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EXTENDED ABSTRACT

A Numerical Study on the Impact of Geometric and Hydraulic Parameters on Hydraulic Sedimentation in Storage Dam Reservoirs

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1. Introduction

Given the significant rate of sediment accumulation in reservoirs and the urgent requirement for additional storage space due to the impracticability of constructing new reservoirs, multiple methods have been explored and implemented to assess sediment deposition, regulate sediment inflow, and facilitate sediment flushing while considering their downstream implications. Hydraulic sediment removal is a highly efficient method for recovering occupied reservoir volume without incurring exorbitant costs linked to mechanical sediment removal methods, thereby achieving enhanced operational efficiency. In this approach, erodible sediments accumulated within the reservoir are targeted for removal by opening deep gates, thereby inducing erosion and facilitating the extraction of a portion of the sediment. This can be accomplished through two approaches: under pressure, where the reservoir water level remains unaffected, and by decreasing the reservoir water level to align with that of the river.

The aim of this study is to investigate the influence of variations in hydraulic and geometric parameters of reservoirs and sediment on sediment discharge and the subsequent release of free storage volume during pressurized flushing operations in dams. Additionally, the study examines the uniformity of sediment particles across different levels of sediment accumulation in the reservoir and evaluates the non-uniformity effect of particle size distribution when equal proportions of particles with varying diameters are present in cases related to uniform grading at different sediment accumulation levels. Furthermore, the study explores the impact of the number of active gates during operation on the volume and geometry of the scour hole resulting from flushing operations and the relative percentage of sediment discharged from the reservoir.

- This study investigates the impact of the average particle diameter of accumulated sediment in the reservoir on the geometry and volume of the scour cone under conditions of uniform particle grading.
- This study investigates the influence of a non-uniform particle size distribution of settled sediment within the reservoir, while maintaining an equal proportion of particles with the average diameter as in the case of uniform grading, on the geometry and volume of the scour cone, in comparison to uniform particle grading.

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- This study investigates the impact of the sedimentation level in the reservoir on the geometry and volume of the scour cone.
- This study investigates the influence of the number of sub-flushing outlets on the geometry and volume of the scour cone.

Given that the primary goal of sediment removal from reservoirs is to restore the maximum lost storage volume resulting from sediment accumulation, the main objective of this study is to determine the optimal value for each parameter. This value should result in the highest discharge of accumulated sediment from the reservoir. It is evident that the success of the project is directly linked to the amount of sediment directed out of the dam reservoir.

2. Methodology

2.1. Flow-3D

FLOW-3D is a powerful software tool in the field of fluid dynamics, developed and supported by Flow Science, Inc. It is highly regarded for its ability to simulate three-dimensional flow fields, making it widely applicable in scientific research and various industries. The software employs a mesh consisting of rectangular cubic cells in Cartesian and cylindrical coordinate systems for conducting simulations. It effectively solves governing equations, including continuity equations, Navier-Stokes equations, and sediment transport equations, while utilizing five turbulence models. The utilization of rectangular cubic cells in FLOW-3D simulations offers several advantages, such as reduced memory consumption, ease of geometry generation, and the ability to employ FAVOR and VOF methods for analyzing both solid geometry and the free surface of the fluid.

2.2. Verification

To validate the software, benchmark values from laboratory experiments conducted by Fathi-Moghadam et al. (2010) were employed. These experiments were conducted in the hydraulic laboratory of Ahvaz University, utilizing a flume with dimensions of 3.2 meters in length, 1.5 meters in width, and 4 meters in height. The objective was to simulate pressurized flushing and determine the parameters influencing the volume and length of the scour cone resulting from hydraulic sediment removal.

In the experimental setup, the first meter of the flume was dedicated to providing a consistent inflow towards the accumulated sediment in the reservoir, which had a deposition level of 0.42 meters from the reservoir floor. Once the desired reservoir level was achieved, a 2-inch diameter outlet valve was opened to initiate the main part of the experiment, involving pressurized hydraulic sediment removal. The outflow, consisting of water and sediment, was directed into a sediment settling basin in the first section. The dimensions of this settling basin were 3.5 meters in length, 0.1 meters in width, and 0.8 meters in height. The outflow rate was measured using a V-shaped weir. To maintain continuous water circulation within the system, a pump and suction equipment were utilized. The sediments used inthe experiments were non-cohesive, with a density of 2650 kilograms per cubic meter. Three different sizes of sediment particles were tested, with average diameters of 0.27mm (fine grain), 0.42mm (medium grain), and 1.01 mm (coarse grain). The experimental model is illustrated in Fig. 1.

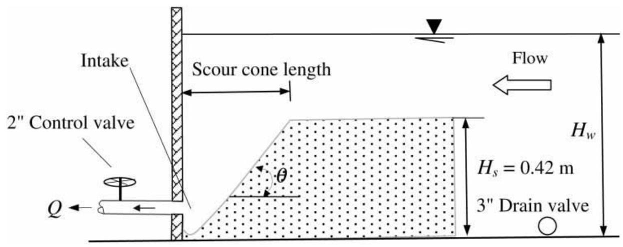

Fig. 1. Laboratory model of pressurized hydraulic sediment removal (Fathi-Moghadam et al., 2010)

The numerical solution derived from the utilization of the FLOW-3D software was compared to the turbulent k-ε model as well as three different sediment transport equations: Meyer-Peter, Nielsen, and Van Rijn. The results of this comparative analysis were carefully examined and documented in Table 1.

Table 1. Validation results of pressurized flushing using numerical simulation by FLOW-3D

sediment transport equation	L (m)	Percentage Error L	V (m^3/s)	Percentage error V
Meyer - Peter	0.500	3.8	0.0396	8.0
Nielsen	0.501	3.7	0.0397	7.7
Van Rijn	0.543	4.4	0.0470	9.3

The analysis considered three sediment transport equations. The Nielsen equation caused significant delays and complexity after a certain simulation period. The Van Rijn equation led to premature termination due to small time steps in the early stages. To overcome these challenges, shorter simulation duration and more simulation steps were used, increasing the computational workload and memory usage. As a result, the Meyer-Peter sediment transport equation was chosen as the primary numerical model for the study.

3. Results and discussion

To determine the length, a selection of images depicting the two-dimensional output of accumulated sediment fractions on the baffle plate in the longitudinal half-section of the reservoir were obtained, as illustrated in Fig. 2. Furthermore, Fig. 7 showcases the corresponding section on the upstream wall of the dam. The three-dimensional geometry of the sediment removal cavity was estimated using the Surfer software, as depicted in Fig. 2.

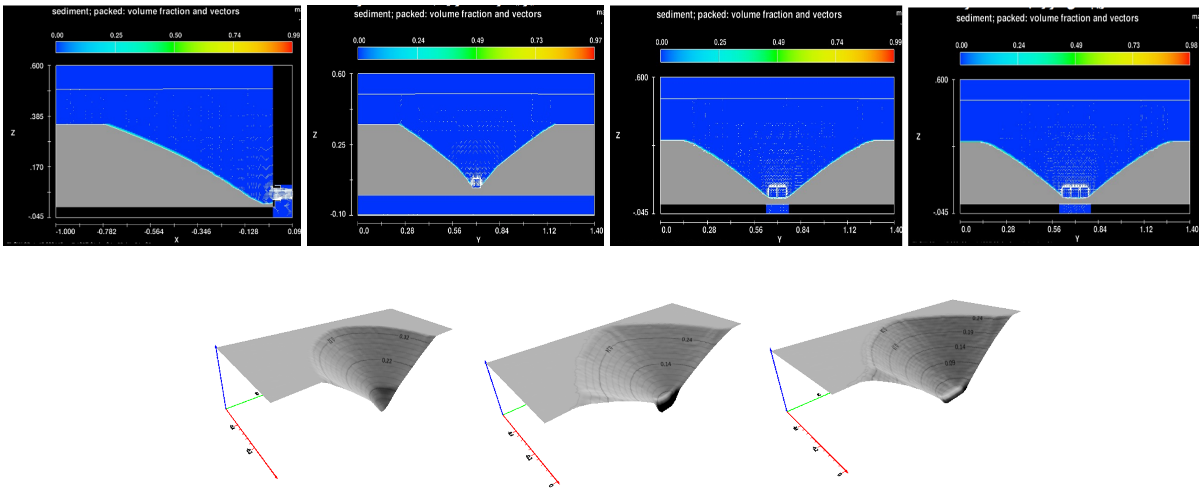

Fig. 2. The 2D and 3D images of the maximum width of the sediment removal cavity after analyzing the models

3.1. impact of sediment accumulation level on the volume of the sediment removal cone

Based on the analysis of sediment removal in reservoirs, regardless of sediment grading, the sediment removal cavity's dimensions and volume increase with higher sediment accumulation levels. The width of the cone is generally greater than its length. Non-uniform sediment grading shows similarities to medium-grained sediment conditions, particularly at an accumulation level of 0.25 meters. In terms of sediment removal, higher sediment levels in the reservoir result in a greater relative amount being removed, except for fine-grained sediments where the maximum removal occurs at an accumulation level of 0.03 meters. The highest percentage of reservoir volume restoration is achieved for fine-grained sediments at a level of 0.35 meters.

3.2. The impact of the average diameter size of sediment on the volume of the sediment removal cone

The size of sediment particles, particularly the average diameter, plays a significant role in shaping the sediment removal cone. Increasing the average diameter results in a decrease in the dimensions and volume of the removal cavity, as well as a reduction in restored reservoir volume and the percentage of sediment removed. The width of the removal cavity consistently exceeds its length in all models studied. For fine-grained sediments, the maximum reservoir volume restoration occurs at an accumulation level of 0.35 meters, while the highest relative percentage of sediment exiting the reservoir is observed at an accumulation level of 0.30 meters. Fig. 3 shows the results.

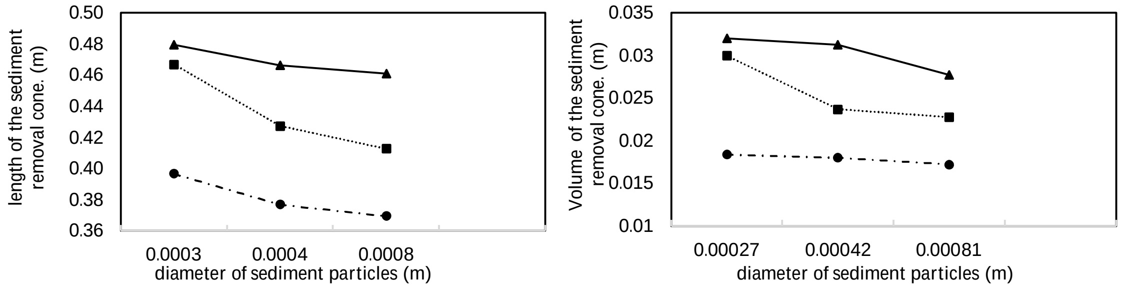

Fig. 3. The effect of sediment particle diameter on the length and on the volume of the sediment removal cone

4. Conclusions

This study aimed to investigate the impact of various factors on the sediment removal cone resulting from hydraulic flushing. Factors such as sediment accumulation level, particle diameter, distribution uniformity, and the number of active bottom outlets were considered. By simulating 18 models using FLOW-3D software and analyzing the results graphically, the optimal conditions for maximizing sediment removal were identified. The study validated the pressure flushing through simulation and presented key findings.

The size and volume of the sediment removal cone increase as sediment accumulation levels in the reservoir rise. Conversely, they decrease with larger average particle diameters. When comparing non-uniform particle size distributions with uniform distributions at various accumulation levels, the results closely align with those of uniform distributions. Increasing the number of bottom outlets increases the size and volume of the sediment removal cone. However, the rate of sediment removal increase is less significant for configurations with two or three outlets at lower levels. Therefore, a two-bottom-outlet configuration is recommended for lower levels to minimize water loss and environmental impact. The width of the sediment removal cone consistently exceeds its length in all models analyzed. Among the analyzed models, one particular model stood out, utilizing three simultaneous bottom outlets, a sediment accumulation level of 0.35 m, and a uniform particle size distribution of 0.042mm. This model achieved the highest sediment removal (78690m^3), restored the greatest percentage of reservoir volume (11.24%), and exhibited the highest relative sediment discharge (16.06%). To ensure successful pressure flushing operations, it is recommended to maintain a constant discharge rate, position the bottom outlets equally, and conduct the operation in a reservoir with smaller sediment diameter, higher accumulation level, and more active bottom outlets. However, it is important to note that these findings are specific to the current simulation and further research is needed for generalization to other models.