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Water Injection Dredging for improving and preserving reservoir storage capacity: modelling and measuring tools

Dragage par injection d'eau pour améliorer et préserver la capacité de stockage des réservoirs

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Abstract. Water Injection Dredging (WID) has been successfully applied for removing sediment deposits in reservoirs, which results in an increase of their storage capacity. This dredging method is based on the fluidization of the top sediment layer by pressurized injection of water by a dredging vessel. The fluidized sediment can be transported towards the dead storage of the reservoir or sluiced out of the reservoir through the bottom outlets of a dam. This flow can either occur by gravity induced flow or especially directed by the dredging strategy of the WID vessel. This dredging technique can increase the water storage capacity of the reservoir and prevent the erosion of the river downstream, hence the sediment blockage. Recent developments in modelling and measuring tools have enabled stakeholders to design, optimize and monitor WID in reservoirs. In this paper, we will demonstrate how modelling and measuring tools can be used to evaluate alternative dredging strategies for reservoir maintenance. In particular, we show how a mid-field and far-field modelling can be applied for designing WID actions and predicting sediment plume dynamics in a given reservoir. Additionally, we will present recently-developed in-situ measuring tools, that are currently used for monitoring turbidity in a water column and sediment properties during and after WID actions. Finally, potential benefit of applying WID in Shihmen Reservoir (Taiwan) is discussed.

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Résumé. Le dragage par injection d'eau (WID) a été appliqué avec succès pour éliminer les dépôts de sédiments dans les réservoirs, ce qui permet une augmentation de leur capacité de stockage. Cette méthode de dragage est basée sur la fluidisation de la couche sédimentaire supérieure par injection d'eau sous pression par un navire de dragage. Le sédiment fluidisé peut être transporté vers le stockage inactif du réservoir ou évacué hors du réservoir par les sorties de fond d'un barrage. Cet écoulement peut se produire soit par écoulement gravitationnel, ou déterminé par la stratégie de dragage du navire WID. Cette technique de dragage peut augmenter la capacité de stockage de l'eau du réservoir et éviter l'érosion de la rivière en aval, et par conséquent le blocage des sédiments. Les développements récents des outils de modélisation et de mesure ont permis aux parties prenantes de concevoir, d'optimiser et de surveiller le WID dans les réservoirs. Dans cet article, nous démontrons comment des outils de modélisation et de mesure peuvent être utilisés pour évaluer des stratégies de dragage alternatives pour l'entretien des réservoirs. En particulier, nous montrons comment une modélisation en champ moyen et en champ lointain peut être appliquée pour concevoir des actions WID et prédire la dynamique du panache de sédiments dans un réservoir donné. De plus, nous présenterons des outils de mesure in-situ récemment développés, qui sont actuellement utilisés pour surveiller la turbidité dans une colonne d'eau et les propriétés des sédiments pendant et après les actions WID. Enfin, les avantages potentiels de l'application du WID dans le réservoir de Shihmen (Taiwan) sont discutés.

1 Introduction

Sediment dynamics and specifically, the siltation of fine sediments in reservoirs is of great interest to those responsible for the maintenance of the dams and water quality of reservoirs. The amount of siltation is dependent on the influx of fine sediments (from runoff, landslides, bank erosion etc.) which gets trapped and settles in the reservoir due to the low flow velocities. Sediment management in reservoirs becomes more challenging due to the aging of existing infrastructure.

Typically, the sediment management strategy for a given reservoir depends on the location, infrastructure and circumstances at each site. Often no action is taken to manage sedimentation in reservoirs as a certain amount of siltation in dead storage is taken account for in the design of dams and reservoirs. Siltation is tackled when it is so much that it influences the functioning or safety of the dam or creates undesired environmental impacts downstream, but measures are very costly. Thus, necessary knowledge is needed for better understanding and mitigating sedimentation challenges. Apart from existing reservoir management strategies, there is a need for innovative effective and cost-efficient solutions.

In this paper, water injection dredging (WID) is proposed as an innovative, efficient and cheaper method to tackle siltation in reservoirs. The paper focusses on the numerical and monitoring tools that can be used to determine the necessary knowledge for applying and optimizing this method.

Density current venting is a technique used in reservoirs to sluice fine suspended sediments that are transported by turbidity currents. Turbidity currents, i.e. density currents driven by suspended-sediment concentration, can be generated naturally by river inflows, or artificially with some method of agitation of muddy deposits. Turbidity currents can transport fine sediments over much longer distances than a normal suspension and can transport the sediments to the dam. As in many situations dam operations do not always allow for sluicing fine sediments from normal suspended loads and turbidity currents. Therefore, the fine sediments arriving at the dam tend to deposit in front of it, forming a bottom-set deposit. After settling and consolidation, a major part of these sediments cannot be remobilized again with normal operations or successive turbidity current venting operations. Low-energy currents in the deep reservoir do not have enough energy to entrain significant amounts of (consolidated) deposits (unless with full water-level draw-down flushing operations). In these situations, it is useful to explore the use of water-injection dredging to artificially remobilize the turbidity currents that move sediments to deeper areas, where they can be vented through outlets.

Water injection dredging (WID) has long been a part of the dredging portfolio for port and waterways maintenance. It has been predominantly applied in ports and waterways with fine grained sediment, however examples of WID applications in coarse sediment are also known within the dredging industry. The principle of the water injection process is based on fluidizing the sediment bed using water jets (Figure 1). The more water jet nozzles used, the greater the amount of water entering the bed. Since water is injected with relatively low pressure, re-suspension and dispersion of the fine sediment throughout the water column is avoided. Instead, the water injection creates a water-sediment mixture closer to the bed. After WID operation, fluidized mud layers are formed with densities lower than the bed sediment, but higher than the surrounding water density. This WID-made turbidity current spreads itself in the water under the influence of gravity induced hydrodynamic processes. Depending on sediment properties and operational parameters, the thickness of the fluidized mud layer and resulting density current can vary between 0.25 and 3 m. Over the last decades, WID becomes more popular dredging method for port maintenance because economical, operational and ecological aspects of WID seem to be highly competitive in comparison to standard maintenance strategies.

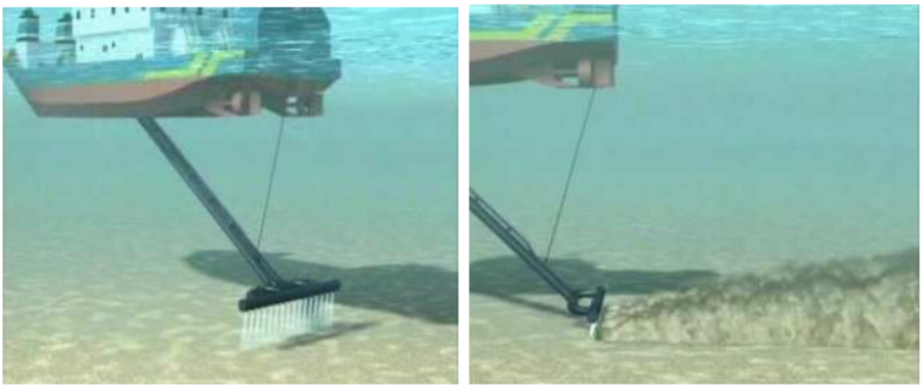

Fig. 1. A sketch of WID from [1].

In recent years, different tools have been developed for optimizing WID processes and to enable better prediction of the resulting sediment plume transport. Generally, numerical tools that are used in dredging engineering are categorized in 3 groups depending on the scale of the models: near-field, mid-field and far-field models. In this paper, the area around a water jet, where a dynamic plume is formed, is called the near-field. When the dynamic plume is flowing in the WID area, we refer to this area as a mid-field. Finally, the larger area that is beyond the immediate area being dredged, e.g. the reservoir, is referred as a far-field.

This paper is structured as follows: first, show few some examples of TUDflow3d model applications for estimating mid-field WID sediment plume dispersion and sedimentation. Outcome of a mid-field model can be used as input to a far field model. Here we present a Delft3D-based modelling tool that is used for far-field prediction of sediment distribution once the turbidity current as a result of WID is dispersed over a wider area in the reservoir. Then, several examples of lab experiments that help to better understand near-field effects during WID is demonstrated. The monitoring tools that can be used for surveying during and after WID are presented. Finally, benefits of applying WID in Shihmen Reservoir (Taiwan) is illustrated.

2 WID modelling and monitoring

2.1 Mid-field modelling of WID

Mid-field modelling of WID is carried out by the 3D CFD model TUDflow3d [2]. Originally, TUDflow3d has been developed for accurate mid-field simulations of Trailing Suction Hopper Dredger overflow plumes on real scale. It has also been used for WID density currents in harbour basins, MFE (Mass Flow Excavation) plumes, deep sea mining tailing plumes, sedimentation in a hopper or caisson and salinity driven density flows. TUDflow3D is fully 3D with variable density taken into account in all three dimensions (not just in the vertical), non-hydrostatic pressure and turbulence modelled by either a RANS (Reynolds Averaged Navier Stokes) approach or by the accurate LES (Large Eddy Simulation) approach employing a fine grid. The sediment bed is treated with an immersed boundary technique. In the model, sediment can settle out of the WID density current, deposit on the bed and the WID density current can accelerate itself by eroding sediment from the bed. Hindered settling of the fine sediments near the gelling concentration is taken into account. The feedback of the sediment concentration on the mixture density is captured and this feedback derives the spreading of a WID plume as a density current.

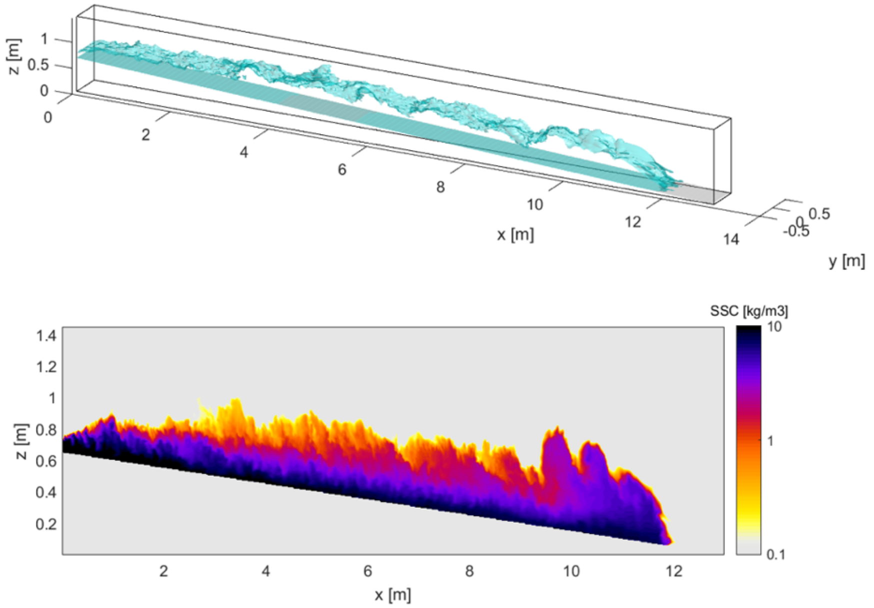

Fig. 2. Instantaneous LES snapshot of 3D contour (top) of turbidity current and SSC at 2Dv slice through centre of turbidity current (bottom).

An instantaneous snapshot of a modelled density current along a sloping erodible bed in a flume is shown in Figure 2. The individual turbulent eddies and whirls resolved on the grid in LES are clearly visible. Comparison for time averaged velocity and Suspended Sediment Concentration (SSC) profiles with measured ones in an experiment of Parker et al. [3] is given in Figure 3. Here, different manners of capturing turbulence are compared. In addition to LES, the Reynolds averaged Navier Stokes (RANS) and RANS with reduced eddy viscosity near the bed are tested. Both RANS runs use a damping function to take turbulence damping on the upper edge of the turbidity current into account. An advantage of LES is that it does not need such damping function as the influence of a sharp gradient in density is automatically captured in the resolved eddies in LES. Of the two RANS results the ones with reduced near bed viscosity are slightly better. The LES results are most accurate. The vertical SSC profile and layer thickness of the density current is captured very well in the CFD LES model and the velocity profiles are captured reasonably well with a small overprediction of the near bed velocity.

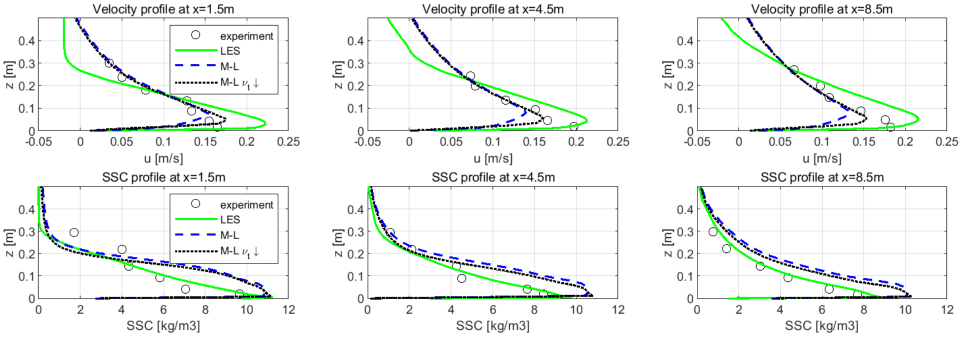

Fig. 3. Comparison modelled time averaged velocity and SSC profiles with 3 different turbulence model settings (LES; Mixing Length RANS and Mixing Length RANS with reduced near bed viscosity) and measurements from an experiment of Parker et al. [3].

Additionally, TUDflow3d is used for an example application of modelling WID in a reservoir. The Shihmen Reservoir (in Taiwan) is used for this example. Fictitious application of WID is modelled for a location in the reservoir with visible silt deposits, see Figure 4. The bathymetry of the reservoir and the domain of CFD model is shown in Figure 5. In this CFD run a WID works along a 300m long track indicated with a black dashed line. The resulting WID density current is shown in Figure 6. It moves down the slope of the bathymetry. This example shows that TUDflow3d can be used as a tool to model mid-field WID density current behaviour in a reservoir. It can be used to design and optimize WID actions and it can provide input for the far field model runs that are described in Section 2.2.

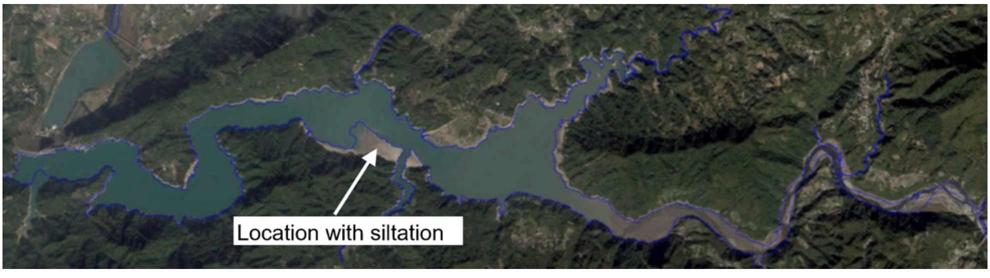

Fig. 4. Google Earth image of the Shihmen Reservoir at a moment with low water level in 2015. A location with siltation is indicated.

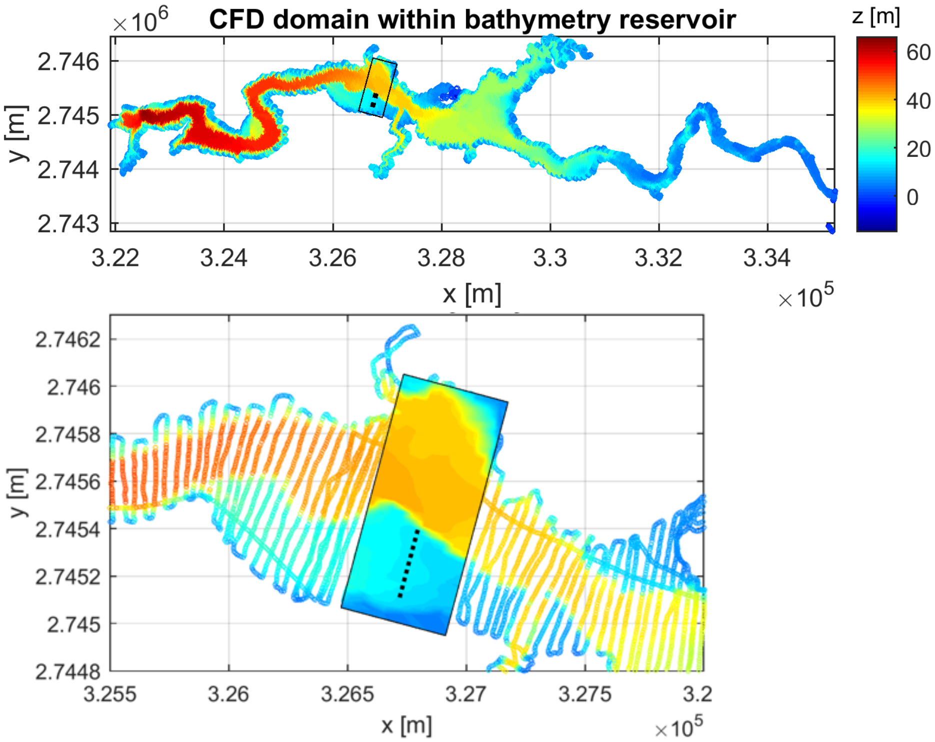

Fig. 5. Bathymetry of Shihmen Reservoir and a zoom of the extend of the domain of CFD model indicated with black lines in the lower panel. In the simulation the WID is working along the black dashed line.

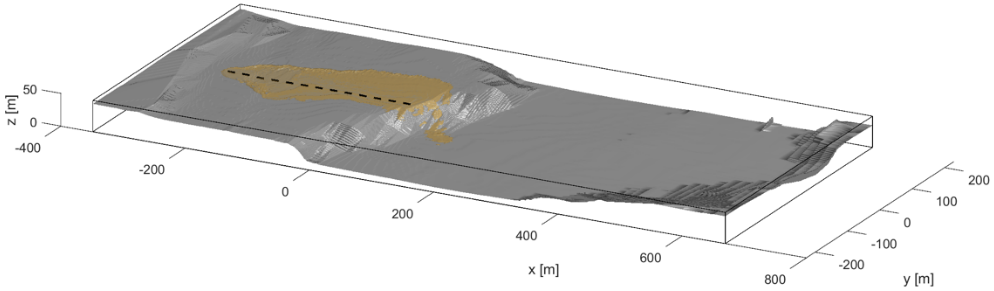

Fig. 6. Example of TUDflow3d simulation: density current from WID action along the black dashed line. The bathymetry is indicated by the grey surface and the WID density current is indicated by the brown contour.

2.2 Far-field modelling of WID

In order to assess the optimum dredging criteria and the resulting turbidity plume generated as a result of WID, a combination of mid and far field models is used. The turbidity current behaviour and transport can be assessed, but also the suspended transport, as both mechanisms are important, and will determine the amount of fine sediments that can be flushed. A mid-field model was used to determine the initial behaviour of the turbidity current generated through WID and transport mechanisms as described in the previous section. This model provided input into a larger scale Delft3D model that was set-up to create a tool that could be used to test the driving processes of turbidity current dynamics and to test the impact of different dredging strategies e.g. different locations in the reservoir.

Deltares' open source software Delft3D is a flexible, integrated modelling framework which simulates two and three-dimensional flow, waves, sediment transport and morphology (as well as dredging and dumping) on a time-scale of days to decades. The sediment transport module includes both suspended and bed/total load transport processes for an arbitrary number of cohesive and non-cohesive sediment fractions. It can keep track of the bed composition to build up a stratigraphic record. The suspended load solver is connected to the 2D or 3D advection-diffusion solver of the hydrodynamic module and importantly for fluid-mud simulations, density feedback can also occur.

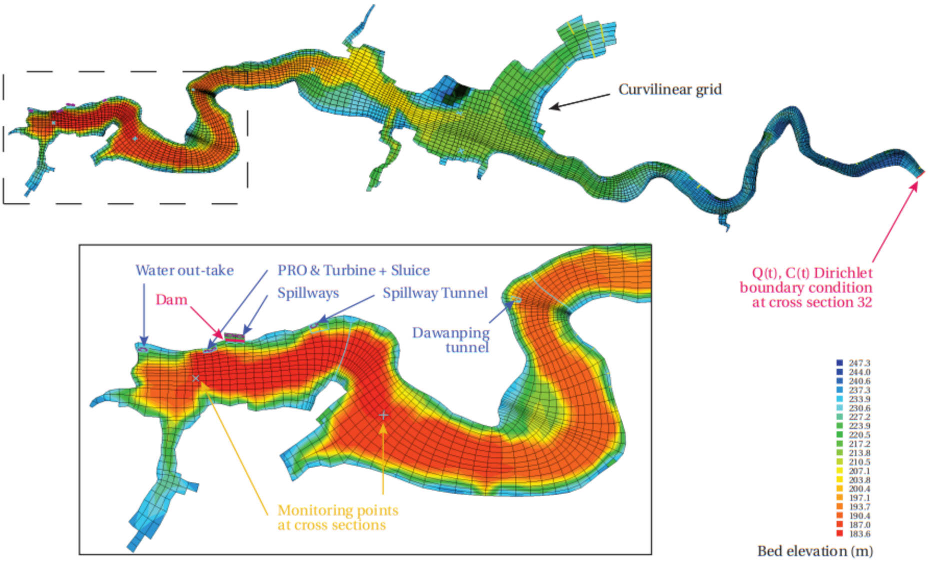

Fig. 7. Far-field modelling example for the Shihmen Reservoir in Taiwan from [4].

For this work, a Delft3D model of the Shihmen Reservoir in Taiwan was set up by Commandeur [4, 5], which was originally created to test the efficacy of practical solutions to achieve a higher venting efficiency rate for turbidity currents in that reservoir (see Figure 7). This model can now be taken a step further by also controlling the location and generation of turbidity currents through WID with respect to the location of the bottom outlet in the reservoir. Specific inputs on the density and velocity of the initial plume are provided from the mid-field model. The Delft3D system model can assess the full cycle of siltation and siltation management. The model can be used to pre-determine where siltation is mostly likely to occur in reservoirs by simulating sediment loads into the reservoir. After WID has occurred, the model can be used to track the suspended sediment that exits the reservoir through the outlets and assess subsequent transport or deposition downstream of the dam.

2.3 Near-field and mid-field laboratory experiments for WID

Over the last decades, laboratory experiments have been intensively used for generating new knowledge on WID. Understanding physical processes, which take place in sediment during

WID, helps to determine the most optimal operational parameters that can guarantee efficient WID actions. For instance, in order to be able to control the WID process, speed of a WID vessel, WID cycles, the standoff distance as well as a number and size of nozzles, and pump pressure in relation to sediment properties should be managed carefully. Ill-defined operational parameters can potentially result in an extensive dilution, turbidity generation or uncontrolled re-suspension, thus in inefficient WID processes.

Few examples of laboratory flume experiments conducted for understanding the physical processes behind WID are shown in Figure 8. In these experiments, a consolidated layer of cohesive sediment (mud) is placed on the bottom of a flume. Jet with a single nozzle as well as with multiple nozzles are used for fluidizing consolidated cohesive bed and creating a density current (shown in left/right panels and in middle panel, respectively).

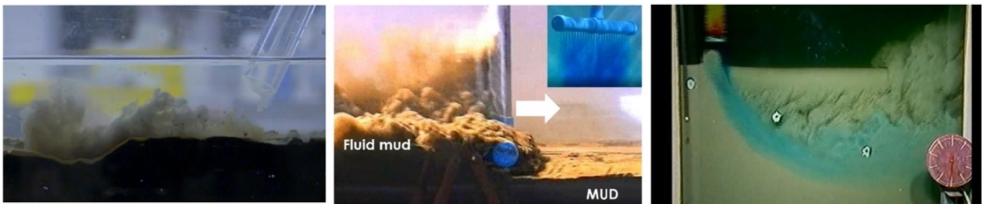

Fig. 8. Conducting laboratory experiments for understanding the physics of WID. A jet with a single nozzle (left and right panels) and with multiple nozzles (middle panel) are used for fluidizing consolidated mud and creating a density current.

Conducting tests for defining the most optimal operational parameters (e.g. standoff distance, pressure speed of WID vessel, etc.) can greatly help to optimize WID operations in order to achieve the most efficient outcome of WID as function of reservoirs specific properties. Furthermore, the lab measured properties serve as input parameters for far-field and mid-field models that are developed for assessing the impact of WID in reservoirs. For instance, Figure 9 shows a time series of a fluidized density current, that is transported along the flat bed by water injection in a flume. Modern measuring technologies allowed us to measure the physical properties of the WID-induced mud layer, such as the velocity of plume, rheology (yield tress and viscosity) of mud (see [6] for measuring rheological properties), the density and the height of the WID-induced mud layer. Most of these physical properties depend on the operational parameters (e.g. pressure and standoff distance), thus connecting the physical properties of mud and operational parameters of WID is the key in maximizing the effect of WID in the field.

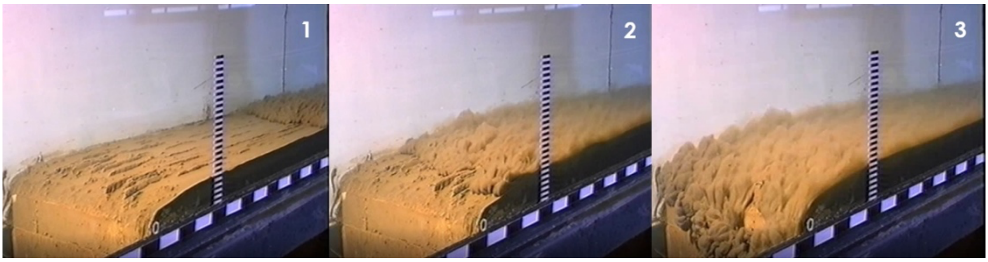

Fig. 9. Demonstration of density currents after water injection in laboratory.

2.4 Field monitoring tools for WID

There are various monitoring tools that can help to assess the efficiency and environmental impact of WID. Typically, bathymetric surveys are performed from the water surface using an echo-sounder for measuring the depth of water and a GPS tool for measuring geographic location. These measurements provide knowledge about water-mud interface, which can be used for planning WID operations and monitoring the results of WID. Figure 10 shows an example of a bathymetric measurements performed by a multibeam echosounder. These surveys are carried out using high frequency acoustic measurements (about 200 kHz).

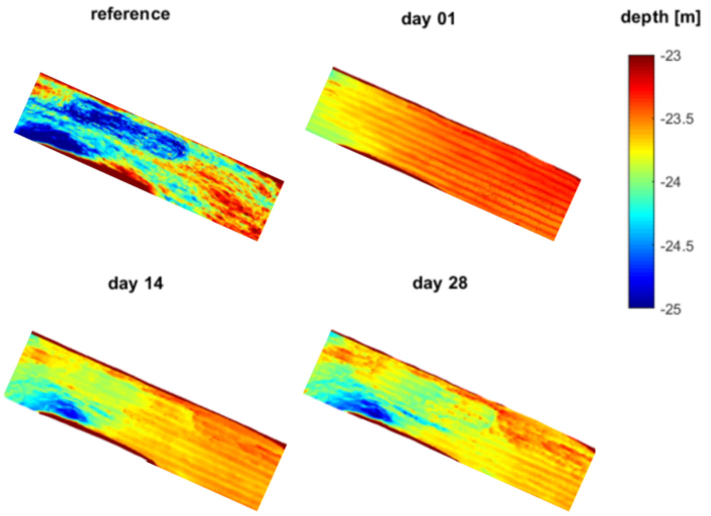

Fig. 10. Multibeam echosounder measurements indicating water-mud interface before WID (reference), during WID (day 1) and after WID (day 14, day 28).

In addition to the traditional bathymetric surveys, more insightful surveys can be conducted in order to detect the original bottom surface of the reservoir. For these surveys, sub-bottom profiling tools are generally used in combination with multibeam echosounders. These emitted low-frequency (5-40 kHz) can penetrate soft sediment deposits and reflect from a denser layer consisting of soil or rock. Figure 11 shows an example of low- and high-frequency vertical profiles right after WID and 1 month after WID.

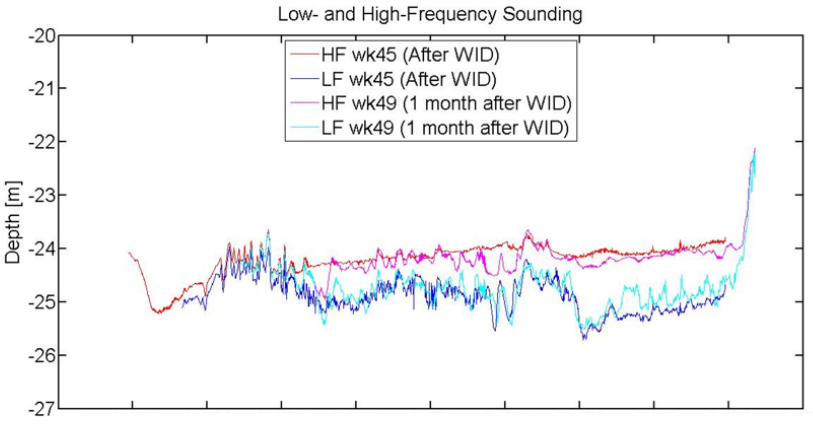

Fig. 11. Low- and high-frequency vertical profiles indicating the bed level and the water-mud interface, respectively.

Difference between low- and high-frequency levels indicate a layer of WID-fluidized mud layer. An additional knowledge of the physical properties (e.g. shear strength and density) of this layer can be also measured and used for modeling the transport of this layer or for predicting consolidation. The measured vertical density profiles are shown in the right panel of Figure 12. The measurements can be done by different penetrometers [7]. In this case, the densities are measured by DensX (from dotOcean). It can be observed that the measured density profiles show a good resemblance with the 1DV consolidation modelling (more details in Kirichek et al. [8]).

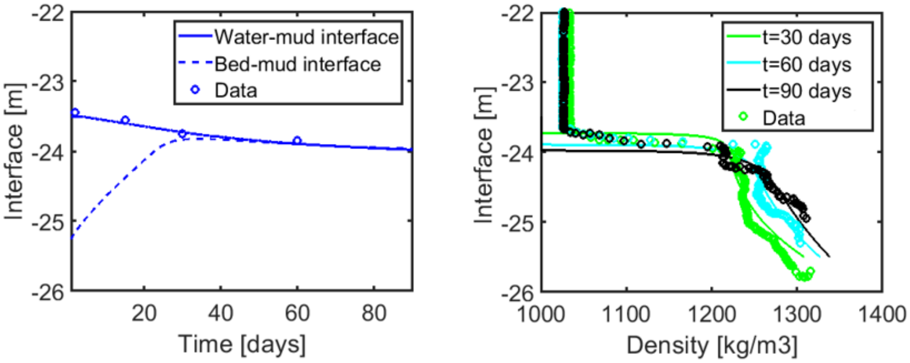

Fig. 12. Estimating consolidation of fluidized mud layer after WID. Left panel shows development of water - fluidized mud interface as well as fluidized mud – consolidated bed interface. Right panel show model predictions (solid lines) and in-situ measurements (symbols) of densities in water-mud vertical column.

The use of Distributed Temperature Sensing (DTS) with optical cables can be used for near and mid field assessment of the sediment density before and after WID and at deposition sites, monitoring the consolidation rate. Figure 13 gives an example based on thermal heating and the difference in heat capacity of solids versus water in sediment.

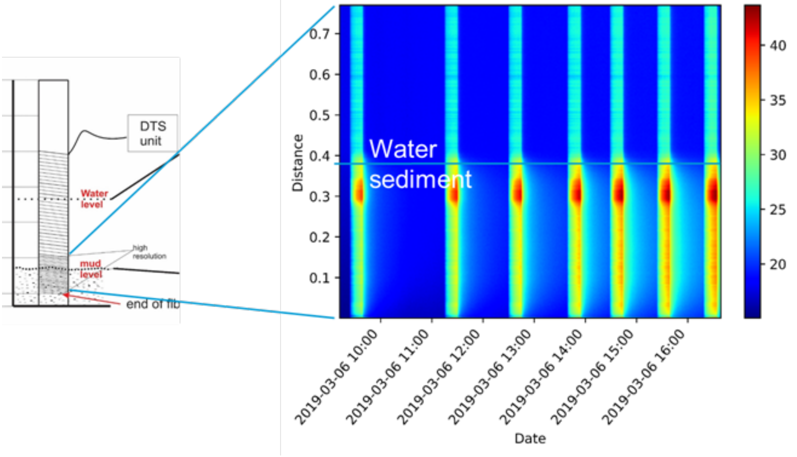

Fig. 13. Sediment density measurements as function of thermal capacity.

The turbidity during and after WID can be monitored using the backscatter data of an Acoustic Doppler Current Profiler (ADCP) [9]. ADCP backscatter monitoring can help to assess the mid field impact of WID.

3 Potential of WID for Shihmen Reservoir

The Shihmen Reservoir (Fig. 7) in the north of Taiwan is an example of a reservoir with high sedimentation rate which has significantly impacted the reservoir storage capacity. The purpose of the reservoir is to provide irrigation and drinking water as well as to generate hydro power. It was designed and constructed in 1964 with a volume of 309 million m3. However, already during construction a typhoon caused 19 million m3 of sedimentation leading to an initial volume of 290 million m3 at the moment of completion being 6% less as the intended 309 million m3. In 2015 the reservoir volume was reduced by about a third to 205 million m3 leading to an average volume loss of about 2 million m3 per year [10]. Main reasons for sedimentation in the Shihmen Reservoir are the heavy rainfalls associated with typhoons which erode significant amount of sediment from the 763 km2 mountainous watershed upstream of the reservoir. The sediment mainly consists of fine clay, silt and fine sands with a d50 near the dam of 80μm [10]. Inside the reservoir high concentration conditions are found near the bed driving density currents down the reservoir towards the dam. A turbidity monitoring system to keep track of the suspended sediment concentration profiles is installed in the reservoir. Upstream of the reservoir more than 100 dams have been constructed to trap sediment, but in 1996 only one is still functioning and all others are filled up [11]. From 2012 onwards, a discharge tunnel is used to bypass the density current from the deeper parts of the reservoir. The discharge tunnel is opened when a density current is detected in the reservoir. During 5 medium typhoons, this system vented almost 2 million m3 of sediment out of the reservoir, proving that this system is effective [10]. There are plans for additional sediment discharge tunnels.

Since the mid-eighties dredging is performed in the Shihmen Reservoir on a daily basis, but it cannot keep up with the sedimentation. As above mentioned, the sediment the Shihmen Reservoir consists of mainly fine sands, silt and clay and this leads to low dredging production rates and large wear when using traditional dredging equipment. WID on the other hand is very suitable to dredge fine sands, silt and clay without significant equipment degradation. When WID is combined with the bypass density current strategy, preliminary estimation shows, there is huge potential for more efficient removal of sediment from the Shihmen Reservoir. In such hypothetical operation WID would fluidize large amount of sediment which flow as a density current towards the dam where it is vented away via the sediment tunnel. Typical WID production rates are 500-2500 m^3/h in silt, clay and fine sands [12]. Assuming a dredging period of 225-245 days (24h per day production and 25% downtime), around 2 million m^3 of sediment can be fluidized per year by only one WID unit. This amount is equal to the average yearly loss in reservoir volume and therefore one WID unit dredging could preserve the reservoir storage capacity of the Shihmen Reservoir. This shows the potential for application of WID in maintenance dredging of reservoirs in particularly those that face siltation issues with silt, clay, fine sands. Those are sediment types which pose a challenge for more traditional dredging equipment as a Cutter Suction Dredger, Grab Dredger or Auger Dredger, but are well suited for efficient application of WID.

4 Conclusions

This paper focusses on insights gained using a combination of monitoring, numerical modelling and laboratory experiments for WID in reservoirs. By combining measurements from the field, laboratory experiments on fluid mud properties, with a state-of the art modelling approach new insights can be gained not only on the best approach for implementing WID as a maintenance strategy for reservoirs with siltation problems but also on the impact of flushing excess sedimentation downstream.

The research focused on cohesive sediment (fluid mud) behavior and transport, but also the resulting sediment plume after WID. Both mechanisms are important and depend on the hydrodynamic conditions. A WID pilot demonstrated that WID is efficient in fluidizing fluid mud deposits. The pilots provided high quality quantitative and qualitative monitoring of fluid mud behavior after WID. This information was used to fine tune a mid-field 3D CFD model of dredge plume behavior. The mid-field WID plume layer thickness and WID production estimates were used as input in to the far-field model. By combining measurements from the field, laboratory experiments on fluid mud properties, with a state-of-the-art modeling approach new insight were gained not only on the best approach for implementing WID in reservoirs but also cost reduction and sustainable management for the reservoir procurator was achieved during the development of these techniques. Finally, the potential of applying WID is illustrated for the case of the Shihmen Reservoir which faces significant losses in reservoir storage by sedimentation of fine sediments.

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