions. Consequently, the performance and efficiency of the entire dredging process heavily depend on the experience and insight of the operators.

Nowadays, the dredging industry frequently becomes involved in large-scale projects, dealing with complex dredging environments and increasing amounts of sand production. Therefore, there is a demand for efficient management and operation of hopper dredgers. Recent developments in sensing, computing and information

technology have provided new tools for centralized data acquisition. However, the large amounts of gathered data rule out the possibility of manual inspection. Automatic techniques are therefore needed to analyze the data and to extract useful information.
In this paper, a model-free method is proposed to evaluate the dredging performance of a trailing suction hopper dredger (TSHD) based on data measured onboard. This approach differs from model-based methods (Rhee 2002), (Miedema 1996) and (Braaksma et al. 2007), in that it is purely data based and does not use models. The performance is evaluated from the sand production and time efficiency point of view. Furthermore, based on the evaluation results, the dredging performance is classified into several subsets to assist the decision-making process.
This paper is organized as follows. Section Phase Partition presents the partitioning of the dredging cycle into three phases. Performance indices and classification criteria are proposed in section Performance Indices and Classification Criteria. The results obtained on an available data set are presented and analyzed in section Evaluation and Classification Results and the section Conclusions and Recommendations concludes the paper.

PHASE PARTITION

In this paper, the dredging cycle is defined as the time interval between the start and the end of dredging, disregarding the sailing and discharging process. Considering the total volume V_t, the mass m_t of the hopper content, the heights of the overflow pipe h_o and the hopper content h_t, the dredging cycle can typically be divided into three phases, see Figure 2.

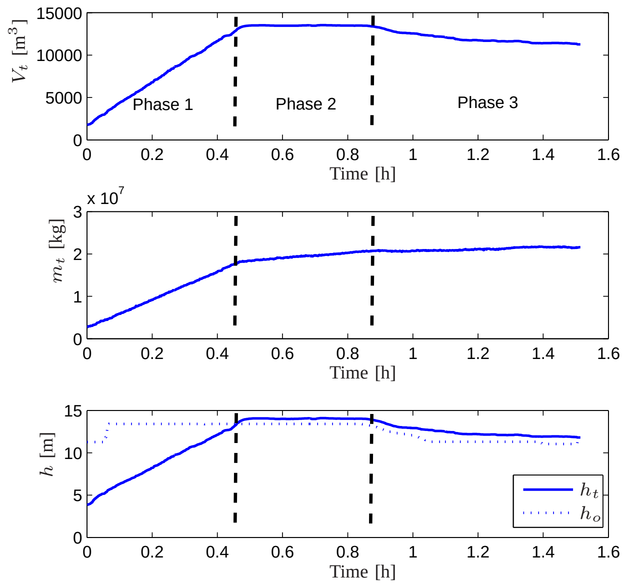

Figure 2. Cycle partition: V_t, m_t and h_t are the total volume, mass and height of the hopper content, respectively, and h_o is the height of the overflow pipe.

- *Phase 1* is the interval from the start of dredging until the mixture in the hopper reaches the overflow pipe, i.e., the interval in which $h_t < h_o$. There is no overflow in this phase and $m_t < m_{tmax}$ and $V_t < V_{tmax}$.
- *Phase 2* is the constant-volume phase: it starts as soon as h_t exceeds h_o and lasts until the total mass m_t reaches its maximal allowed value m_{tmax}. In this phase, $m_t < m_{tmax}$ and $V_t = V_{tmax}$.
- *Phase 3* is the constant-tonnage phase: it starts as soon as m_t exceeds m_{tmax} and lasts until the end of the dredging cycle. During this phase, the overflow pipe is lowered, either manually or automatically, such that m_t does not increase too much above m_{tmax}, see Figure 2. In this phase, $m_t \approx m_{tmax}$ and $V_t < V_{tmax}$.

The phase partition allows us to evaluate the dredging process in more detail and the separate evaluation of these three phases also helps to structure the subsequent control decisions.

PERFORMANCE INDICES AND CLASSIFICATION CRITERIA

Four numerical performance indices (PI) are proposed to quantify the dredging performance from different points of view.

Added Tons of Dry Solids – ΔTDS

The added tons of dry solids (ΔTDS) is the increment of tons of dry solids (TDS) during a given time interval:

$$\Delta TDS(t) = TDS(t) - TDS(t_s) \tag{1}$$

where t_s and t are the start and the end of the time interval, respectively. The time interval can be either the entire cycle or a particular phase of the cycle. The tons of dry solids is a standard index frequently used in the dredging industry. It is calculated as

$$TDS(t) = \frac{V_t(t)(\rho_t(t) - \rho_w)\rho_q}{1000(\rho_q - \rho_w)} \tag{2}$$

where ρ_q = 2650 kg/m^3 is the quartz density, ρ_w = 1024 kg/m^3 is the density of sea water and $\rho_t(t) = m_t(t)/V_t(t)$ is the total density of the hopper content at time t.

TDS Rate – TDSR

The TDS Rate (TDSR) quantifies the dredging efficiency by taking the duration of the time interval into account:

$$TDSR(t) = \frac{\Delta TDS(t)}{t - t_s} \tag{3}$$

Sand Storage Ratio – SSR

In Phase 2 and 3, light mixture above the overflow pipe is discharged. The Sand Storage Ratio (SSR) quantifies the relative amount of incoming sand that stays in the hopper:

$$SSR(t) = 1 - \frac{m_{so}(t) - m_{so}(t_s)}{m_{si}(t) - m_{si}(t_s)} = 1 - \frac{\int_{t_s}^{t}(\rho_o(t') - \rho_w)Q_o(t')dt'}{\int_{t_s}^{t}(\rho_i(t') - \rho_w)Q_i(t')dt'} \tag{4}$$

where m_{si} is the incoming sand mass and m_{so} is the outgoing sand mass due to the overflow losses. Further, ρ_i and ρ_o are the incoming and outgoing mixture density, respectively. A low sand storage ratio means large overflow losses, and therefore a waste of the incoming material and energy. The sand storage ratio is always within the interval $[0, 1]$, with the following (theoretical) limit values:

$$SSR = \begin{cases} 0, & \text{all the incomming sand is discharged overboard} \\ 1, & \text{all the incomming sand stays in hopper} \end{cases}$$

TDS Mass Ratio – TMR

The TDS Mass Ratio (TMR) index quantifies to what extent the hopper is filled by sand. It is computed as the ratio of TDS and m_t (expressed in tons):

$$TMR(t) = \frac{TDS(t)}{m_t(t)} \tag{5}$$

By inserting TDS from (2), we obtain:

$$TMR(t) = \frac{\frac{\rho_q}{\rho_q - \rho_w}(\rho_t(t) - \rho_w)V_t(t)}{m_t(t)} = \frac{\rho_t(t) - \rho_w}{\rho_q - \rho_w}\frac{\rho_q}{\rho_t(t)} = \frac{\rho_q}{\rho_q - \rho_w}\left(1 - \frac{\rho_w}{\rho_t(t)}\right) \tag{6}$$

and can easily see the two limit values of TDS mass ratio

$$TMR = \begin{cases} 0, & \text{for } \rho_t = \rho_w \\ 1, & \text{for } \rho_t = \rho_q \end{cases}$$

When dredging pure water, TMR is zero, and when dredging pure quartz, the TDS mass ratio would be one. However, in practice, it has a maximum around 0.8.

EVALUATION AND CLASSIFICATION RESULTS

In this section we illustrate the use of the proposed indices. Data from 12 dredging cycles are available. We classify them according to the dredging performance into good, average and poor, based on the sum of the performance indices. Cycles with the index sum ranking within the first 33% are regarded as good cycles, and the cycles with the index sum ranking within the last 33% are regarded as poor cycles.

Overall Performance of the Cycle

The indices TDS rate, sand storage ratio and TDS mass ratio are employed to evaluate the overall dredging performance. In Phase 3, mass m_t is constant until the dredging stops. Therefore, the final mass m_t is approximately the same in all the cycles. From this viewpoint, the TDS mass ratio is closely related with the TDS (refer to Equation 5). If m_t is exactly the same for all the cycles, then TDS mass ratio gives exactly the same evaluation result as TDS does. And since the initial TDS value is also similar for all cycles, the added tons of dry solids is abandoned when evaluating the overall dredging performance.

The TDS rate in the left panel of Figure 3 illustrates the dry solids productivity during the entire cycle. A high value of the TDS rate means that more sand was produced within the same dredging time. The right panel of the same figure shows the sand storage ratio. A higher value of sand storage ratio means that a higher percentage of the incoming sand is stored in the hopper. The TDS mass ratio index is shown in Figure 4. A low TDS mass ratio means that the total density in the hopper is low.

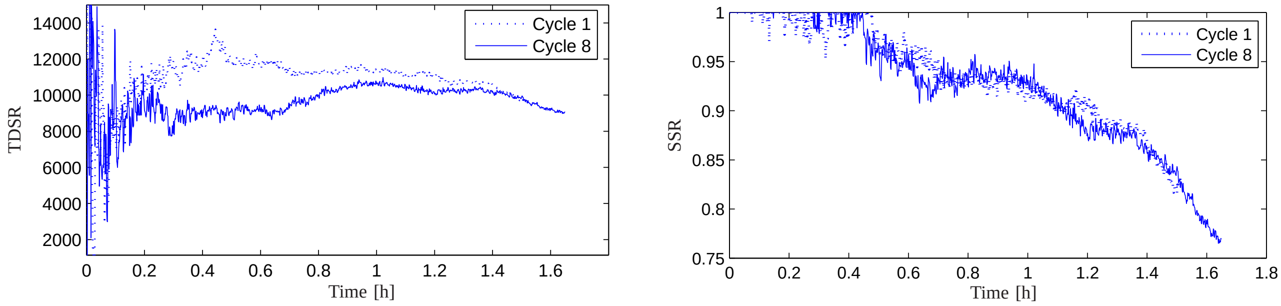

Figure 3. The indices TDSR(t) (left) and SSR(t) (right) for cycles 1 and 8.

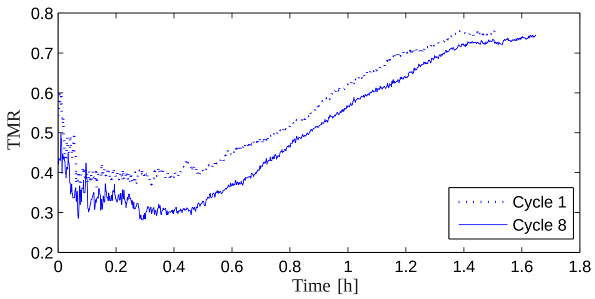

Figure 4. The TMR(t) index for cycles 1 and 8.

Table 1 lists the final values of the indices (i.e., the values at the end of the cycle) for the whole data set. As already discussed, the sand storage ratio and TDS mass ratio are in the interval $[0, 1]$. For comparison and analysis, the TDS rate is normalized to the interval $[0, 1]$ by the using the following formula

$$TDSR^* = \frac{TDSR - \min(TDSR)}{\max(TDSR) - \min(TDSR)} \tag{7}$$

where the minimum and maximum are taken over all the cycles in the data set.

Table 1. Performance indices for Cycles 1–12.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
TDSR*	0.65	0.59	0	0.33	0.62	0.42	0.50	0.37	0.53	1	0.59	0.22
SSR	0.83	0.87	0.86	0.84	0.82	0.88	0.88	0.77	0.78	0.81	0.91	0.86
TMR	0.76	0.74	0.72	0.75	0.75	0.72	0.74	0.74	0.74	0.75	0.61	0.72
Sum	2.23	2.21	1.57	1.91	2.19	2.02	2.13	1.88	2.05	2.56	2.11	1.80
Ranking	2	3	12	9	4	8	5	10	7	1	6	11

The TDS rate directly reflects whether a dredging cycle is efficient in terms of sand production. During a cycle with a high sand storage ratio, more sand remains in the hopper. This performance index, however, does not account for the total amount of sand in the hopper. To this end, the TDS mass ratio is employed to detect to what extent the hopper is filled by sand. The following combinations can be encountered in dredging projects.

- A high sand storage ratio and a high TDS mass ratio: Such a cycle is optimal. It has efficient sand storage and high sand production.
- A high sand storage ratio and a low TDS mass ratio: Such a cycle has efficient sand storage, but has a low sand production.
- A low sand storage ratio and a high TDS mass ratio: Such a cycle loses a large amount of sand, but has a high sand production.
- A low sand storage ratio and a low TDS mass ratio: Such a cycle has a poor performance with low sand production and high overflow losses.

The first three groups are the most frequent combinations of the sand storage ratio and the TDS mass ratio. If a cycle has a high sand storage ratio and TDS mass ratio, together with a high TDS rate, it is regarded as a good one. If either one of these two indices is low, the performance is clearly less than optimal. In our data, it is rare that all of these three indices are high, therefore an average or high TDS rate, together with a high sand storage ratio and TDS mass ratio, already indicate a good cycle.

The following analysis gives the reasons and examples for the above combinations of sand storage ratio and TDS mass ratio.

- A high sand storage ratio and a high TDS mass ratio: An optimal cycle in the data set (e.g., cycle 10).
- A high sand storage ratio and a low TDS mass ratio: There is still excessive water in the hopper, which should have been discharged through the overflow pipe (e.g., cycle 12).
- A low sand storage ratio and a high TDS mass ratio: The sand losses are too high because of inadequate control of the overflow pipe, which typically means that the cycle lasted longer than necessary (e.g., cycle 8).
- A low sand storage ratio and a low TDS mass ratio: This extreme condition is rare in practice because with excessive water in the hopper, it is still economical to continue the overflowing. Therefore a low sand storage ratio and a low TDS mass ratio are to a certain extent contradictory.

In Table 1, a sum of the indices is used to classify the overall dredging performance (regarding the indices as having the same importance). However, depending on the project management purpose, other (weighted) criteria can be used as well. For example, if the amount of production is most important, the added tons of dry solids should have a higher weight than the remaining indices. If the emphasis is on the productivity, TDS rate should have a higher weight. For example, one can use the following formula as the classification criterion for the overall performance.

$$P = \frac{aTDSR + (1-a)SSR}{10^{|TMR-c|}} \tag{8}$$

The weight a determines the relative importance of $TDSR$ and SSR. The denominator $10^{|TMR-c|}$ accounts for the load of the hopper. In Table 1, most of the cycles have TDS mass ratio values around 0.74. A low TDS mass ratio means the hopper is not fully filled by sand (e.g., cycle 11). The value of $10^{|TMR-c|}$ will stay below 1.1 when the value of $|TMR - c|$ is smaller than 0.04. However, when the TDS mass ratio becomes smaller, the value of $10^{|TMR-c|}$ will increase much faster, and will greatly decrease the value of P in (8). The value of P is always within the interval $[0, 1]$. The bigger it is, the better performance it indicates. Table 2 shows the classification results using this index.

Table 2. Performance classification of Cycles 1–12, with $a = 0.5$, $c = 0.74$.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
P	0.71	0.73	0.41	0.57	0.71	0.62	0.69	0.56	0.65	0.89	0.55	0.51
Ranking	3	2	12	8	3	7	5	9	6	1	10	11

For on-line decision-making support, combinations of the proposed indices are applied to the individual phases, as shown in the following sections.

Performance of Phase 1

The measured incoming mixture density ρ_i and flow-rate Q_i give information on the mass-flow of the mixture entering the hopper, and therefore direct quantify the performance in Phase 1, see Figure 5. As there is no overflow in this phase, the incoming flow Q_i determines the duration of Phase 1, and the incoming sand mass

$$\frac{\rho_q}{\rho_q - \rho_w}(\rho_i - \rho_w)Q_i$$

gives the sand production rate. Therefore, the TDS and TDS rate indices are used to evaluate the performance in this phase.

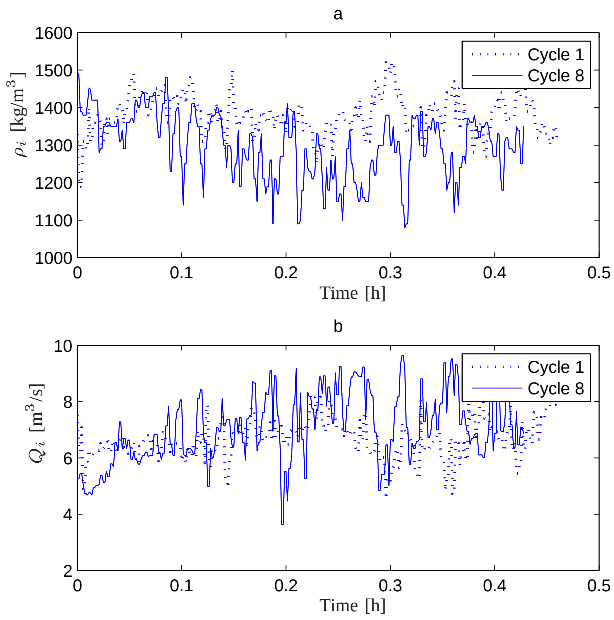

Figure 5. Two cycles with different ρ_i and Q_i in Phase 1.

The other two indices are not suitable: the sand storage ratio is always 1 in Phase 1, since there is no overflow, and the TDS mass ratio is always low due to the low total density ρ_t. For all the cycles, the tons of dry solids increases linearly in Phase 1 and the TDS rate is the slope of the line. It therefore quantifies the efficiency of sand production.

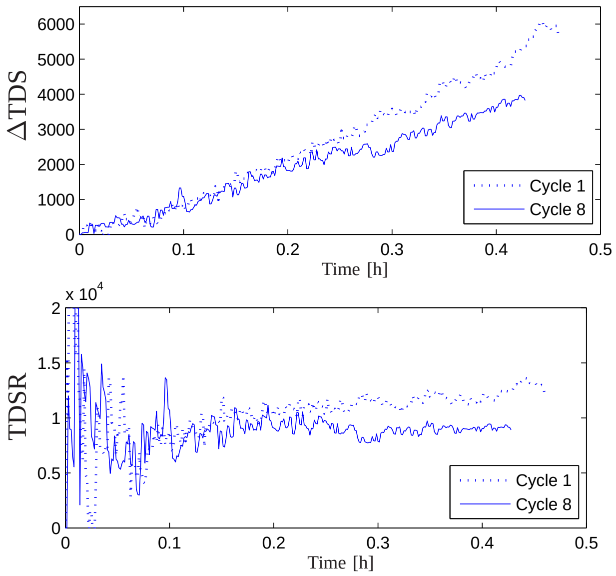

Figure 6. ΔTDS (left) and TDS rate (right) in Phase 1 of cycles 1 and 8.

Figure 6 shows an example of two different cycles. Note that the added tons of dry solids and TDS rate indices for cycle 1 are larger and grow faster than for cycle 8. Their values at the end of Phase 1 indicate the dredging performance in this phase. Clearly, cycle 1 has a much better performance than cycle 8. Table 3 gives the performance indices and the normalized performance indices (PI*) for all 12 cycles in the data set.

Note the difference between the added tons of dry solids and the TDS rate. For example, cycle 7 has a ΔTDS* of 0.6, which ranks 4th in all the 12 cycles. At the same time, its TDSR* only ranks 8th, which means although in cycle 7 a large amount of sand was excavated in Phase 1, the overall performance is worse due to the long duration of this phase.

Table 3. Performance indices for Phase 1 of cycles 1–12.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
ΔTDS(10^3)	5.67	5.08	4.71	5.54	4.81	4.96	5.26	3.82	6.19	6.01	3.86	4.62
ΔTDS*	0.78	0.53	0.37	0.72	0.41	0.48	0.60	0	1	0.92	0.02	0.34
TDSR(10^4)	1.23	1.15	0.92	1.16	1.03	1.04	0.99	0.89	1.35	1.25	0.86	1.02
TDSR*	0.75	0.58	0.12	0.61	0.35	0.37	0.25	0.06	1	0.80	0	0.31
Sum	1.53	1.11	0.49	1.33	0.76	0.85	0.85	0.06	2	1.72	0.02	0.65
Ranking	3	5	10	4	8	6	6	11	1	2	12	9

The following analysis gives the reasons and examples for the combinations of the added tons of dry solids and the TDS rate.

- A high added tons of dry solids and a high TDS rate: An optimal phase performance (e.g., cycle 9).
- A high added tons of dry solids and a low TDS rate: The incoming density ρ_i is satisfactory, while the incoming flow rate Q_i is low, which causes a long phase duration (e.g., cycle 7).
- A low added tons of dry solids and a high TDS rate: The incoming density ρ_i is low which causes a low sand production, while the incoming flow rate Q_i is relatively high. In practice, this combination does not occur, because a low sand production hardly brings a high sand production rate.
- A low added tons of dry solids and a low TDS rate: Both the incoming density ρ_i and the incoming flow rate Q_i are low (e.g., cycle 8).

Performance of Phase 2

Phase 2 the constant-volume phase. Both the sedimentation rate and the overflow losses influence the performance. Due to the overflow of low-density mixture, the total density of sand in the hopper is increasing, as shown in Figure 7.

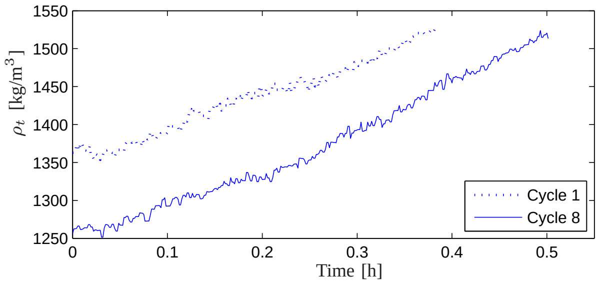

Figure 7. Different ρ_t in Phase 2 (cycles 1 and 8).

In this phase, the added tons of dry solids is not a useful index, because at the end of the phase, all the cycles have the same total volume V_t and total mass m_t. Therefore it can be expected that at the end of Phase 2, the total mixture density ($\rho_t = m_t/V_t$) in the hopper will be the same (or almost same) for all the cycles, see Figure 7. Therefore the sand production at the end of Phase 2 for all the cycles will be (almost) the same. If one cycle has a high added tons of dry solids at the end of Phase 1, then it cannot also have a high added tons of dry solids at the end of Phase 2. In our example, cycle 1 cannot store that much sand as cycle 8 in Phase 2, due to the capacity limitation of the hopper.

However, the TDS rate can be used to evaluate the Phase 2. It is effective because the duration time of Phase 2 taken into account. One cycle with a good Phase 1 (characterized by a high added tons of dry solids and TDS rate) can still have a high TDS rate in Phase 2.

Besides the TDS rate, the sand storage ratio applies to this phase. Since the position of the overflow pipe does not change in Phase 2, the incoming flow Q_i is the same with outgoing flow Q_o (in steady state). Therefore, sand storage ratio mainly depends on the difference between ρ_i and ρ_o. Figure 8 shows an example of two different cycles. Clearly, cycle 8 has a better Phase 2 than cycle 1.

Table 4 gives the performance indices and normalized performance indices (PI*) at the end of Phase 2 for all the cycles in the data set.

The following analysis gives the reasons and examples for the combinations of TDS rate and sand storage ratio.

- A high TDS rate and a high sand storage ratio: An optimal phase (e.g., cycle 5).
- A high TDS rate and low sand storage ratio: The incoming density ρ_i is satisfactory, while the overflowing density ρ_o is too high, which causes high sand losses (e.g., cycle 1).

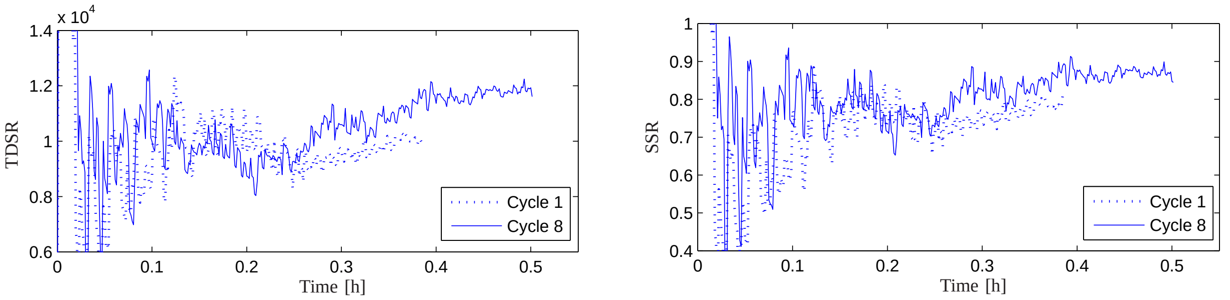

Figure 8. TDSR (left) and SSR (right) in Phase 2 of cycles 1 and 8.

Table 4. Performance indices for Phase 2 of cycles 1–12.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
TDSR(10^4)	1.0	0.97	0.74	0.69	1.23	0.92	0.94	1.16	0.95	1.22	1.03	0.84
TDSR*	0.57	0.51	0.09	0	1	0.43	0.46	0.87	0.47	0.99	0.62	0.28
SSR	0.78	0.80	0.76	0.56	0.84	0.8	0.85	0.85	0.72	0.82	0.87	0.79
SSR*	0.70	0.78	0.64	0	0.92	0.78	0.93	0.93	0.52	0.85	1	0.75
Sum	1.27	1.39	0.73	0	1.92	1.21	1.39	1.80	0.99	1.83	1.62	1.03
Ranking	7	6	11	12	1	8	6	3	10	2	4	9

- A low TDS rate and a high sand storage ratio: Both the incoming and overflowing densities are low (e.g cycle 7).
- A low TDS rate and a low sand storage ratio: The incoming density ρ_i is low, while the outgoing density ρ_o is relatively high (e.g., cycle 4).

Performance of Phase 3

In Phase 3, not only the efficiency in dry solids production, but also the efficiency in sand storage is important. Overflowing too much sand in Phase 3 is a waste. If the overall process is properly controlled, such a waste is avoidable. The time duration of Phase 3 is also important. Many cycles have a good Phase 1 and 2, but a poor Phase3 (e.g., cycle 10). This is mainly caused by a too long duration of this phase, reflected in a low TDS rate and sand storage ratio values.
Similarly to Phase 2, the TDS rate and sand storage ratio indices are employed in Phase 3, see Figure 9. Higher values indicate better performance Phase 3 they indicate. A low TDS rate means that the sand productivity is low, and a low sand storage ratio indicates that too much of the incoming sand is discharged. Table 5 shows the values of the TDS rate and the sand storage ratio at the end of Phase 3.

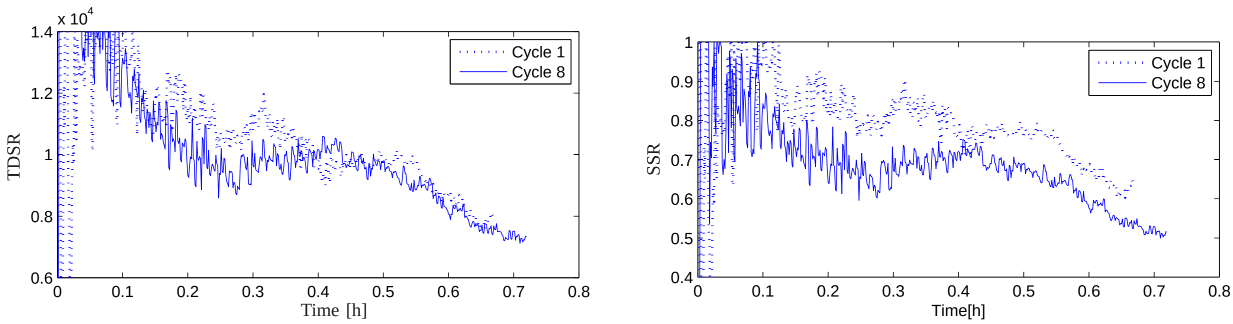

Figure 9. TDSR (left) and SSR (right) in Phase 3 of cycles 1 and 8.

Table 5. TDSR and TDSR* for Phase 3 of cycles 1–12.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
TDSR(10^4)	0.8	0.84	0.78	0.82	0.79	0.82	0.90	0.73	0.69	0.86	1.0	0.77
TDSR*	0.35	0.48	0.28	0.41	0.33	0.41	0.68	0.15	0	0.54	1	0.26
SSR	0.64	0.77	0.78	0.76	0.61	0.77	0.75	0.53	0.55	0.58	0.79	0.72
SSR*	0.43	0.95	0.96	0.92	0.29	0.93	0.85	0	0.06	0.19	1	0.75
Sum	0.78	1.43	1.24	1.33	0.62	1.34	1.53	0.15	0.06	0.73	2	1.01
Ranking	8	3	6	5	10	4	2	11	12	9	1	7

Phase 3 is the last Phase of dredging and sedimentation process. Cycles with good Phase 1 and 2 do not necessarily have a good Phase 3 (cycle 10, for example). In several cycles, too much sand is discharged in Phase 3, or this phase lasts too long, with poor sand productivity. The following analysis gives the reasons and examples for the combinations of the TDS rate and the sand storage ratio.

- A high TDS rate and a high sand storage ratio: An optimal Phase 3 (e.g., cycle 11).
- A high TDS rate and a low sand storage ratio: The incoming density ρ_i is satisfactory, while the overflowing density ρ_o is very high, which causes high sand losses (e.g., cycle 10).
- A low TDS rate and a high sand storage ratio: Both the incoming density ρ_i and the overflowing density ρ_o are low (e.g cycle 3).
- A low TDS rate and a low sand storage ratio: The incoming density is low while the overflowing densities is high (e.g., cycle 9).

Performance Evaluation and Classification Summary

The classification results are obtained based on classifying the sum of PI's into three equally-sized subsets: 'Good', 'Average' and 'Bad', in Table 6 abbreviated to 'G', 'A' and 'B', respectively.

Table 6. Classification results for cycles 1–12.

Cycle	1	2	3	4	5	6	7	8	9	10	11	12
Overall	G	G	B	B	G	A	A	B	A	G	A	B
Phase 1	G	A	B	G	A	A	A	B	G	G	B	B
Phase 2	A	A	B	B	G	A	A	G	B	G	G	B
Phase 3	A	G	A	A	B	G	G	B	B	B	G	A

From this table we conclude that most of the cycles with a poor overall performance exhibit two poor phases (cycles 3, 8, 12). Cycles with a good overall performance have at least one good phase and one average phase. Cycle 11 is an extreme case, as it stopped earlier than it was supposed to. Therefore the hopper does not overflow enough water, and the sand loss is also low. From the view point of phase performance, it has good Phase 2 and 3. However, a low TDS mass ratio of cycle 11 indicates that the hopper is not fully filled. In addition, cycles 6 and 7 exhibit a satisfactory performance in all three phases, but have a relatively low overall value of the TDS rate.

Interestingly, in our data set, the overall as well as phase-related performance correlate with the ship's speed. Figure 10 shows the relationship between the sum of the performance indices and the average sailing speed. We found that a high sailing speed correlates with good performance in Phase 1, but at the same time with poor performance in Phase 3. In Phase 1, a high sailing speed will enable the drag head to excavate more sand in the same time interval and so result in a high sand production rate. However in Phase 3, this same strategy will cause more sand losses and energy waste. The dashed lines in the figure represent a linear fit, which shows the trend of the performance with respect to the mean speed. Phase 2 correlates most with the overall performance and least with the sailing speed.

CONCLUSIONS AND RECOMMENDATIONS

We have proposed four different performance indices to evaluate the dredging performance: *Added tons of dry solids*, *Dry solids production rate*, *Sand storage ratio* and *TDS–Mass ratio*. These indices facilitate the performance evaluation from the production and time-efficiency point of view, both for the entire cycle, as well as for the individual phases of the cycle. Based theoretical analysis and computations with available data, we conclude that the indices are suitable for the individual phases according to Table 7.

Table 7. Performance indices suitable for the individual phases and the overall cycle.

	ΔTDS	TDSR	SSR	TMR
Phase 1	√	√		
Phase 2		√	√	
Phase 3		√	√	
Overall		√	√	√

In our future research, we will explore in more detail the reasons behind the variation in performance and develop control laws for the variables that influence the performance most, such as the sailing speed. The relationship between the performance and energy consumption will also be investigated.

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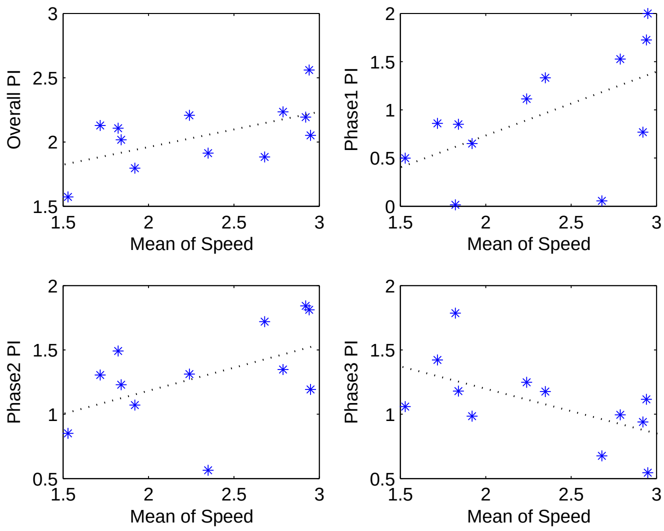

Figure 10. Relationship between the mean sailing speed and the performance indices.

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