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GEOMETRIC SHAPE FOR IRRIGATION SEDIMENT TRAPS VORTEX SETTLING DESILTING BASIN

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ABSTRACT: Modern irrigation schemes are increasingly demand-based, which means that the crop water requirements determine the water flow in a canal. The sediment transport aspect is a significant factor in irrigation development as it determines to a large extent the sustainability of an irrigation scheme, particularly in the case of unlined canals in alluvial soils, and as a trigger in reducing the wet capacity of the irrigation canal. The conventional sediment traps with a rectangular shape, rapidly advancing development, are challenging to construct because they require adequate space. The Vortex Settling Desilting Basin (VSDB) has proposed to replace the rectangular shape with more effectiveness considering the more concise area, deposition rate and removal efficiency, and minimum human resources as an operator. The method uses numerical methods with Computational Fluid Dynamic (CFD) simulations by Ansys R.21 2020 Student to acquire a geometric shape approach, then laboratory experiments with a model scale 1:40 prototype to an undistorted 3D physical model. This study aims to develop a two-dimensional numerical model and the optimal regression equations for determining settling basin dimension and then simulate and compare the efficiency of the selected settling basins. The VSDB shape is slimmer at 42% than the rectangular shape by optimizing the slope orifice chamber. As a result, by comparing the performance of rectangular sediment traps with the apple-to-apple hydraulic parameters and sediment variables, the results obtained based on deposition performance increased from 69.12% to 84.90% and flushing performance by leaving the minimum sediment fraction increased from 53.33% to 87.90%.

Keywords: 3D physical model, Irrigation, Performance, Sediment traps, Vortex settling desilting basin

1. INTRODUCTION

Settling basins are large reservoirs located at the entrance of the irrigation scheme. In these hydraulic structures, the fluid's velocity is considerably decreased to promote sedimentation. Trapping efficiency is important in some systems, such as hydropower facilities with turbines, valves, and irrigation systems.[1]. This parameter is the proportion of inflowing sediment accumulated in the reservoir compared to the total inflowing sediment load. Fluid flow in the settling basins is a multiphase flow. Multiphase flows, found widely in nature and industry, are categorized based on constituent components and the topology of the interfaces [2].

There are two descriptions for the two-phase flows. In the Lagrangian approach, every particle with a path line follows motion equations without considering the continuous phase. In this study, sediment deposition and trapping efficiency in shallow rectangular basins were numerically estimated considering secondary flows. In order to do this, three-dimensional (3D) steady, incompressible, Reynolds-averaged Navier-Stokes equations with the standard k - ε turbulence model were used as the governing equations [3]. Vortices form when flow passes around a bluff structure. They can move with the flow, distorting themselves and interacting with each other. Vortices have been a subject of interest to engineers and scientists for decades, but they are complex, and understanding their mechanisms remains challenging [4].

River sediments are heterogeneous aggregates, composite structures composed of amorphous or poorly crystalline mineral particles, organic matter, and biological matter (biofilms, bacteria, viruses, and biomacromolecules). While fresh sediment deposits are often close to fluid mud, older and deeper riverbed sediments tend to be consolidated, with the state of consolidation higher for deeper sediment. These vertical gradients complicate the modelling of sediment erosion, transport, and deposition [5].

A considerable effort is required to improve irrigation operations and modernize them. A desilting basin is a temporary sediment control structure to intercept sediment-laden runoff and retain the sediment. It aims to detain sediment-laden run off from the disturbed area for sufficient time and allow most deposits to settle within the sediment trap [6].

Land use change is becoming an issue for many river basins worldwide, including Ciasem River Basin in West Java as a sub-watershed of Citarum [7]. Erosion occurring upstream of Citarum Watershed must be treated as necessary because the longer sediment accumulates, the more significant reduction in water capacity at Citarum [8]. Most of the reservoir flow is a three-dimension flow where its flow regime depends on the flow velocity and the reservoir geometry [9]. Soil erosion is a global environmental problem that threatens the lives of the majority of small farmers. Approximately 80% of agricultural land is degraded due to global soil erosion. [10]. This phenomenon results in the flow of water for irrigation required that is diverted through the weir, resulting in a decreased supply of irrigation water.

Water flowing in the canal from head works on such rivers also carries sediment load. The canal gets silted if it receives a sediment load over its transporting capacity, and effective measures should be taken for its control. This results in a decrease in the discharge-carrying capacity of the canal. Further, the canal slope is generally smaller than the main river; hence, sediment always tends to be deposited in the canal [11].

To address it, the weir as a head structure requires a sediment trap that can deposit non-cohesive type sediments and quickly flush out because the water required for irrigation is complicated to stop during the cropping pattern because farmers need it. This study examines and develops the modern shape of sediment traps as a proposal to replace sediment traps with rectangular geometric shapes. In the present investigation, vortex-settling chambers are studied.

The vortex settling chamber was investigated by Athar (2000), Athar et al. (2002), Athar et al. (2005), Keshavarzi et al. (2006), Ansari and Athar (2013) [12],[14]. However, the development by the previous study is to deposit sediment in a power plant and electrical energy to avoid a larger diameter of non-cohesive sediment entering the turbine drive system. In irrigation, the sediment diameter allowed to enter the irrigation canal is cohesive type sediment whose diameter is < 0.06 mm. It is challenging to deposit this type of sediment because it is suspension sediment that moves with the water flow [12].

Different types of ejecting devices are used to control sediment in the canal. These are tunnel-type ejectors, vortex tube types, settling basins, and vortex settling chambers. Settling chambers suffer two main disadvantages, i.e. requirement of large dimensions compared with other types and long residence time. Vortex settling chamber has overcome the disadvantages of rectangular settling chambers treating the same volume of sediment load. It is a continuous device that applies a certain fraction of flow for flushing sediment particles. The vortex settling chambers can also be used to separate solids from their transporting fluids, such as in treating sewage and industrial wastes [13],[14].

This study improves the vortex desilting basin sediment traps that will gradually test their hydraulic behaviours. Obtaining the nature of sediment rheology is very important because future research aims to find out the flushing force to flush non-cohesive sediment.

2. RESEARCH SIGNIFICANCE

No studies focused on VSDB in Indonesia for Irrigation Systems. In Indonesia, 1,304 units of weir did not have sediment traps yet. At that time, the river flow had not too much sediment transport because there was not much damage to the land covering in the watershed. When a rectangular sediment trap is built, there is no sufficient space based on hydraulic parameters. These VSDB geometric shapes could propose to replace rectangular shapes to modernize irrigation in Indonesia.

3. METHODS

3.1 Research Location

The location of the study on the contribution of this study is Macan weir, in Subang Regency, as shown in Fig. 1 below:

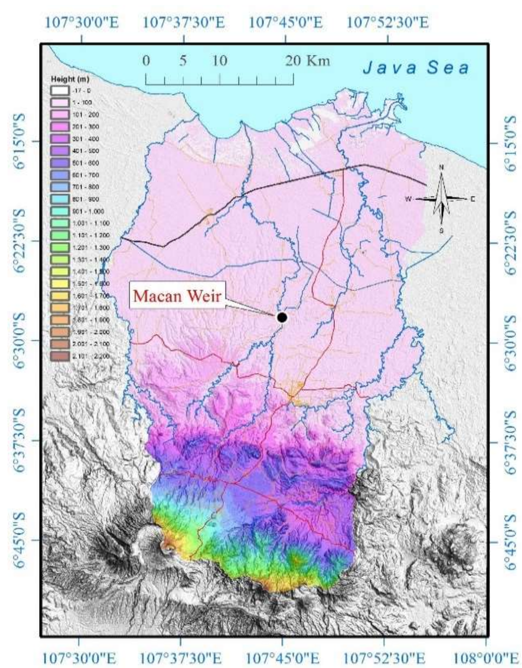

Fig. 1 Macan Weir, Located in West Java, Indonesia

As a case study, this research takes an example of one weir which does not have a sediment trap. This weir services a technical irrigation area of 9,670 ha, where the current condition of the wet perimeter section area is reduced by ±35%, caused by sedimentation. In the future, the sediment trap planned will be built with rectangular sediment traps located right side of the head structure, see Fig. 2.

3.2 Sediment Gradation Classified

This research started by taking data on sediment properties obtained from primary data in 2019 tested at the Laboratory of Engineering Geology, Padjajaran University in Bandung, to obtain sedimentation properties and physical properties. The sediment sample was extracted on site in the Cibeet and Ciasem rivers. The sediment properties in the Macan weir sediment trap take in upstream (3 samples) and downstream (3 samples) sampling points, with laboratory test results at 20°C water temperatures summarised as shown in Table 1 and Table 2 below:

Table 1 Result of sediment laboratory test

No	Sample Location	Density ρ_s (kg/m^3)	Sieve Analysed #200 = <0.07mm (%)	Mass Concentration S (kg/m^3)
1	u/s S1	2,672	33.1	910
2	u/s S2	2,681	34.3	654
3	u/s S3	2,699	34.5	577
4	d/s S1	2,710	35.6	1,011
5	d/s S2	2,716	36.5	674
6	d/s S3	2,739	39.4	593

Table 2 Result of sediment laboratory test

No	Sample Location	Consolidation Time (minute)	Volume Concentration C_v	Mud Density $\rho_{s=kg/m^3}$
1	u/s S1	5	0.37	1,498
2	u/s S2	5.10	0.29	1,543
3	u/s S3	5	0.22	1,511
4	d/s S1	5	0.34	1,412
5	d/s S2	5	0.24	1,432
6	d/s S3	5	0.19	1,411

Previously, research has been conducted for the sediment deposition rate at this location by choosing a Fergusson-Church (2004) that resulted in 0.822 cm/s for particles 0.06 mm, and the sedimentation transport rate at the study site has been calculated at 52.66 m^3/day [15]. Sediment samples on prototypes were similar to the model to obtain geometric similarity and the deposition rate of sediment particles under laminar flow conditions. They obtained the results by using sediment in the model with brick powder that had passed the sieve test analysis in the Laboratory, as shown in Fig. 3.

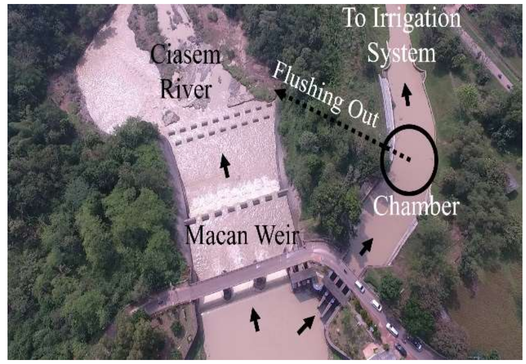

Fig. 2 Bird view of Macan Weir layout, as proposed of the location of the VSDB

Fig. 3 Laboratory activities to observe sediment properties in Fluids Laboratory ITB

3.3 Numerical Analysis by Computational Fluid Dynamic (CFD) and Dimensional Analysis

As a numerical approach, the method used in CFD to analyze the flow behaviours. This simulation will be carried out by modelling three fluid phases, namely air, water, and sediment or mud so that the sediment's flow characteristics can be obtained against time (transient). Because, in this simulation, several fluids have different phases (air, water, and mud), multiphase modelling must be used. For flows with a clear separation between one phase and another, the Volume of Fluid (VoF) model is used. This model is also relatively simple and efficient compared to eulerian or mixture [11],[13].

Dimensional analysis is formulating fluid mechanics problems regarding non-dimensional variables and parameters [16]. Dimensional analysis can be used in some cases to provide a complete set of dimensionless products constructed from the pertinent process variables. Similitude by dimensional analysis requires that the dimensionless products have the same value in the prototype as in the model [17].

Physical problems are described by relations, which are determined by quantities having a particular dimension length, time, mass, force, and temperature. These relations must be so structured that dependent and independent quantities are combined to yield dimensionally correct formulas. The similarities that have been tested in this study are geometric, kinematic, and dynamic [5].

3.4 Experiment Set-up in Laboratory

Physical model tests are performed to investigate the hydraulic behaviours of the entire sediment trap or each component. Physical model tests often solve fluid mechanics and hydraulics problems to discover the hydraulic behaviours that are not obtained in numerical models with CFD. Fig. 4 illustrates the scheme of the experimental structure in the Laboratory.

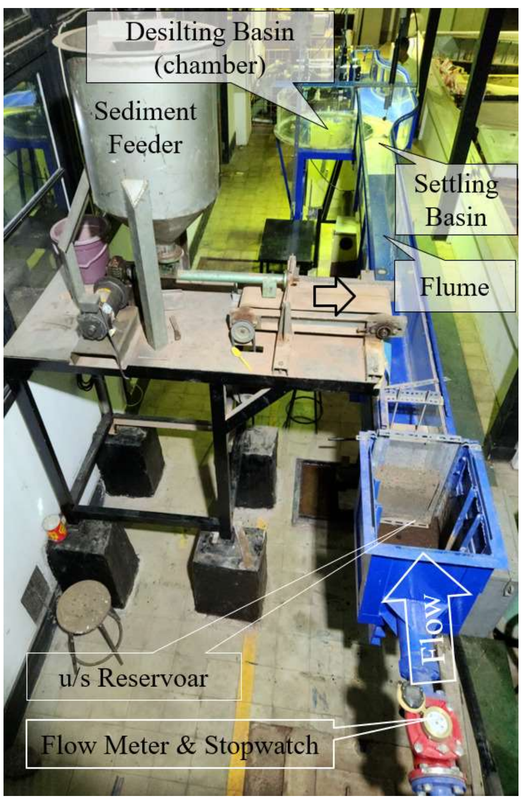

Fig. 4 Visual view of the laboratory test undistorted physical model with a scale of 1:40

3.4.1 Accessories of the Experimental Set-up

This test used a 3D speed meter programmable Electro-Magnetic Liquid Velocity Meter (PEMS). The Acoustic Velocimeter (ADV) Doppler was designed to perform the speed of measurement points in water with scientific accuracy. Simple Micro ADV performance interface, enabling fast data collection by a data logger by a computer. Laboratory test used 2 units Micro ADV 16MHz down and side-looking, 1 unit Probe Propeller Current Meter H33 with data logger and 8 units Camera Highspeed DSLR.

3.4.2 Schematic of Laboratory Test

A 3D test of this physical model was carried out in the hydraulics laboratory of the Faculty of Civil and Environmental Engineering Institut Teknologi Bandung (ITB), conducted from February to May 2022 (see Fig. 4). The determination of the scale model in the analysis of the relationship between scales prototype to model, considering: Space in a laboratory, accuracy, and facilities/accessories.

This physical model test is intended to test or check the performance of sediment traps in the efficiency of deposition and desilting that have been previously tested in numerical analysis with CFD [17].

3.5. Experiment Procedure

The sediment removal efficiency of the vortex settling/desilting basin was measured by systematically varying the inlet discharge, underflow flushing discharge, sediment size, underflow outlet orifice diameter, and the canal's width. The sediment trap efficiency is the ratio of deposited sediment to the total sediment inflow for a given period within the economic operation.

3.6. Limitations

In this study, the authors limited several variables so that the focus of the study became clear and not pseudo; here are the limitations of the research: a). Laboratory 3D Physical Model, Undistorted Scale 1: 40; b). Inlet irrigation main canal's length at Model: 5.5 m equal to Prototype 220 m and static with 0.2 m in model equal to 8.00 m at prototype; c). A circular cylindrical type of VSDB having a diameter at model 1.00 m equal to 40 m at prototype was used for experimentation in the present study: d). Sediment to be deposited cohesionless type > 0.06 mm, and < 0.06 mm neglected and allowable enter to the main irrigation system; e). Water depth has variations based on Q 50%, 100% and 120% by Nett Field Required (NFR); f). The underflow outlet orifice static diameter is 0.025 m, equal to a diameter of 1.00 m; g). Cohesion-less uniform sediments having sizes 0.008 mm to 0.825 mm were used, and: h). Suspended sediment concentration in the physical model test in Laboratory varied from 11,200 ppm to 190,000 ppm by weight. Recent numerical simulations of turbulent flow over the chamber orifice can include the structures' elastic response. However, most of these studies are limited to low turbulent Reynolds numbers and for the linear-elastic regime.

4. RESULTS AND DISCUSSIONS

Decreasing the flow velocity in the basin to ensure the sediment particle's remaining time is longer than the settling time is the main experiment idea of the settling basin. To achieve this goal, the standard procedures are widening the basin width and lowering the basin bottom. However, different length, width, and depth combinations may attain the same deposition efficiency. This study focuses on the economic design of the settling basin with specific efficiency. This study comprehensively analyses the energy separation phenomenon observed inside a vortex chamber. In the first part of the study, the flow characteristics inside the vortex chamber were studied and the second part was devoted to identifying the dominant factor for shear stress separation.

4.1 Rectangular Shape Sediment Trap

The performance of a sediment trap is expressed in how effectively it is depositing and quickly flushing out the sediment fraction. As a comparison, in 2018, an undistorted 3-D of the physical model of the rectangular shape of sediment traps was conducted in the Hydraulics Laboratory of PUSSAIR Bandung, with a similar location and hydraulic parameters (as a result, see Table 3). However, due to the Macan main canal's alignment in the irrigation system's direction, if it is built on a space with curved alignment is not optimal in terms of performance.

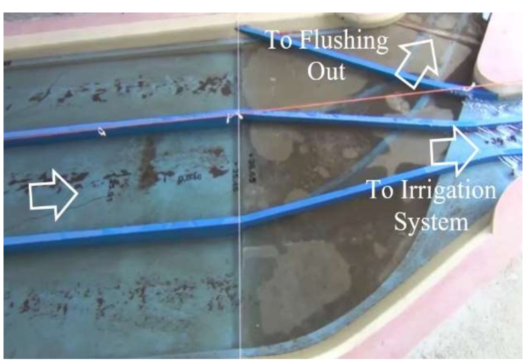

Fig. 5 Fraction of sediment on black land in rectangular sediment trap

In the DC-04 design criteria issued by the Ministry of Public Works and Housing, sediments deposited in diameter > 0.07 mm, for diameters < 0.07 mm, can be neglected and allowed to enter the irrigation system with operational, routine and periodic maintenance conditions [12]. The alignment of sediment traps on the curved line leaves many sedimentary fractions in the inner curve, see Fig. 5. The results of physical modelling on rectangular sediment trap forms with a model scale of 1:20 are not optimum. The deposition efficiency is measured at 69.12%, and this sedimentary fraction is desilting to be flushed out by 53.33%.

4.2 Simulation for Approach Geometric Shape by CFD

For the approach of geometric shapes of sediment traps with the model of vortex settling desilting basins, a numerical approach with the help of AnSys R.21 2020 Student. All 22 runs were conducted for sediment removal efficiency of vortex settling/desilting basin by varying slope chamber of underflow outlet, whereas 44 runs were conducted for this experiment. Here are the inputs used in boundary conditions: Mass-flow-Inlet: a). In the inlet section, it is defined as a mass flow inlet either for water or mud. b). Wall: On walls, it is defined as a wall with a no-slip condition to represent the friction between the fluid and the wall. c). Surface: At the top of the domain, the effects of wall friction are removed to represent atmospheric air, and d). Outlet: The outlet section is defined as a pressure outlet representing the flow's "exit" [17].

Computational Fluid Dynamics (CFD) is the art of transforming fluid dynamics set equations in the form of integrals and derivatives into discrete algebraic forms, which a computer can solve to obtain the values of the flow field at a particular discrete point or time. Here are the equations used in CFD, the equation of momentum in the direction of the x-axis: as for the regulatory equations in fluid dynamics: the continuity equation, the momentum equation, and the energy equation [17].

$$\frac{\partial(\rho u)}{\partial t}+\vec{\nabla}\cdot\left(\rho u\vec{V}\right)=-\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+\rho f_x \quad (1)$$

The equation of momentum in the direction of the y-axis:

$$\frac{\partial(\rho v)}{\partial t}+\vec{\nabla}\cdot\left(\rho v\vec{V}\right)=-\frac{\partial p}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+\rho f_y \quad (2)$$

The equation of momentum in the direction of the z-axis:

$$\frac{\partial(\rho w)}{\partial t}+\vec{\nabla}\cdot\left(\rho w\vec{V}\right)=-\frac{\partial p}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+\rho f_z \quad (3)$$

The energy equation is written in the form of internal energy:

$$\frac{\partial}{\partial t}\left[\rho\left(e+\frac{V^2}{2}\right)\right]+\vec{\nabla}\cdot\left[\rho\left(e+\frac{V^2}{2}\right)\vec{V}\right]=\rho\dot{q}-\frac{\partial(\rho p)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}+\rho\vec{f}\cdot\vec{V} \quad (4)$$

Where ρ is Liquid density (kg m^{-3}), A is a mass area, $\vec{V}$ is Velocity vector (m s^{-1}) or velocity fluid parcel, e for internal energy, three velocity components are u,v,w, $\vec{\nabla}$ vector, f any vector function. The solution of a partial differential analytical equation results in a continuously closed-form dependent variable expression across domains. In contrast, the solution of numerical equations can only give values to discrete points in the domain, also called grid points [17]. As a shaping approach to the vortex geometric shape settling/desilting basins proposed, as shown in Fig. 6, then input all the hydraulic variables and applying Eq.1 – Eq. 4 above in CFD resulted in shape as shown in Figures 6 - 7. It showed that the sediment fraction on the free vortex flow along the forced vortex flow side of the chamber is relatively high and states that sediment is well flushing. The percentage of sedimentary volume flushed from sediment transport within the continuous flow in seven days of flow amounting to 82.11%.

On the longitudinal section of this sediment trap is shown a fraction of sediment deposited present by the predominance of red in the following Fig. 6 below:

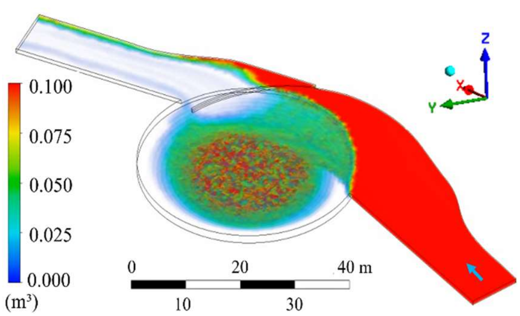

Fig. 6 Sediment's volume fraction longitudinal section view (settling time)

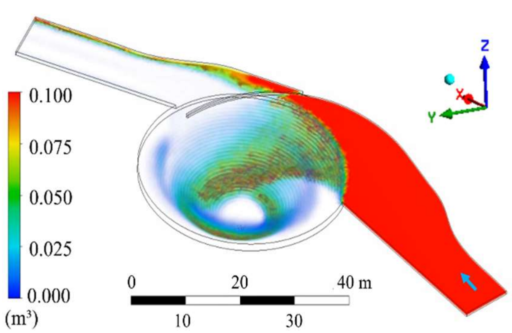

Fig. 7 Sediment's volume fraction longitudinal section view (desilting time).

The volume of fraction 82.11% of sediment deposited, as shown in Fig. 6 and Fig. 7, a total of 69.31% of the sediment fraction can be drained. Leaving approximately 30.69% in cyan colour cannot be flushed out due to the position of the sediment in the transition of the free vortex flow to the forced vortex. This shape is also maximum at the time of desilting, although not all sediment fractions can be deposited because sediment diffusion exerts an influence. In addition, the rheological process of sedimentary sediments also influences the classification of this type of sediment gradation.

The physical model in Laboratory resolves most of the turbulent structures with the exception of the smallest eddies, but for highly complicated flows, the computational expenses are considerable. Therefore, a multi-region flow structure is being established as the flow achieves a steady state, and this is where CFD can assist by providing a detailed view of the flow structure inside the vortex chamber. However, a CFD analysis is only as good as the turbulence model used since most models are semi-empirical, developed for certain classes of flows and therefore may not be suitable for specific cases.

4.3 Result Laboratory Undistorted 3-D Physical Model Test

The geometric approach of the VSDB with a numerical approach to its results was tested with a physical model in the Laboratory. The geometry utilized in the current study was obtained from this study with CFD. After the dimensional analysis, stages are carried out, and geometric, kinematic, and dynamic similarity tests and the available space, a model scale of 1:40 is determined.

The following equation calculates the deposition efficiency value:

$$T_{ef}=\frac{V_{in}-V_{out}}{V_{in}}\times 100 \quad (5)$$

Where T_{ef} is trap efficiency (%), V_{in} is the volume of sediment entering the sediment trap, V_{out} is the volume of sediment as flushed at the outlet. To calculate the efficiency of flushing-out/desilting, use the following equation:

$$\eta_0=\frac{\text{Ws flush}+\text{Ws Settled}}{\text{Total Ws Feeding}}\times 100 \quad (6)$$

Where η_0 is flushing efficiency (%), Ws flush is the flushed volume of a sediment chamber, and Ws is settled as sediment deposited. Ws were feeding the total amount feeding of sediment transport rates [6]. This equation is applied to the calculation of sediment fractions in physical test models in the Laboratory.

Fig. 8 Measurement of settled/deposition sediment's volume

Fig. 9 Flushed removal out of sediment's fraction

As shown in Figures 8 - 9, 11 runs were conducted for this study and feeding the sediment was through a sediment feeder to determine the deposition volume and flushing efficiency using Eq. 5 and Eq. 6. Then the results obtained are tabulated in the following Table 4.

Table 3 Results of Running in 2018

Parameters	Rectangular Shape 3-D Physical Model Undistorted Scale 1:20
Q 100%. NFR	1.057 lps
Daily sediment rate transport	5,367.80 cm^3/day
Continues settling time	24.63 hours
Volume fraction settled	3,710.22 cm^3
Desilting time	5.4 hours
Volume fraction desilting	1,978.66 cm^3
Parameters	Rectangular Shape 3-D Physical Model Undistorted Scale 1:20
Velocity	20.43 cms
Froude number	2.015
Reynold number	4.63E-01
Sediment concentration	96.774 ppm
Trap efficiency (Te)	69.12%
Desilting efficiency (η_0)	53.33%

Table 4 Results of running for VSDB in 2022

Parameters	VSDB 3-D Physical Model Undistorted Scale 1:40
Q 100%. NFR	0.526 lps
Daily sediment rate transport	2,670.55 cm^3/day
Continues settling time	12 hours
Volume fraction settled	2,267.29 cm^3
Desilting time	3 hours
Volume fraction desilting	1,992.95 cm^3
Velocity	8.158 cms
Froude number	0.98
Reynold number	3.363E-01
Sediment concentration	96.774 ppm
Trap efficiency (Te)	84.90%
Desilting efficiency (η_0)	87.90%

5. CONCLUSIONS

Present research for a steady flow, vortex, and open channel flows over smooth, rough, and movable beds, independent and based on Reynolds and Froude numbers. Comparing two different geometric shapes of sediment traps with hydraulic parameters such as discharge and the exact characteristics of sediments to deposition and flush out, the running results showed an increase in the number of volumes that could be settling from 69.12% to 84.90%. Meanwhile, for flushing, the sediment fraction of 53.33% increases to 87.90% from the settling can be flushed out. For future research, it optimizes the geometric shape of the chamber to be optimum based on the diameter ratio chamber effect. The following conclusions are based on the above-described laboratory experiment under well-defined and ideal conditions of the impact of an axisymmetric laminar vortex ring on the chamber orifice. Most importantly, the height of the chamber here corresponds to the size of the vortex core.

6. ACKNOWLEDGMENTS

This study aims to develop a 3-D rectangular sediment trap for a vortex settling/desilting basin shape. The authors would like to thank the Water Resources Engineering Research Group of the Faculty of Civil and Environmental Engineering Institut Teknologi Bandung for supporting this publication.

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