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The paper was published in the proceedings of the 11th International Conference on Scour and Erosion and was edited by Thor Ugelvig Petersen and Shinji Sassa. The conference was held in Copenhagen, Denmark from September 17th to September 21st 2023.
Using an artificial guiding channel to prevent sediment deposits and increase erosion potential in a reservoir

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ABSTRACT
In order to achieve effective management of reservoir desiltation, sediment management planning of a reservoir often requires the cooperation of various management strategies rather than a single strategy or project. During the flood control and desilting operation of a reservoir, it is also necessary to adjust the appropriate sediment management strategy according to different flood seasons and extreme events. In addition, it also needs to cooperate with numerical simulation and hydraulic model test research to effectively utilize the appropriate hydrological and hydraulic environment to achieve effective desilting efficiency. However, the more feasible desilting strategies are mainly divided into hydraulic sand removal and mechanical dredging. Therefore, with the help of a two-dimensional model, this study tests an artificial bottom guiding channel structure and explores the impact of turbid water entering the reservoir under different hydrological conditions. The behavior of scouring and deposition following the entry of turbid water into the reservoir is first described. Then, the empty flushing is mainly investigated for the desilting operation and condition of a reservoir. Then, it reveals that an artificial bottom guiding channel is essential to prevent the sedimentation of the incoming sediment. Additionally, the flow velocity within the channel increases, potentially accelerating the erosion of the channel bottom of the reservoir. However, if the water level rises, the erosion potential of the reservoir bottom and desilting efficiency decrease due to the velocity decreasing, and coarse sediment deposit is significant.

INTRODUCTION
Worldwide reservoir sedimentation volume has surpassed the capacity of recently built reservoirs, resulting in a reduction in effective reservoir capacity. Therefore, efficient water and sand management measures are required to keep reservoirs operational. Since Taiwan has frequent typhoons and torrential rain, a large amount of sediment gets flushed into reservoirs due to continuous reservoir catchment region erosion. As a result, the problem of sedimentation in reservoirs has gradually begun to affect the stability of the regional water supply. The problem of sedimentation significantly affects reservoirs and reflects the issues faced by the entire river ecosystems. To comprehensively handle this problem, sediment management strategies must account for discharges from upstream catchment areas to downstream estuary drainages. Reducing the amount of sediment in the catchment area is the primary strategy for the upstream reservoir
catchment area. Further, side slopes, soil and water conservation, and the installation of check
dams are comparable strategies that can be employed. Addressing the problems in the midstream
reservoir area involves identifying methods of using sediment prevention facilities to effectively
remove sediment from the reservoir, reduce reservoir sedimentation, and ensure a stable water
supply. Two key feasible strategies for achieving these objectives are hydraulic sediment removal
and mechanical dredging. However, a strategy that should be implemented downstream of a
reservoir area is balancing the water and sand balance of the overall waterway through flow
diversion and river rehabilitation.

Sediment flushing, sediment sluicing, sediment bypassing, turbidity current venting, and
longitudinal or lateral erosion enhancement are some of the various sediment desiltation
techniques. During sediment flushing, the bottom outlets of the reservoirs are first opened to lower
the water level or drain water from the reservoir. This procedure can accelerate the water flow
velocity around the outlets, agitate previously accumulated sediment near the dam, and create a
deep groove channel or drawdown cone in the reservoir near the intake of the outlets. In addition
to discharging water stored in a reservoir, this method can flush previously accumulated sediment
out of the reservoir alongside water flow through the dam bottom outlets. Flushing reduces the
amount of deposition in the reservoir and helps restore the storage capacity of a reservoir. The
results of sediment flushing are better with lower and more significant outlets. Therefore, this study
focuses on flushing and using an artificial guiding channel to prevent sediment deposits. Additionally, it is anticipated that this strategy can make the reservoir more erosive.

SITE DESCRIPTION
The dam site of Agongdian Reservoir is located at the confluence of Wanglai Creek and Zhuoshui
Creek (Figure 1). The elevation of the dam crest is 42 meters, the normal water level is 35.50
meters, the highest flood level is 40 meters, and the total water storage capacity is 45 million cubic
meters. Therefore, it is a multi-target reservoir that mainly focuses on flood control and has
irrigation and water supply targets. The Agongdian Reservoir, in response to the characteristics of
incoming water from sediment in the catchment area, has a "water storage and utilization period"
from September 11th to May 31st of the following year. After that, water storage is adjusted to
supply the household, public, agricultural, and industrial water. From June 1st to September 10th,
every year is the "empty reservoir desilting period," adopting low water level operation (between
EL. 31m and EL. 32m) using spill shaft or irrigation shaft outlets.

In recent years, due to the increasing demand for water in Southern Taiwan, Agongdian Reservoir
serves empty flushing and water supply to work with the characteristics of sedimentation ratio 7:3
coming from Zhuoshui Creek and Wanglai Creek, respectively. Therefore, the utilization of
appropriate operational strategies, construction methods, or facilities to achieve the daily increase
of water supply capacity during the desilting period of the empty storage at the same time is
essential. To sustain these desilting targets for empty reservoirs, assessing the hydrological
conditions due to climate change is essential to improve the ideal conditions for desilting
operations and water sources.
Therefore, the position of the flood discharge facilities was taken into account when the Agongdian Reservoir was refurbished and improved, and the overflow spill shaft was planned to discharge sediment and flood from the empty reservoir. Since the upgrade and improvement, an eroded main channel has gradually appeared in the middle of the reservoir, washed by the water from the Zhuoshui River. The Southern Region Water Resources Office expanded the excavation along this trench in 2018 to form a deep artificial channel to discharge incoming sediment. It has been observed in recent years that the effect of sand discharge is efficient, and now it has become a vital flow path for empty flushing.

According to the planning concept, the reservoir is divided into the Wanglaixi Creek area and the Zhuoshuixi Creek area. This study proposes to arrange a dike along the boundary of the existing deep channel. During the empty period of the reservoir, the sediment from the middle and low flow of Zhuoshui Creek can be introduced into the deep channel. This strategy reduces the chance of sediment deposit and sedimentation in the reservoir area (Southern Region Water Resources Office, 2022). The sheet pile dike is set at E.L. 32 m on the north side of the deep channel. The elevation from the inflow section to about 0K+670 is E.L. 32 m, and EL. 30 m, the elevation from 0K+670 to the spill shaft is EL. 30 m, and the outlet elevation is set as E.L. 32 m of the spill shaft.

Figure 1. Watershed and location of Agongdian Reservoir.

METHODOLOGY
Considering hydraulic scour depths, most open-channel flows are assumed shallow, and the effect of vertical flow motions is not calculated. Therefore, the 3D Navier-Stokes equations can be vertically taken and averaged to a format of depth-averaged 2D equations to estimate water depth and flow velocity (Lai, 2009, 2010). The SRH-2D model is a depth-averaged 2D model developed for studying open-channel flows in this research. The model is adopted for solving the 2D shallow-water flow equations and using the finite-volume numerical method with an unstructured hybrid
A mesh system (Lai, 2010). Moreover, the model has been verified and implemented in several experimental or field cases in shallow-water flows (Lai, 2009, 2010), which has demonstrated that the model is suitable for practical applications in hydraulic and sediment transport engineering. Examples include flows with in-stream structures such as weirs, diversion dams, release gates, coffer dams, etc.; bends and point bars; perched rivers; and multi-channel systems. Therefore, the SRH-2D is adopted to simulate an artificial guiding channel to prevent sediment deposits and increase erosion potential in this study.

The scour and erosion of the reservoir bottom results from incoming sediment and deposited sediment of the reservoir bottom, including suspended and bed loads. Therefore, the calibration and verification processing calculated the appropriate general scours estimation. We adapt the bed load equation of Parker (1990) for the bed load transportation and the advection-dispersion equation for the suspended load dissipation in the study area (Water Resources Planning Institute, 2009). Parker’s (1990) equation is well suited to rivers composed of both coarse sediments (e.g., gravels) and fine sediments (e.g., sands).

RESULTS AND DISCUSSIONS

The 2D model simulation area covers the Agongdian Reservoir area. SMS version 13.0 (Surface-water Modeling System) has been used to generate the grid required for simulation in SRH-2D. The upstream boundary extends from the reservoir’s inflow section about 600 meters upstream along the Zhuoshui River, and the inflow width is about 100 meters. The downstream boundaries are located at about 0K+220 and 0K+440 along the dam site in the reservoir area, and they are the irrigation shaft and spill shaft. The irrigation shaft outlet has a designed water intake of 15 m$^3$/s and a shaft diameter of 1.5 meters. The spill shaft outlet has a design discharge capacity of 85 m$^3$/s and a shaft diameter of 2.8 meters.

The digital elevation terrain (D.E.M.) data adopts the topographic measurement results of Agongdian Reservoir in 2020. The grid density of the upstream is set to be about 10-15 meters, the grid density of the reservoir area is about 5-10 meters, and the grid density of the deep main channel is about 2-10 meters and 2.5 meters. The interpolated terrain analysis uses the inverse distance weighting (Inverse distance weight) method to interpolate D.E.M. data into each grid cell.

In this study, whether there is a separation dike in the current terrain, design cases A and B are simulated scenarios. The upstream boundary considers the inflow of Zhuoshui Creek and Wanglai Creek, and the downstream boundary is the operation of opening the spill shaft. The setting method is to set the outflow water level at the nozzle. In each case, the Manning value of the reservoir area and the upstream channel is 0.020, and the sediment's median particle size ($d_{50}$) is 0.039mm. This plan aims at different flow rates to understand the difference in the desilting efficiency of the deep main channel before and after the sheet pile dike installation. Four groups of hydrological scenarios were designed for the simulation conditions. In addition, the comparison of the two-dimensional simulation scenario case settings is shown in Table 1. The terrain elevation of each simulation scenario case is shown in Figure 1. The calibration curves give the boundary conditions for the inflow sediment yield of the two creeks (Southern Region Water Resources Office, 2020).

<table>
<thead>
<tr>
<th>Cases</th>
<th>Sheet pile dike</th>
<th>Zhuoshui River Inflow (m$^3$/s)</th>
<th>Wanglai River Inflow (m$^3$/s)</th>
<th>Spill shaft Water level(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>a without</td>
<td>71.7</td>
<td>0</td>
<td>30.0</td>
</tr>
<tr>
<td>c</td>
<td>197.3</td>
<td>340.7</td>
<td>34.0</td>
<td></td>
</tr>
<tr>
<td>Case B</td>
<td>a with</td>
<td>71.7</td>
<td>0</td>
<td>30.0</td>
</tr>
<tr>
<td>c</td>
<td>197.3</td>
<td>340.7</td>
<td>34.0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2. Topographic of Agongdian Reservoir (a) without sheet pile dike (b) with sheet pile dike.

The hourly water depth, flow velocity, and concentration distribution results of the two-dimensional simulations of Cases A and B are shown in Figures 3 to 6, respectively. Comparing the current terrain and the setting of dikes (Cases A-a and B-a), it is evident that in low flow and low water levels, the dividing dikes can concentrate the turbid water of the Zhuoshui River in the deep channel. In addition, the flow velocity of the deep channel is also significantly greater than that of the reservoir area and concentrated. As a result, the overflow spill shaft can discharge water with a higher concentration.

Comparing the situation with or without restraint on the south side (case B-a), part of the muddy water diffuses to the water body on the south side of the reservoir area. Therefore, the no-restraint area in the south will spread the turbid water faster. Under the current terrain conditions, the inflow of turbid water flowing into Zhuoshui Creek is quickly distributed to the entire water body. Still, it is affected by the inflow of Wanglai Creek. Therefore, the turbid water of Zhuoshui Creek is restricted and concentrated in the reservoir area to the east of the spill shaft.

If the flow of the Zhuoshui Creek increases and the water level is high since most of the turbid water inflowing from the Zhuoshui Creek overflows to the outside of the deep channel. It is affected by the water body with a higher water level in the reservoir area, the concentration of the outflow from the spill shaft is relatively low, and the flow rate of the deep channel will be relatively low. The section at an elevation of 30 meters on the south side of the deep channel (0K+670 to the spill pipe) has slowed down significantly.

In other words, using dikes to concentrate the turbid water flowing from the upstream is more effective in the 32-meter elevation section (0~0K+670) on the south side. However, the benefit has been reduced. For example, suppose the reservoir's water level reaches an elevation of 34 meters (cases A-c and B-c), the benefits of concentrating the muddy water of Zhuoshui Creek in the deep channel decrease. In addition, the benefits of increasing the flow velocity in the deep channel and increasing the outflow concentration are also decreased significantly.

From the simulation results of Cases A and B, it can be seen that the effect of the current separation dike is most effective when the water level is below EL.32 m due to the limitation of the elevation of the north and south sides. However, as the water level rises, the benefits of slowing down the silting of the sediment or increasing the scour of the bed gradually decrease.
In addition, from the shear force distribution diagram in Figure 7(a), it can be seen that although there is no sheet pile dike, the main shear force distribution is concentrated in the streamline of the main deep channel. However, as the inflow increases and the water level rises, the more obvious area of shear force distribution tends to move back to the upstream side (Fig. 7(b)). Relatively, under the setting of the sheet pile dike, the distribution of shear force moves to the vicinity of the outlet (Fig. 7(c)), so it is beneficial to concentrate the effect of scouring and silting reduction on the main deep channel. However, the water level increases with the inflow under the elevated condition, the area where the shear force distribution is a more obvious move to the upstream side (Fig. 7(d)). But, its influence range is still larger than the condition without sheet pile dike setting. It can be seen that setting sheet pile dike forms an artificial guiding channel that can help to prevent sediment deposits and increase erosion potential in a reservoir.

![Figure 3. Case A-a distribution of water depth, velocity, and concentration of (a)1hr (b)3hr (c)6hr.](image)
Figure 4. Case A-c distribution of water depth, velocity, and concentration of (a)1hr (b)3hr (c)6hr.

Figure 5. Case B-a distribution of water depth, velocity, and concentration of (a)1hr (b)3hr (c)6hr.
Figure 6. Case B-c distribution of water depth, velocity, and concentration of (a) 1hr (b) 3hr (c) 6hr.

Figure 7. Shear stress distribution and potential area of erosion (a) without sheet pile dike, Case A-a (b) without sheet pile dike, Case A-c (c) with sheet pile dike, Case B-a (d) with sheet pile dike, Case B-c
CONCLUSIONS
The two-dimensional bedload model (SRH-2D) is used to simulate the water-sand transport in the Agongdian Reservoir, the outflow from the spillway, and the transport and concentration changes of the turbid sediment in the reservoir area with and without sheet pile dike along with the main channel. A noticeable difference between the current terrain and the sheet pile dike scenario can be observed. Under low flow and low water level conditions, the sheet pile dike can concentrate the turbid water of Zhuoshui Creek into the deep channel, where the flow velocity is significantly higher and more focused compared to the reservoir area. As a result, the spillway can also discharge water with higher concentrations. However, due to the influence of the influx from Wanglai Creek, the turbid water from Zhuoshui Creek is restricted and mainly concentrated in the eastern area of the spillway. When the reservoir's water level reaches 34 meters, the concentration of the inflowing turbid water in the deep channel, the increase in flow velocity in the deep channel, and the benefit of discharging water with higher concentration from the spillway become less significant. Therefore, the sediment removal and desilting efficiency are more evident at low water levels. However, the concentration of the incoming sediment can accumulate in the main channel after the sheet pile dike is installed, leading to potential sedimentation. Therefore, it is recommended to prioritize the removal of sediment in the main channel during annual mechanical dredging, which can improve the effectiveness of hydraulic sediment removal during the flood season.

REFERENCES