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Study on the Hydraulic Performance and Efficiency of a Siphon Sediment Discharge Device with Bottom Hole Opening through Simulation Experiments

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Abstract: In this study, the hydraulic behavior and sand transport efficiency of the siphon automatic sand discharge device were studied by software simulation tests. By simulating the actual situation, this study analyzed how factors such as the difference in water level, sediment concentration, and pipeline layout affected the sediment discharge effect. The results show that the sediment discharge device can effectively discharge sediment under diverse operating conditions and show adaptability to different environmental conditions, which indicates that it is suitable for various types of reservoir environments.

Keywords: Siphon sand discharge; Bottom hole opening; Sand transport efficiency; Simulation experiment.

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1. Introduction

The problem of sediment deposition in reservoirs has always been a major challenge in the field of hydraulic engineering. Traditional methods of sediment removal, such as mechanical excavation and hydraulic irrigation, often require a large amount of energy support and have a large impact on the environment. Siphon sand drainage technology has attracted attention due to its advantages of energy saving and environmental protection. To improve the efficiency of sand discharge and reduce the environmental impact, this paper studies the siphon automatic sand discharge device through the model test.

2. Research status

2.1. Current situation of sediment deposition in the reservoir

Globally, the problem of sediment deposition in reservoirs has become increasingly prominent, which has a serious impact on the water storage, flood control, and water supply functions of reservoirs [1]. The sediment carried by the upper reaches of rivers accumulates in the reservoirs for a long time, resulting in the effective storage capacity of the reservoirs decreasing year by year. According to a report by the United Nations Environment Programme, about half of the world's reservoirs are suffering from sediment accumulation, and the problem is getting worse [2].

2.2. The development and application of silting removal technology

In response to the widespread problem of silting in reservoirs around the world, researchers and engineers have developed a series of silting technologies. In addition to traditional methods of mechanical excavation [3–5], hydraulic flushing, and sediment discharge [5–8], emerging technologies such as ecological dredging, chemical conditioning, and microbial remediation [9–14] are now emerging. These new technologies aim to solve the sediment problem in a more environmentally friendly and economical way, although their practical application still needs to overcome the challenges of technology maturity and affect stability.

2.3. Research on siphon sediment removal technology

Siphon drainage technology is gradually becoming the focus of reservoir dredging research because of its high automation, low operating cost, and small environmental interference. Through the negative pressure caused by the water level difference, the technology realizes the siphon effect, so that the sediment can be continuously discharged. Although most of the current literature focuses on optimizing the design of siphons, improving the efficiency of sediment removal, and reducing the impact on water quality, this technology still faces challenges in practical application, such as complex system design, strict start-up conditions, and poor adaptability to working conditions.

Therefore, there is an urgent need for a more efficient and environmentally friendly silting removal technology to solve the problem of sediment deposition in reservoirs. The research and application of siphon-type automatic sediment discharge devices provide an innovative solution. Through the model test, this study aims to deeply explore the hydraulic principle of this technology and its application effect in engineering practice, in order to provide a more scientific solution strategy for reservoir sediment management.

3. Research objectives, contents and methods

3.1. Main purpose of the study

This study focuses on the key problems and challenges in the field of reservoir dredging, especially for the problems encountered in the practical application of siphon sand removal technology, aiming to propose innovative solutions and optimization strategies. The core objectives of the study include:

(1) To improve the efficiency of sediment removal by simulating its physical characteristics and hydraulic parameters.

(2) Design a new siphon-type sand discharge device and optimize the parameters to ensure the performance stability and reliability of the device under various working conditions.

(3) Based on the principles of ecological engineering, the methods of sediment discharge and silting removal were studied and optimized to minimize the interference and potential negative impacts on aquatic ecosystems.

3.2. Main contents of the study

3.2.1. Theoretical study on siphon sediment discharge mechanism

(1) Using the principle of fluid dynamics, the key influencing parameters of the siphon phenomenon are studied.
(2) A model of siphon sediment drainage was established to simulate the effect of sediment drainage under different conditions.

3.2.2. Design and optimization of siphon sand drainage device

Design a prototype of a new siphon-type sand discharge device and test its performance through laboratory and computer software simulation.

3.2.3. Simulation experiment and parameter sensitivity analysis

(1) Conduct a series of simulation experiments in a controlled environment to collect data on sediment movement and sediment removal efficiency.
(2) Parameter sensitivity analysis was conducted to determine the key design parameters affecting the sediment removal effect.

3.3. Research methods

3.3.1. Theoretical analysis

Based on the basic theory of fluid dynamics and sediment kinematics, the siphon sediment drainage mechanism was deeply analyzed, and a mathematical model was established to predict the law of sediment movement and the efficiency of sediment drainage.

3.3.2. Model experiment

Under laboratory conditions, the reservoir sediment model and siphon sediment drainage system model were constructed, and the simulation experiment under large working conditions was carried out by software simulation.

3.3.3. Data analysis

Statistical methods and data analysis software were used to process experimental and prototype observation data, identify key influencing factors, and optimize the design scheme.

4. Experimental model study

4.1. Physical model design

The model is mainly composed of four parts: a water inlet device (suction pipe), an upstream water tank, a pipe composition, and a suspension device. The upstream water tank is spliced with acrylic plates. The pipe is polyvinyl chloride (PVC), the pipe diameter is 1.5 cm, and the sand discharge pipe is divided into three different ways of opening, in which the siphon pipe is opened with a water injection hole (1), the outlet pipe valve (2), and the sand suction hole (3). The water level difference between upstream and downstream is 1 m, 1.25 m, and 1.5 m. The water level difference is kept constant through the water inlet device. The influence of water level difference and sediment concentration on outlet flow velocity and the influence of opening mode on sediment discharge were mainly observed. A schematic diagram of the design is shown in **Figure 1** and **Figure 2**.

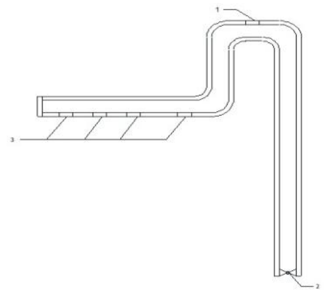

Figure 1. Side view and top view of the siphon

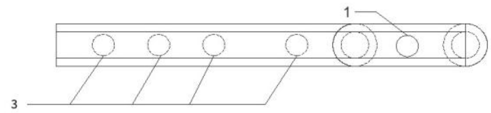

Figure 2. Top view of the siphon

4.2. Selection of simulation software and model

Ansys Fluent is a general-purpose computational fluid dynamics (CFD) software for modeling and analyzing fluid flow, heat transfer and mass exchange, and chemical reaction processes. The Euler model is the most complex multiphase flow model in FLUENT. The coupling is realized by the pressure and the phase exchange coefficient, and the Euler model has the highest calculation accuracy. Therefore, it is decided to use the Euler model as the model of numerical simulation.

4.3. Result analysis

The data from the simulation experiment and physical model experiment were plotted in Excel. The correlation between the fitting curve equation and the experimental data was more than 0.94, and the conclusion was highly correlated. It can be seen from the two curves in **Figure 3** and **Figure 4** that the simulated results are basically consistent with reality.

4.3.1. Comparison of sand discharge effect by opening mode

The form of the bottom opening can be divided into equal spacing opening and variable spacing opening. Compared with the tail opening, the bottom opening has obvious advantages in sediment discharge. Specifically, the bottom opening has a wider range of sediment discharge, which means that under the same conditions, it can cover a wider area and remove the silt in front of the dam more effectively. This design not only improves the efficiency of sediment discharge but also can better cope with sedimentation problems in different situations.

4.3.2. The impact of the head difference

Through comparative experiments, we found the influence of head difference on the sediment

discharge effect of the bottom opening system. With the increase of head difference, the outlet flow velocity gradually increased. However, with the increase of the flow velocity, the

sediment carrying capacity of the flow decreased slightly, which may be caused by the decrease of sediment suspension capacity caused by the excessive flow velocity. Nevertheless, the sediment discharge showed an increasing trend at the same time, which indicated the positive effect of head difference on sediment discharge.

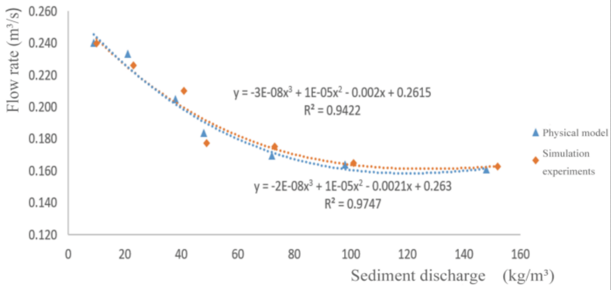

Figure 3. Plot of flow and sediment concentration

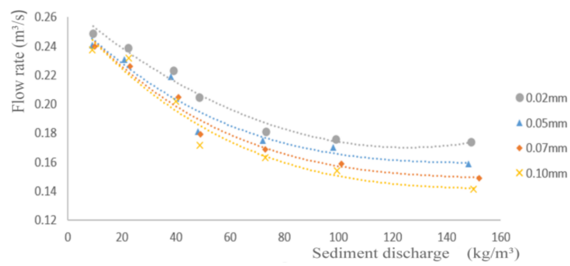

Figure 4. Plot of flow and sediment concentration

4.3.3. Effect of hole opening method on flow rate and sediment discharge

Through comparative experiments, the influence of different opening methods on the outlet flow velocity was found. As shown in **Figure 5**, compared with the tail opening, the outlet flow velocity of the bottom opening is smaller under the condition of the same head difference, which may be because the bottom opening way increases the head loss at the intake of the sand suction device. At the same time, this also means that the bottom hole has a lower flow rate for the same pipe diameter.

The flow rate can be obtained by multiplying the outlet flow rate by the pipe diameter, and the data analysis of the flow rate and sediment discharge can be obtained in **Figure 6**. It can be analyzed from the figure that under the condition of the same head difference, although the flow rate of the bottom opening is smaller, the overall sediment discharge is better than that of the tail opening. This may be due to the bottom of the opening of the sand suction range being more uniform, making the suction device contact with a wider sediment area, resulting in a small flow, but a large amount of sediment discharge.

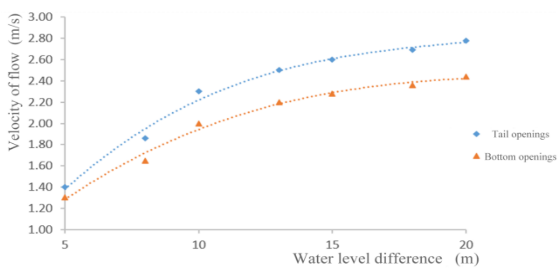

Figure 5. Relationship between water level difference and flow velocity of different ways of opening

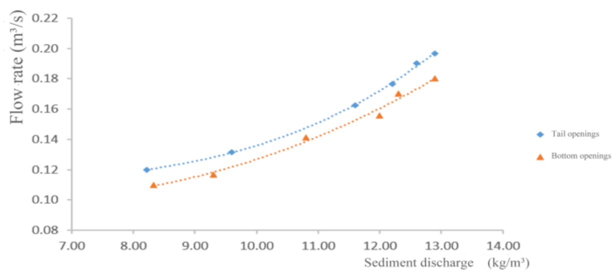

Figure 6. Relationship between discharge and flow for different types of openings

5. Conclusion

(1) The test results show that the overall sand discharge efficiency of the siphon-type sand discharge device is significantly improved when the water level difference is increased, but the growth rate of the outlet flow velocity will gradually slow down.

(2) The test results show that, under the same hydraulic conditions, the higher the sediment content in the water, the larger the sediment particle size, and the slower the outlet flow velocity of the pipeline.

(3) The test results show that the bottom hole usually has a larger sediment discharge than the tail hole. This is because the bottom hole can absorb sediment deposited on the bottom more effectively. In contrast, the tail hole may be affected by weak water flow, and the sediment discharge efficiency is relatively low.

Therefore, under the same conditions, the bottom opening tends to be able to remove sediment from the water body more quickly and improve the efficiency of sediment discharge.

(4) The test results show that in the siphon-type sediment discharge device, the suction part of the sand has little influence on the sediment disturbance. This finding may mean that the siphon sediment drainage device can effectively separate the sediment from the water body without excessive disturbance of the flow and sediment distribution. This indicates that the siphon automatic sediment discharge device has good adaptability and efficient sediment discharge capacity compared with other traditional sediment discharge methods, and is significantly superior to the traditional sediment discharge method in terms of energy saving, labor intensity reduction, and water pollution reduction.

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Disclosure statement

The authors declare no conflict of interest.

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