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Evaluation path for the mud transportation performance of grab dredgers based on calculation methods

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SUMMARY: *Under the circumstances of continuous advancement in offshore dredging operations, port expansions and land reclamation projects, suction dredgers are confronted with technical challenges such as increased pressure loss, unstable flow state and excessive energy consumption in the mud transportation process. To enhance the accuracy and practicality of the performance evaluation for mud transportation and improve the engineering application, this study developed a performance evaluation system based on computational analysis. By calculating key parameters such as slurry density, average flow velocity, critical flow velocity, total pressure loss and unit solid mass transportation power, a set of evaluation indicators covering dimensions such as transportation capacity, operational reliability, system load and economy were constructed. Finally, a complete comprehensive evaluation framework was formed. Experimental data show that under typical operation conditions, the average relative deviation of total pressure loss is 4.72%, the average relative deviation of unit solid mass transportation power is 5.36%, and the accuracy of comprehensive grade determination reaches 91.7%. Its overall performance is significantly superior to traditional CFD simulation and empirical formula calculations. The study confirmed that this evaluation system can effectively identify the mud transportation conditions of suction dredgers, providing reliable data support for parameter optimization, fault diagnosis and construction scheme optimization.*

Povzetek: Prispevek obravnava ocenjevanje učinkovitosti transporta mulja pri bagrih s sesalnim lijakom na podlagi računskih metod. Oblikovan je okvir, ki povezuje izračun ključnih parametrov, sistem kazalnikov in celoviti model vrednotenja. Rezultati kažejo boljše ravnotežje med natančnostjo, učinkovitostjo in uporabnostjo pri odločanju kot pri klasičnih pristopih v tipičnih delovnih pogojih med poglabljanjem.

KEYWORDS: *Grab dredger; Mud transportation; Calculation method; Performance evaluation*

1 Introduction

With the continuous expansion of the scale of coastal channel improvement, harbor basin excavation, and coastal dredging projects, the role of suction dredgers in the dredging construction system has become increasingly prominent. Compared to simple excavation operations, the mud transportation process is more directly related to the release of ship capacity, the utilization of cargo space, and the continuity of the construction process, and is an important link determining the efficiency and energy consumption level of the operation [1]. In actual conditions, the mud transportation process of suction dredgers is not a stable

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single-phase flow, but is a complex solid-liquid two-phase transportation process affected by multiple factors such as particle size composition, volume concentration, flow velocity fluctuations, pipeline structure, local losses at elbows, and pumping conditions [2]. Once the parameter matching is unbalanced, it will often cause abnormal increase in pressure drop, intensified local deposition, decreased transportation efficiency, and even pipe blockage, which not only increases construction costs but also weakens the stability of the entire ship's operation organization [3]. Therefore, how to establish a reliable, comparable and interpretable assessment approach for evaluating the performance of mud transportation has become a key issue in the refined construction management of grab dredgers.

At present, there are literature reports on aspects such as pipeline mud pressure drop prediction, particle size movement analysis, CFD numerical simulation, CFD-DEM coupled calculation, and digital twin state monitoring [4], providing a good foundation support for the understanding of mud transportation mechanisms. However, directly applying these methods to the evaluation of grab dredger operations has the following shortcomings: There are still two problems: First, some methods only consider a single type of motion state or local water dynamic characteristics, and cannot incorporate all factors such as pressure drop, transport concentration, flow stability and energy consumption into the same evaluation framework; Second, some methods, although having high calculation accuracy, have complex modeling. A large number of parameters are required and difficult to implement, resulting in the correlation between the evaluation results and actual operation decisions needing to be strengthened [5]. In simple terms, we urgently hope to have a clearer path to connect the "calculable" aspect of mud transportation with the "easy-to-assess, clear and convenient-to-use" aspect.

To address this issue, we attempt to start from developing new calculation methods. By using measured empirical relationships, numerical simulation methods and parameter estimation methods, the relationship between the flow velocity changes, pressure drop, particle size distribution and energy consumption of the drilling fluid circulation system can be expressed, and it can be used for quantitative analysis and grading evaluation of the drilling fluid transport performance [6]. Therefore, this paper studies the sludge discharge system of the grab dredger and designs the mathematical model of key links, the index evaluation system and the comprehensive evaluation model, forming an efficiency evaluation path that takes into account both accuracy and timeliness. The main contents include literature review; design of efficiency evaluation methods; then comparative analysis of different algorithms and simulation tests; finally, study the effectiveness and optimization space of this evaluation method and its application boundary conditions, with the aim of providing a reference for the diagnosis of the sludge discharge pipe working condition of the grab dredger and parameter optimization.

2 Relevant Work

The evaluation research on the mud transportation capacity of suction dredgers mainly focuses on two technical approaches: one is based on the hydraulic and mathematical simulation of the water flow within the mud pipes during the flow process; the other is based on the engineering application research of the construction practice, state monitoring, and process optimization of suction dredgers. The former aims to answer questions such as "how does the sediment flow within the pipes, what are the reasons for its loss, and how to calculate it"; the latter pays more attention to "what stability the vessel should maintain during actual operation and how to improve its efficiency and safety". The results of these two studies have different emphases, but they are all the basis for the assessment made in this paper.

In terms of slurry transportation calculation, the research focus is mostly concentrated on key issues such as pressure loss, particle distribution, critical flow velocity, and local resistance. Haimoni et al. [7] proposed a simplified method for predicting the pressure drop of solid hydraulic transportation, providing an empirical basis for rapid engineering estimation. Doron et al. [8] and Gillies et al. [9] established a layered description approach for slurry flow in horizontal pipes, providing a more detailed explanation of the forces and energy losses of the solid-liquid two-phase system under different flow states. With the development of computational fluid dynamics, Kim et al. [10] and Joshi et al. [11, 12] used CFD to conduct numerical analysis of slurry pressure drop and the influence of roughness, proving that the calculation method has obvious advantages in parameter sensitivity studies. For transportation conditions with more complex particle shapes, Chen et al. [13] and Li et al. [14] further introduced the CFD-DEM coupling method to characterize the movement characteristics of non-spherical particles in bends, vertical-bend-horizontal combinations, and other pipe sections. Ravelet et al. [15] and Peretz et al. [16] also supplemented relevant data on large-diameter horizontal transport and pipe bend pressure drop based on an experimental combined with model approach. Overall, on the basis of the established multi-level calculation method for debris flow pipeline transportation that incorporates empirical formulas, most studies are still based on a single pipeline system. The studies do not fully consider factors such as the periodic changes in working conditions, the pulsation of sludge discharge, changes in soil quality, and the limitations of the ship machinery for vessels like dredgers with scoop suction.

Research on vessels like dredgers with scoop suction has mostly focused on their construction efficiency, operational stability, and monitoring status. For instance, Bai et al. [17] analyzed the relationship between the operation plan and productivity of the scoop suction dredger; at the same time, they also used the grey system method to optimize the progress of dredging projects and provided a quantitative method for adjusting the working conditions of the vessel operation. Additionally, Li et al. [19] proposed a virtual sensing technology based on digital twins to improve the ability to detect construction status and ensure safe operation. Wang et al. [20] focused on the ship movement mode and its connection with the accuracy of dredging, pointing out that the performance of the operation is not only dependent on the function of the equipment but also influenced by dynamic conditions. Finally, Chen et al. [21] and Zhou et al. [22] conducted detailed studies on the flow field patterns and key parameters in the process of sediment dispersion and online prediction of key parameters during the operation of the scoop suction dredger, indicating that the scoop suction dredger has evolved from an empirical management model in the past to a data-based and model-based management approach. However, the evaluation criteria for the slurry transport capacity of the scoop suction dredger still need to be further clarified. The existing results either focus on construction organization or on the identification of certain local parameters, and have not yet integrated pressure drop, concentration, transportation stability, energy consumption level, and engineering applicability into a set of assessment paths that can be compared and judged. Table 1 summarizes the main contents and shortcomings of the relevant research.

Table 1: Summary of Relevant Studies and Their Main Findings

Research Category	Representative References	Methods and Objects	Main Conclusions	Implications for This Study and Limitations
Empirical prediction of slurry pipelines	[15][18]	Empirical pressure-drop equations; transport of bidisperse particles	Pressure drop can be estimated rapidly, which is convenient for engineering applications	Computationally efficient, but adaptability to complex operating conditions is limited
Stratified-flow and two-phase flow models	[21][22]	Experiments and models of slurry flow in horizontal pipes	Can better explain the interaction between the sediment layer and the main flow region	Helpful for understanding flow-pattern evolution, but difficult to directly cover shipborne composite pipeline systems
CFD numerical simulation	[12][13][20]	Straight-pipe flow, roughness, and pressure-drop calculation	Can analyze parameter sensitivity and flow-field distribution	High accuracy, but computational cost is high and boundary-condition settings are demanding
CFD–DEM coupled analysis	[10][11]	Transport in non-spherical particles, bends, and combined pipe sections	Can reveal particle trajectories, local deposition, and elbow-loss mechanisms	Suitable for refined mechanism analysis, but difficult to use for rapid engineering evaluation
Studies on pumping and local devices	[14][16][17][19]	Experiments on slurry pumps, horizontal pipes, and elbow transport	Supplementary data are provided on local losses and device performance	Valuable for constructing an index system, but mainly focused on individual components
Optimization of cutter suction hopper dredger operations	[2][3][5]	Analysis of construction cycle, productivity, and motion accuracy	Can improve operational organization efficiency and dredging accuracy	More focused on construction procedures, with limited attention to slurry transport performance evaluation

As shown in Table 1, the existing studies have provided a relatively solid foundation for the calculation of mud transportation parameters, the explanation of the flow mechanism, and the identification of the construction status. However, there are still significant differences between different studies: the pipeline transportation research focuses on the mechanism and local calculations, while the dredger-pusher research focuses on the operation process and operation management. These two aspects have not yet achieved effective integration at the "performance evaluation" level. That is to say, at present, there is no shortage of calculation methods, but what is lacking is an evaluation framework that can convert the calculation results of key parameters into a comprehensive performance judgment. Based on this, this paper intends to, on the basis of the existing calculation methods, extract the key parameters of mud transportation for dredger-pusher, construct an index system including transportation capacity, energy consumption level, flow stability, and engineering applicability, and further form an evaluation path that can be used for comparing different methods and explaining the differences in actual working conditions, in order to improve the completeness and usability of the analysis of mud transportation performance.

3 Design of Evaluation Method for Mud Transport Performance of Grab-Type Dredgers Based on Computational Methods

To more accurately assess the mud transport performance of grab-type dredgers, this chapter focuses on the method design based on the evaluation concept supported by computational methods. By considering the flow characteristics and transportation conditions of the mud in the onboard pipelines, the key parameters that affect the transport efficiency are first analyzed through calculation, including flow velocity, concentration, pressure drop, energy consumption, and local losses, etc. On this basis, the core indicators that can reflect the transport capacity, stability, and economy are extracted. Based on different calculation results, a model for evaluating the performance of mud transportation is established. The characteristics and evolution patterns presented under different working conditions are studied and analyzed. The mud transportation effect is objectively evaluated from qualitative to quantitative, thereby improving the operational capacity of the suction dredger and making the selection of engineering measures more scientific and reasonable.

3.1 Calculation Method for Key Parameters of Mud Transport in Grab-Type Dredgers

For the assessment of the mud transportation capacity of the barge cutter dredger, we need to break away from the state of relying solely on experience and instead base it on a complete set of measurable and comparable key parameters. Compared to traditional fluid transportation devices, the transportation system of the barge cutter dredger is affected by various factors such as the excavation depth, soil properties, particle size, the operating state of the ship's pumps, the curvature of the pipelines, and the frequency of operation. Its movement pattern is dynamic. Simply looking at the liquid flow rate or the pressure at a certain point may not be sufficient to truly understand the reasons for why the transportation capacity has decreased, the pressure drop is too large, or local siltation is severe, etc. Based on this understanding, this paper classifies the calculation of the main parameters into four categories: mud physical property parameters, flow state parameters, resistance loss parameters, and energy consumption parameters. Eventually, a cyclic research mechanism is formed, providing a basis for the subsequent construction of the evaluation index system.

The identification of the mud physical properties provides a foundation for calculating the mud transportation. When the barge cutter dredger is conducting dredging operations, it does not inhale a uniform medium, but rather a mixture containing water, sand particles, fine soil, and a small amount of very small particles. Its density will change with the volume concentration. Let the solid phase density be ρ_s, the liquid phase density be ρ_w, and the volume concentration be C_v. Then the mixed-phase density of the mud is as follows:

$$\rho_m = C_v\rho_s + (1 - C_v)\rho_w \tag{1}$$

Equation (1) is the basic expression of the mass configuration of the slurry. The mixing factor density is not merely a descriptive parameter; it plays a crucial role in subsequent flow rate determination, pressure drop prediction, and energy consumption evaluation. During on-site construction, the slurry concentration may change due to soil layer disturbance or suction effect. Therefore, converting each working condition into the mixing factor density can enhance the homogeneity of parameter comparison.

With the basic properties of the slurry, the average velocity inside the pipe can be calculated. Let the flow rate be q and the pipe diameter be d, then the average velocity v is.

$$V = \frac{4Q}{\pi D^2} \tag{2}$$

Whether the fluid slurry can be transported stably mainly depends on its average flow rate. When the flow rate is small, the particles are prone to deposit at the bottom of the pipe and may cause sedimentation; while a large flow rate will increase the power consumption of the pump and the wear of the pipe wall, which is not an ideal state for continuous operation. Therefore, for a grab dredger, it is not necessarily the larger the better; the key is to find an appropriate transportation distance.

Therefore, to determine whether the current flow rate is within the safe range, a critical velocity needs to be introduced. For the research on slurry transportation, we can use the commonly used expression in engineering to define V_c as:

$$V_c = K\sqrt{2gD\left(\frac{\rho_s - \rho_w}{\rho_w}\right)d_{50}} \tag{3}$$

In the above equation: g represents the gravitational acceleration; d_{50} indicates the characteristic diameter of particle size; K is a coefficient that takes into account the geometric characteristics of the particles, the mass fraction, and the characteristics of the pipeline. From equation (3), it can be seen that this is the condition that needs to be met for the particles to maintain a suspended motion state or a continuous motion state. In practical work, the current working state can be determined by comparing V obtained from equation (2) with V_c calculated from equation (3): when V is much smaller than or close to V_c, it indicates that the system has entered an unstable operation stage; while when V is greater than V_c and has a certain safety margin, it indicates that this transportation mode is relatively stable.

After determining the fluid motion state, the resistance loss needs to be calculated. The dredging vessel's sludge transportation system mainly consists of the feed pipe, the pipes before and after the pump, the elbows, the valves, and the pipeline to the sludge tank. The resistance does not come from a single local position but is the result of the combined effect of all components. There are overall losses on the long-distance pipeline and local losses at each node on the branch lines. The pressure loss along the line can be expressed as the following equation:

$$\Delta P_f = \lambda\frac{L}{D}\cdot\frac{\rho_m V^2}{2} \tag{4}$$

In this equation, ΔP_f represents the pressure drop along the pipeline, λ is the resistance coefficient, and L is the equivalent pipe length. This equation retains the classic framework for calculating pipe flow losses, while introducing the mud mixing density, enabling it to adapt to the conditions of solid-liquid two-phase transportation. During the operation of a clamshell dredger, as the soil quality and concentration change, λ is not a fixed value. Usually, it needs to be corrected by considering the pipe wall roughness, flow state, and particle influence.

Compared to the more regular pipeline systems on land, the onboard transportation pipelines are often space-constrained, with a large number of bends and connectors, and local losses cannot be ignored. The pressure drop can be expressed as:

$$\Delta P_l = \sum \zeta_i \cdot \frac{\rho_m V^2}{2} \tag{5}$$

In the formula, ΔP_l represents the local pressure drop, and ζ_i is the resistance coefficient of the i-th local component. Different types of elbows, reducers, and valves have significantly different contributions to the local energy loss. If this part is ignored in the assessment, it is easy to simply attribute the abnormal pressure drop to high concentration or insufficient flow rate, thereby affecting the accuracy of parameter diagnosis.

Taking into account the total pressure drop ΔP, which includes the loss along the pipeline, local loss, and the static pressure difference formed by the height difference, it can be expressed as:

$$\Delta P = \Delta P_f + \Delta P_l + \Delta P_h \tag{6}$$

In the formula, ΔP_h represents the static pressure difference caused by elevation changes. During the transportation process of the suction dredger, there is usually a certain height difference between the suction inlet, the pump body and the mud tank inlet. Especially during different loading stages, the flow path in the pipe and the effective head will change. Equation (6) integrates all the aforementioned types of losses within a single calculation framework, and can be directly applied to pump matching, pipeline load, and transportation state discrimination.

Pure pressure drop cannot fully reflect the mass transfer efficiency. Energy consumption factors should also be taken into consideration. The suction dredger aims to achieve the effective output within a unit time rather than simply the water flow volume. If the energy consumed for the transmission of a unit mass of solid matter is used as the evaluation index of efficiency, it can be expressed as:

$$E_s = \frac{\Delta P}{\eta \rho_s C_v} \tag{7}$$

In this equation, E_s represents the energy consumption for transporting unit solid mass, and η represents the comprehensive efficiency of the pump and transmission system. This equation is derived from the pump power and the solid mass transportation rate, and it can more directly reflect the relationship between "being able to transport" and "whether the transportation is worthwhile". If the pressure drop is too large, even if the system can still maintain transportation, the energy consumption corresponding to the unit effective sand will significantly increase; if the concentration is too low, although the flow rate may be high, the effective output is insufficient, and the energy consumption indicators are also not ideal. Thus, it can be seen that the energy consumption parameters actually link the pressure drop, concentration, and equipment efficiency together, and are an indispensable part of performance evaluation. To make the relationship between key parameters clearer, this article arranges its calculation process into Figure 1.

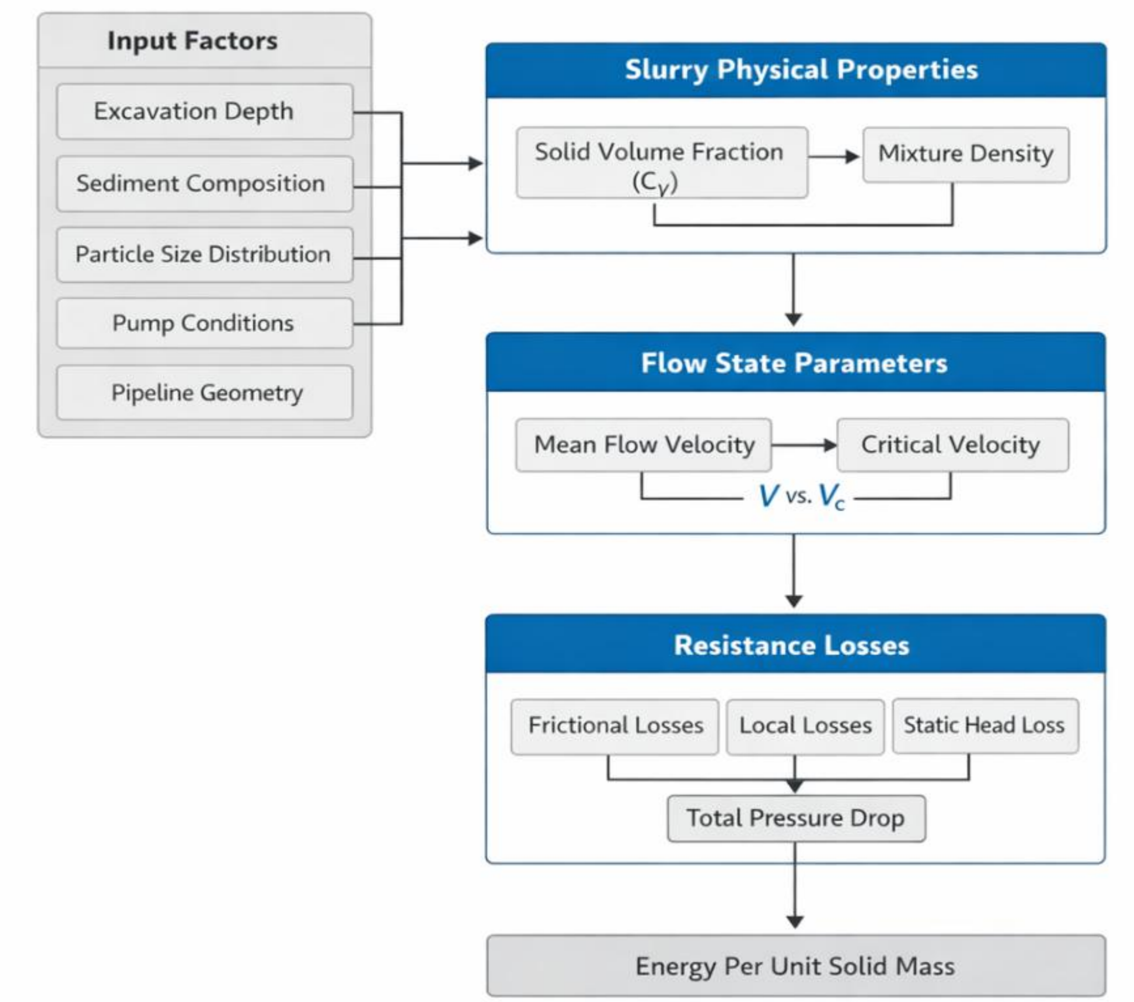

Figure 1: Calculation Process of Key Parameters for Mud Transport in Scraper-Scavenging Dredging Vessels

It can be clearly seen from Figure 1 that the calculation of the main indicators is not a simple addition of several formulas, but rather a process of interrelation: the performance of the slurry determines the basic flow state, the flow velocity and the critical flow velocity determine the transportation state; the resistance loss indicates the system load level, and the energy consumption coefficient further reveals the operational efficiency. Thus, the characteristics of slurry transportation by the hopper dredger can be extracted from the vague experience and transformed into quantitative values. During the process of constructing the evaluation index system, this serves as the basis for evaluating the transportation capacity, operational stability, and economic performance.

3.2 Evaluation Index System and Model Construction for Mud Transport Performance

After calculating key indicators such as mud concentration, average flow rate, maximum flow rate, total pressure drop, and unit solid mass transportation energy consumption, the mud transportation process in the suction dredger has met the conditions for transitioning from empirical estimation to quantitative analysis. However, a single indicator can only reflect a certain characteristic state and cannot simply answer questions closer to engineering management such as "what level is the current transmission efficiency at". For example, in one condition, the flow is large but the pressure loss is high; in another condition, the energy consumption is low but there is also a significant risk of settlement. If we continue to use a single indicator as the good or bad standard, we may make unreasonable judgments. Therefore, we need to form a set of indicator system based on these parameter calculation results and build a model that can be used for comprehensive scoring and evaluation to convert the calculation results into comparable and interpretable ability judgments.

Based on the analysis of the actual sand transportation process of the suction dredger, this paper classifies the evaluation indicators of the sand transportation performance of the rake head into four parts: sand transportation capacity, working stability, equipment load, and economy; the sand transportation capacity is a parameter that reflects the effective amount of soil transported per unit time; working stability refers to whether the particles can be continuously transported in the pipe and maintain uniform fluidity; load is the force degree of the pipeline system under certain working conditions; finally, economy reflects the relationship between transmission efficiency and energy consumption. Therefore, the following indicators are selected as variables in the comprehensive evaluation function: the average transportation rate of effective solid particles, flow margin coefficient, total pressure drop rate, and unit solid material transportation energy consumption, etc.

The effective solid transportation rate is a direct indicator of transport capacity. The operation of grab dredgers emphasizes the amount of effective mud sand entering the mud tank within a unit of time, rather than just the water volume circulation. Therefore, only measuring the transport effect by volume flow rate is not sufficient. Let the transport flow rate be Q and the solid volume concentration be $\mathrm{C_v}$. Then the effective solid transportation rate $\mathrm{Q_s}$ can be expressed as:

$$\mathrm{Q_s} = \mathrm{QC_v} \tag{8}$$

From Equation (8), it can be seen that the flow rate and concentration can be combined to reflect the effective output rate of mud transportation. If the flow rate is high but the concentration is low, although the system's transportation volume increases, the effective input of sand may not be good. Here: The flow rate margin coefficient characterizes the operational stability, which is expressed by the following equation:

$$\mathrm{K_v} = \frac{\mathrm{V}}{\mathrm{V_c}} \tag{9}$$

In the formula, V represents the actual average flow velocity, and $\mathrm{V_c}$ represents the critical flow velocity. This indicator reflects the degree to which the flow velocity meets the suspension conditions of the particles under the current operating conditions. When $\mathrm{K_v}<1$, the system is approaching or entering the deposition risk zone; when $\mathrm{K_v}$ is slightly higher than 1 and maintains an appropriate margin, the transportation is usually stable; if this value is too high, although it helps to inhibit deposition, it will bring additional energy consumption and pipe wall wear. Therefore, the stability evaluation is not that the larger the value, the better; instead, it should be kept within a reasonable range.

To identify the system resistance level, this paper introduces the total pressure drop coefficient $\mathrm{K_p}$ as a load indicator. Let the total pressure drop under the current operating condition be $\Delta\mathrm{P}$, and the total pressure drop under the design reference condition be $\Delta\mathrm{P_{ref}}$, then:

$$K_p = \frac{\Delta P}{\Delta P_{ref}} \tag{10}$$

This indicator serves to unify the pressure drop levels under different operating conditions onto the same reference scale. For a grab dredger, changes in the mud composition, particle size, flow velocity fluctuations, and the number of local components of the pipeline can all lead to variations in the total pressure drop. By comparing K_p, one can more intuitively determine whether the current conveying system is operating at a high load.

In the economic dimension, this paper continues to use the unit solid mass conveying energy E_s obtained in Section 3.1 as the core criterion. This indicator no longer solely focuses on the pumping power itself, but links energy consumption with the effective solid conveying volume, which is more in line with the actual operation of grab dredgers regarding the "unit output cost". As a result, the assessment of conveying performance is no longer limited to "being able to convey", but further shifts towards "conveying stably and economically".

Due to the different units and directions of each indicator, they cannot be directly superimposed. Therefore, it is necessary to first standardize the original indicator data. This paper adopts the extreme value standardization method to handle the forward and reverse indicators separately:

$$r_{ij} = \begin{cases} \dfrac{x_{ij} - x_{j,min}}{x_{j,max} - x_{j,min}}, & \text{Positive indicators} \\ \dfrac{x_{j,max} - x_{ij}}{x_{j,max} - x_{j,min}}, & \text{Reverse indicator} \end{cases} \tag{11}$$

In the formula, x_{ij} represents the original value of the i-th condition in the j-th indicator, and r_{ij} represents the standardized result. The effective solid transportation rate is a forward indicator, while the total pressure drop coefficient and the energy consumption per unit solid mass transportation are reverse indicators. The flow rate margin coefficient, although having an interval suitability feature, can be involved in the comprehensive evaluation after setting a reasonable operating range in the engineering application scenarios of this paper, thereby avoiding the confusion of indicator directions from causing interference to the results.

In terms of weight determination, this paper adopts the entropy weight method, allocating weights based on the degree of dispersion of different indicators in each condition sample. The core expression is:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n}(1 - e_j)} \tag{12}$$

In the formula, e_j represents the information entropy of the jth indicator, and w_j represents the corresponding weight. The smaller the entropy value, the more significant the difference of this indicator among different working conditions, and the stronger its role in distinguishing the comprehensive evaluation. By adopting this method, the arbitrariness of subjective weighting can be avoided, and the estimation results can better reflect the inherent variability of the sample data. After normalization and weighting, the function expression of the drilling fluid pump performance evaluation system can be obtained as follows:

$$S_i = \sum_{j=1}^{n} w_j r_{ij} \tag{13}$$

In the formula, S_i represents the comprehensive score of the i-th working condition. The larger the S_i value, the better the mud transportation performance under that condition. To facilitate engineering application, this paper further divides the comprehensive score into four grades: excellent, good, medium, and poor, which are used to identify the operating status of different working conditions and the sources of their differences. The significance of this processing lies in that the evaluation results not only maintain continuity but also have clear boundaries required for on-site interpretation.

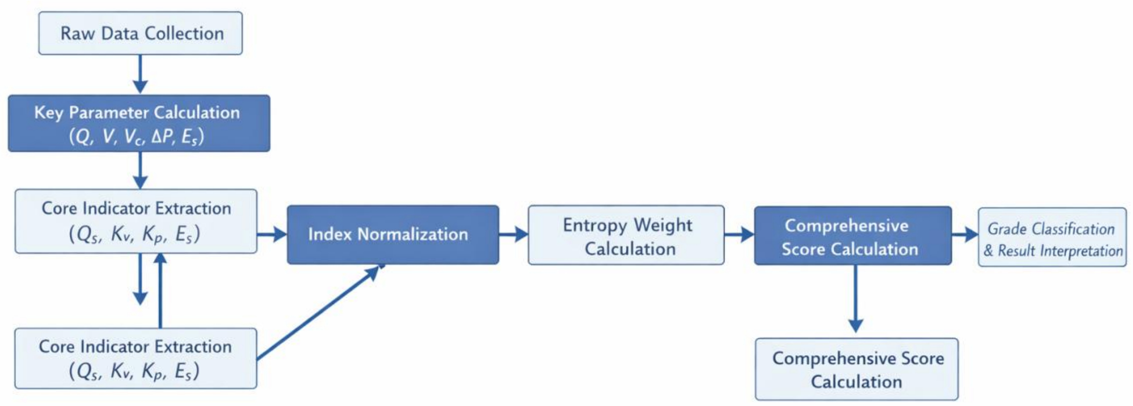

Figure 2: Process for constructing the evaluation model of mud transportation performance

As shown in Figure 2, the model established in this paper does not simply add up multiple calculation results. Instead, it proceeds step by step along the sequence of "parameter calculation - indicator extraction - comprehensive evaluation". In this way, scattered information such as pressure drop, flow rate, concentration, and energy consumption is consolidated into a unified evaluation framework. This not only improves the comparability between different operating conditions but also enhances the traceability of the results. When the comprehensive score is low, one can further trace back to specific indicators to determine whether the problem mainly stems from insufficient transportation capacity, decreased operational stability, or excessive system load and high energy consumption. For a clamshell dredger, this model is closer to the actual needs of the engineering site because it not only serves the comparison of effects between different calculation methods but also provides a basis for the operation diagnosis of the same vessel under different soil types, different concentrations, and different operation stages. At this point, the role of the calculation method is no longer limited to parameter solution itself but extends further to the identification and optimization decision-making of the mud transportation performance.

4 Performance Comparison of Calculation Methods and Empirical Analysis for Evaluation of Mud Transport Performance

To test the application effect of the evaluation method established in the previous section in the analysis of mud transportation for suction dredgers, this chapter conducts research from two aspects: comparison of calculation methods and empirical condition analysis. On one hand, the empirical formula method, conventional numerical simulation method, and the comprehensive evaluation method constructed in this paper are selected to compare the pressure drop prediction, stability identification, energy consumption characterization, and calculation efficiency, in order to examine the differences in accuracy, adaptability, and engineering usability among different methods. On the other hand, combined with typical dredging conditions, the key parameter changes and comprehensive score results during the mud transportation process are verified, and the fluctuation characteristics of transportation performance under different conditions are analyzed. Through comparison and empirical analysis, the effectiveness and applicability value of this method in the evaluation of mud transportation performance can be further demonstrated.

4.1 Performance Comparison of Different Calculation Methods

To test the applicability of the mud transportation performance evaluation method proposed in this paper, 12 representative mud transportation scenarios of suction dredgers were selected as comparison samples, and the empirical formula method, conventional CFD method, and the calculation evaluation method proposed in this paper were compared and analyzed. The comparison contents included pressure drop prediction error, unit solid mass energy consumption error, stable transportation identification accuracy rate, goodness of fit, and average calculation time per working condition. The purpose of this processing is not only to compare "who is closer", but also to examine the balance degree between precision, efficiency and engineering feasibility among different methods.

Figure 3 shows the relative error changes of total pressure drop of the three methods under 12 typical working conditions. From the figure, it can be seen that the error fluctuation of the empirical formula method is relatively obvious, and the deviation is greater in the working conditions with high concentration and local losses in the bend pipe. This indicates that although it is convenient for rapid estimation, its adaptability to complex ship-mounted piping systems and changes in working conditions is limited. The error of the conventional CFD method is overall lower than that of the empirical formula method, and the curve fluctuation is relatively gentle, indicating that it has a stronger advantage in describing the flow field details and local resistance. However, this method is sensitive to grid division, boundary condition setting and convergence control, and has a long calculation period, making it difficult to directly meet the needs of rapid evaluation in the engineering field. In contrast, the error distribution of this method under each working condition is more concentrated, with a smaller overall fluctuation range, and still maintains good stability under medium and high concentration transportation conditions, indicating that this method has a stronger adaptability to complex working conditions while retaining calculation accuracy.

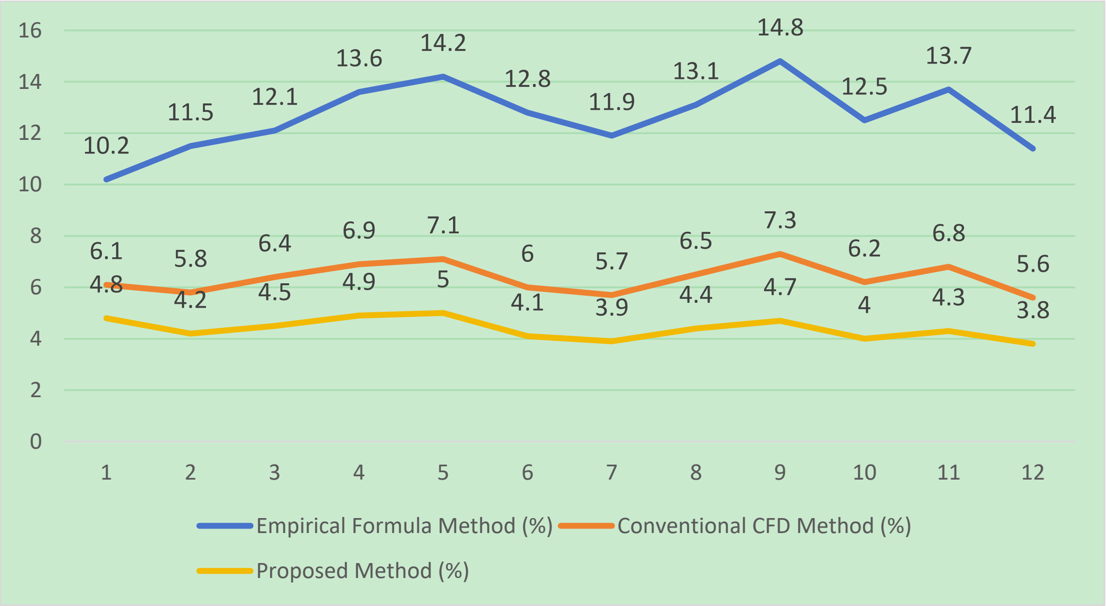

Figure 3: Comparison of the relative errors of total pressure drop for different calculation methods under 12 sets of operating conditions

To further compare the comprehensive performance of the three methods, Table 2 lists the main evaluation results. It can be seen that the empirical formula method has the shortest average calculation time under a single operating condition, but the average relative error of pressure drop and energy consumption are relatively high, and the accuracy of stable conveying recognition is also low. The conventional CFD method performs well in pressure drop prediction and energy consumption characterization, with a high degree of fit, but the average calculation time under a single operating condition is significantly increased, and the actual usage cost is relatively high. The method proposed in this paper outperforms the other two methods in terms of average relative error of pressure drop, root mean square error, and degree of fit, and also controls the single operating condition calculation time within a more reasonable range, demonstrating better comprehensive performance. That is to say, it does not merely pursue the ultimate extremity of a single indicator, but achieves a balance between accuracy and efficiency that is more suitable for engineering applications.

Table 2: Performance Comparison Results of Different Calculation Methods

Method	Average Relative Error of Pressure Drop (%)	Pressure Drop RMSE (kPa)	Average Relative Error of Energy Consumption (%)	Accuracy of Stable Transport Identification (%)	Goodness of Fit (R^2)	Average Calculation Time per Operating Condition (min)
Empirical Formula Method	12.84	18.60	14.27	75.0	0.873	0.8
Conventional CFD Method	6.21	8.90	7.46	83.3	0.942	42.5
Proposed Method	4.38	6.10	5.12	91.7	0.968	6.4

From the perspective of stable output of identification results, the empirical formula method is more likely to misjudge "near-critical operating conditions" as a stable state. The reason for this is that this method fails to adequately reflect the changes in particle distribution and the coupling effect of local resistance. Although the conventional CFD method can describe local deposition and resuspension phenomena more precisely, it has a heavier computational burden in batch condition comparisons. The method proposed in this paper integrates the calculation of key parameters and the assessment of comprehensive indicators, and unifies the flow velocity margin, total pressure drop, and unit transportation energy consumption into the same evaluation framework. Therefore, it is more clear in terms of the ability to distinguish operating conditions. Especially in the transitional zone from "good" to "moderate" in the transportation state, this method is more sensitive to performance changes and can detect the trend of load increase and stability decline earlier.

4.2 Empirical Analysis of Mud Transport Performance Evaluation for Grab-Drilling Dredgers

After comparing the performance of different calculation methods, in order to further test the applicability of the evaluation path established in this paper in actual working conditions, 12 sets of typical mud transport conditions during the continuous operation stage of a grab-drilling dredger were selected as empirical samples. The flow rate, concentration, pressure before and after the pump, power consumption, and transportation status records obtained from on-site monitoring were used as reference data. During the comparison process, this method was defined as Model 1, the conventional CFD method as Model 2, and the empirical formula method as Model 3. The performance of these three methods in total pressure drop prediction, identification of unit solid mass transportation energy consumption, and comprehensive grade determination was compared and analyzed. Such processing not only verifies whether the calculated values are close to the measured results, but also determines whether different methods can convert discrete parameters into performance conclusions that can be used for construction decisions.

From the results of representative conditions, different methods can give relatively close judgments under conditions of medium and low concentrations and relatively stable pipeline loads. However, as the concentration increases, local losses at the bends increase, and the operation rhythm fluctuates, the differences between the models begin to significantly expand. Table 3 lists the comprehensive evaluation results of the three methods under 6 typical conditions. It can be seen that Model 3 shows a higher grade in conditions 4 and 6, indicating that it is insufficient in identifying local resistance and stable transportation boundaries under complex conditions, and is prone to classify conditions close to unstable areas as "good". Model 2 is relatively close to the measured values in pressure drop prediction and the grade determination is basically consistent, but there are still certain deviations in samples with large concentration fluctuations such as condition 5. In contrast, the comprehensive score of Model 1 is more consistent with the on-site status records, and is more sensitive in the transition from "good" to "medium" conditions, and can more early reflect the trend of increasing transportation load and decreasing stability.

Table 3: Comparison of Evaluation Results of Three Methods under Typical Operating Conditions

Operating Condition No.	Measured Total Pressure Drop (kPa)	Field Status Classification	Model 1 Composite Score	Model 1 Grade	Model 2 Grade	Model 3 Grade
1	126	Good	0.79	Good	Good	Good
2	134	Good	0.76	Good	Good	Good
3	149	Moderate	0.64	Moderate	Moderate	Good
4	158	Moderate	0.61	Moderate	Moderate	Good
5	171	Moderate	0.57	Moderate	Good	Good
6	184	Poor	0.46	Poor	Moderate	Good

From Table 3, it can be observed that Model 1's grade determination in the 6 typical operating conditions is consistent with the actual situation on site. Model 2 shows a slight delay in high-load samples, while Model 3 is generally more optimistic. The reason for this difference lies in that the empirical formula method places more emphasis on average hydraulic characteristics, which is suitable for rapid estimation but is difficult to fully reflect the actual transportation state under the combined effects of ship-mounted composite pipelines, concentration fluctuations, and local losses. The conventional CFD method can more accurately reproduce the local flow field, but still needs further connection with the index system at the comprehensive evaluation level. The method proposed in this paper incorporates pressure drop, flow velocity margin, effective transportation rate, and unit energy consumption into a unified framework, thus being more suitable for engineering judgment.

To further understand the application effects of the three methods mentioned above, the results obtained in 12 different scenarios are summarized in Table 4. The results showed that Plan One had the lowest overall average percentage of voltage reduction (4.72%) and the highest peer evaluation judgment rate (91.7%), making it the optimal plan; Although Scheme 2 has a high ability to estimate pressure, the average calculation time is too long, and the cost of large-scale testing in practical engineering is relatively high; Although Mode 3 runs the fastest, it is significantly lower in accuracy and consistency level discrimination. Therefore, judging the superiority of a technology solely from the perspective of computational efficiency is one-sided. For the analysis of sediment characteristics in grab dredgers, it should be able to control errors; Fast response speed; Provide reasonable analysis results under these conditions.

Table 4: Comparison of Empirical Statistical Results of the Three Methods

Method	Mean Relative Error of Total Pressure Drop (%)	Mean Relative Error of Energy Consumption (%)	Consistency Rate of Comprehensive Grade Classification (%)	Average Computation Time per Operating Condition (min)
Model 1 (Proposed Method)	4.72	5.36	91.7	6.8
Model 2 (Conventional CFD Method)	6.08	7.14	83.3	41.6
Model 3 (Empirical Formula Method)	12.46	13.28	66.7	0.9

As can be seen from Table 4, Model 1 did not sacrifice efficiency for the sake of accuracy, nor did it merely rely on empirical methods to increase computing speed. It achieved the optimal solution between accuracy and efficiency, which is very important for grab dredging operations. After all, the mud transportation state is not absolutely stable. If the algorithm is too slow, it cannot provide timely assistance for on-site operation adjustments; if the algorithm is too simple, it will miss the early warning information of equipment performance decline. In summary, the evaluation path established in this paper has shown good recognition and practicality in actual applications. It can assist in the quantitative judgment of decision-making work such as the optimization design of mud transportation parameters, online monitoring, and the revision of construction plans.

5 Discussion

5.1 Comparison of Calculation Methods and Common Performance Evaluation Methods for Mud Transport in Grab-Type Dredgers

From the comparison in the previous text, it can be seen that the new algorithm proposed in this paper comprehensively evaluates the sludge transportation performance of the suction dredger, rather than considering only one of the factors such as flow rate, pressure drop, or pump power consumption as in the traditional empirical methods. It also takes into account various factors such as flow velocity margin, total pressure drop, effective solid transportation rate, and specific energy consumption. Therefore, it can better reflect the performance differences under actual working conditions. Although empirical equations are quick and easy to use and suitable for rough estimations in the early stages of a project, they have limitations when it comes to high-concentration sludges, the impact of cumulative resistance, and the applicability of the ship's mixing pipeline system. This may lead to the neglect of performance deterioration situations. However, standard CFD technology is superior in describing flow details and can understand the particle distribution and changes in local losses. But it is also limited by its high modeling cost and long time consumption, which restricts its use in reality. In contrast, our method not only has a more solid physical calculation basis but also improves the comprehensive evaluation effect. It achieves a good balance between accuracy, discrimination, and practicality. These differences indicate that the estimation of sludge carrying capacity is not only a matter of "correct calculation", but rather a key issue of how to convert the results into clear, reliable, and easily decision-making information.

5.2 Analysis of the Improvement in Accuracy and Efficiency of Slurry Transport Performance Evaluation

The research results of this paper indicate that the proposed evaluation scheme has high accuracy and practical value, and is superior to traditional CFD methods and empirical formula methods. Although traditional CFD can provide a more detailed flow field distribution and local displacement friction resistance changes, its modeling, meshing, and iterative calculation processes are time-consuming, which makes it unable to achieve efficient operation under multiple working conditions; while the empirical formula method is fast and easy to use, but it cannot fully capture the high concentration of slurry, the cumulative loss of bends, and the actual transmission conditions in the mixed pipeline system on the ship. We use the key parameter calculation as the foundation, integrating pressure drop, velocity margin, effective material transportation rate, and energy consumption per watt into a single rating system, reducing the workload of digital simulation calculations throughout the entire process and all working conditions. From the above experiments, it can be seen that the new method can improve the speed of multi-condition calculation and on-site judgment while ensuring a high evaluation accuracy, and is more suitable for application in the actual engineering application of dredging and transporting slurry in suction dredgers.

5.3 Explanation of the Evaluation Path for Mud Transport Performance Based on Calculation Methods

The calculation method of mud transport characteristics is a planned approach to identify and comprehensively consider different levels of information during the transport process of drag suction dredgers; Starting from the calculation of important parameters, the results of mud density, flow velocity, critical flow velocity, total pressure drop, and unit solid energy consumption are collected in the same calculation program. Further transform it into evaluation indicators such as carrying efficiency, work reliability, load intensity, and economic benefits, and form an overall closed-loop process from parameter calculation to grade evaluation. Its value is not to replace a specific algorithm, but to combine the convenience of empirical calculation with the credibility of numerical analysis, and to enhance the resolution of comprehensive evaluation, which helps to describe the characteristics of mud transportation more thoroughly. For trailing suction dredgers, this evaluation method can not only characterize the coupling relationship between flow state, solid content, and resistance, but also reflect where the main consumption factors of transport performance are. In other words, it has entered a new realm of "how to determine and utilize computable conclusions" from the category of "whether they are computable". From this perspective, this approach can not only improve the logical analysis of mud transportation performance, but also provide a more intuitive basis for operation management, parameter regulation, and engineering construction.

5.4 Engineering Application Prospects and Research Limitations

The assessment method for mud transportation capacity established in this paper can be widely applied in the engineering operations of grab dredgers. In various working conditions such as river dredging, harbor basin excavation, and land reclamation construction, it can promptly determine the transportation capacity, system load and energy consumption status of grab dredgers, and use them as the basis for adjusting pump parameters, monitoring the operation of the pipeline system and controlling the operation progress. If combined with the on-site test results, it can also be applied in the warning prompts and performance evaluation during the operation process, further improving the control level of drilling fluid transportation. Of course, this research still has certain limitations: Firstly, it is greatly affected by the quality of parameter input, the setting of benchmark values and the allocation of weights, and needs to be adjusted according to different ship types and strata; Thirdly, the existing research is mostly focused on typical transportation processes, and the applicability to ultra-high concentration concentration, complex particle composition and drastic changing working environments still needs to be further verified through experiments. In the next step, starting from expanding the sample of operation conditions, real-time monitoring data can be introduced into the sample and the dynamic correction algorithm can be optimized to adapt to harsh operation environments, further enhancing the applicability and promotion ability of this evaluation method in complex engineering backgrounds.

6 Conclusion

In order to compensate for the shortcomings of drag suction dredgers in sediment transport, such as large dispersion of sediment parameters, inconsistent evaluation standards, and inability to guide construction management in a timely manner, a method and approach for evaluating the sediment transport capacity of drag suction dredgers is proposed based on numerical simulation. This article calculates key indicators such as sediment concentration change rate, average flow velocity, starting flow velocity, total head loss, and unit sediment transport energy consumption. Subsequently, an indicator system covering capacity utilization efficiency, operational reliability, device load, and economy is established, and a comprehensive evaluation model is constructed. By comparing and analyzing the results of different methods, it can be seen that the method proposed in this article achieves a good compromise between accuracy and practicality; For the measured samples, the mean square error of total load reduction is 4.72%. The mean square error of energy consumption per unit of solid material transport is 5.36%, and the consistency level evaluation reaches level I (91.7%), which is better than traditional CFD method and empirical formula method; This indicates that the method can effectively distinguish the mud transport state and provide a more intuitive basis for comparative analysis of working conditions, parameter regulation, and optimization of construction operation plans. In addition, the sample working conditions used in this article are still dominated by conventional working conditions, and the applicability to working conditions with ultra-high concentration ratios, complex particle size distributions, and drastic changes still needs to be verified. In future research, more on-site data can be used for model calibration and improvement.

About the Author

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