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The Hybrid System of Fluidization and Sediment Flushing for Maintenance Dredging Technique

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Abstract

The Hybrid System of Fluidization-sediment flushing is a dredging technique that combines the functions of fluidization and suction in the same fluidization pipe using a perforation pipe. The purpose of this study was to address an easier dredging method using fluidization pipes. 2-dimensional (2D) experimental physical modeling research and multiple linear regression analysis were used to process the test result. The results found that for optimal sediment flushing after the sediment layer was agitated by fluidization, the influence parameter was analyzed must follow the limitations of the experimental result, such as the hole diameter (*Df*) is not more than 5 mm (*Df* < 5 mm), the hole distance (α) is less than 5 cm (α/db < 5 cm), the pump head (HP) is small, and the fluidization pipe depth/sediment thickness (db) can be larger. The research findings are presented in the correlation equation which indicates the relationship of dimensionless parameters was $Vs/Vw = 1/Df\ ((\alpha/db), (HP/db), (t.(g\times 0.5)/(db^{0.5})), (v/(g.db(S-1)^{0.5}))$ which can be applied to 3-dimensional experiments and field experiments. One of the advantages of the hybrid system of fluidization-flushing sediment is its ease of use and lack of impact on the aquatic environment as a dredging technique.

Keywords: The Hybrid System; Fluidization; Sediment Flushing; Orifices Spacing; Pump Head; Sediment Thickness.

1. Introduction

Shallowing of channels due to sedimentation is an important problem in understanding water resource management. The most popular technique for maintaining channels, such as rivers, dams, shipping channels, harbor pools, and estuaries, involves dredging. In general, the aquatic environment is impacted by dredging methods positively and negatively [1, 2]. Dredging with sand bypass and sand nourishment can provide benefits to ecosystems in areas that have been eroded by waves or currents along the coast. [3]. Dredging methods have developed rapidly with long-standing experience, which in principle are divided into two categories, namely mechanical and hydraulic dredgers [4].

Mechanical dredging sometimes has an impact on the environment [5, 6] and is generally less efficient for less wide channels [7]. Several methods have been developed, such as CWD-Channel, Sand traps, Seawalls, Pile groins, which are grouped in Anti-sediment structures, Neptune, Fluidization Plants, Water injection dredging, Submarine sand shiffer (SSS), Turbo Unit in the Remobilising sediment system group, and the Sand by-passing plant [4], as well as the ejector-pump dredging method [8], which provide efficient advantages for the dredging method.

Removing sediment from the estuary requires more than just using the principle of gravity and flow velocity, as there are multiple influences, such as waves, that need to be addressed [9, 10]. In channels that are influenced by tides, the use of a bypass system for sediment removal requires more than just gravity force. The fluidization bypassing plant was

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designed by BRUUN P to continuously remove sediment by utilizing both fluidization and flushing techniques separately [11].

The fluidization method for channel maintenance was first introduced by Weisman & Lennon (1994) [12] in the United States. Kelley (1977) [13] initiated research activities that were followed by Weisman et al. (1988, 1994, and 1995) [12, 14, 15]. The same research was conducted by Lennon et al. (1990) [6], Law (1995) [16], and Weismann & Lennon (1995) [15]. Weisman & Lennon's (1988 & 1994) [12, 14] research was used to maintain the shipping channel at Anna Maria Harbor and to pump sand in Oceanside, California. Since 2003, these projects have had trouble due to blockages in the orifices and fluidization pipes.

Thaha (2006) [17] studied adding a vent to the perforation orifice to address blockage issues, which apart from preventing the entry of sediment, also increases the range of the jet spray to produce a wide empirical flow. The effectiveness of cleaning sediment that enters through the perforation orifices has been assessed by studying the draining method that uses flow velocity in the fluidization pipe. To remove sediment from the fluidization pipe, the flushing method can be employed during the sediment removal process. The combination of fluidization and sediment flushing systems can create a hybrid method for flushing sediment, allowing agitated sediment to be moved to the disposal location without having to be flushed by gravity [17]. By using this technique, sedimentation problems in downstream areas can be addressed when flushed-out sediment is no longer deposited downstream where the sediment deposition velocity is greater than the surface flow velocity.

The hybrid fluidization and sediment flushing system combines various functions into one fluidization pipe. The combined functions are focused on the role of the suction method in releasing sediment volume. It is an interesting study to examine several important parameters that influence the volume of sediment flushed out of the hybrid system. The use of fluidization as a maintenance dredging technique can be continuously utilized without any hindrance from blockages and sediment deposits in the fluidization pipe.

2. Problems

Several parameters such as perforation orifice parameters [18], sediment parameters [19], and the suction pump are factors that have an important impact on the flushing process with the hybrid system. Studying these parameters is essential to determine how sensitive each parameter is to the volume of sediment flushed.

Perforation is a term used to describe a fluidization pipe's series of orifices that are designed to generate fluid jets in the sediment layer. Weismann and Lennon utilized a series model system for designing their fluidization pipe orifices, which are immersed in a layer of sediment (submerged orifice) [20]. Robert et al. (1986) [20], Demchak (1991) [21] and Thaha et al. (2018) [22] designed perforation orifices with a series system above the sediment layer (submerged orifice). Tang et al. (2017) [23] conducted experimental and numerical research on the sliding behavior of sediment layers caused by upward water jets. The effectiveness of the fluidization process is significantly affected by the size of sediment grains, as stated by the research results.

The design of the perforation orifices is based on a specific diameter (Df) and a specific spacing for the orifices (α). The 2-dimensional experiment conducted by Ledwith uses perforation orifice diameters in four sizes, ranging from 1/16", 1/8, 3/16, and 1/4", and a distance of 2" (5 cm). The perforation orifice size should be no larger than 1/4" and no smaller than 1/16", which implies that 1/8" and 3/16" orifice sizes should be considered [14]. The fluidization pressure requirements were determined using perforations measuring 1/8" (0.3175 cm), which are spaced 2" (5.08 cm) in a 2-Dimensional experiment carried out by Weisman & Lennon (1994) [12].

To obtain optimal results, in this study several problems were formulated that need to be studied, including the influence of the parameters of distance or spacing of perforation orifices (α) and suction pump head (b) on the volume of sediment flushed through the suction pump. Apart from that, the time function resulting from the perforation orifice parameters and pump head needs to be studied for the time limits (t) of flushing, which are varied into two fluidization stages, namely the pre-initial fluidization stage and the full fluidization stage.

3. Material and Method

3.1. Material

This research includes several stages. The first stage of sediment characteristic testing is carried out in the soil mechanics laboratory to obtain sediment parameter data such as specific gravity, porosity, grain size, and settling velocity (ω) (see Figure 1).

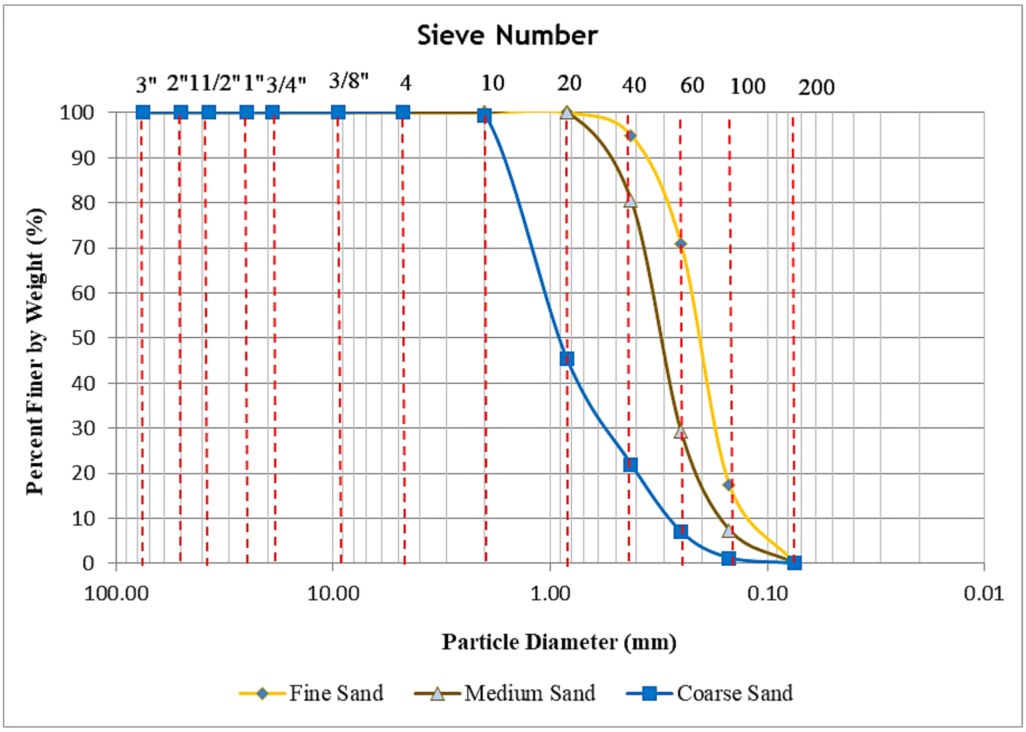


Figure 1. Sediment particle (sand) size diagram

The sediment type is the particle size determined on the Wentworth scale for non-cohesive sediment in the sand, which is categorized into three types: fine sand, medium sand, and coarse sand (Table 1). Non-cohesive sediment types are generally chosen because they are easier to move by fluids in laboratory experiments and are generally dominant in estuaries, beaches, and rivers.

Table 1. Sediment particle (sand) characteristics

Parameters	Coarse Sand	Medium Sand	Fine Sand	Average
Grain size (mm)	$0.5 < d < 2$	$0.25 < d < 0.5$	$0.075 < d < 0.25$	
D_{25}	0.478	0.231	0.164	0.291
D_{50}	0.939	0.321	0.211	0.490
D_{75}	1.476	0.406	0.280	0.721
$So = (d_{75}/d_{25})^{0.5}$	1.760	1.330	1.310	1.463
	non-uniform	***uniform***	***uniform***	
Dry weight (gr/cm^3)	1.708	1.569	1.524	1.600
Specific Gravity	2.598	2.665	2.673	2.645
Porosity (ε)	0.395	0.439	0.477	0.437
Permeability (m/s)	0.00055	0.00119	0.00089	0.00087
Settling Velocity (m/s)	0.100	0.056	0.030	0.063

Determining the dimensions of the perforation orifices is based on several analyses, that have been carried out in several previous studies to determine the dimensions of the orifices in the form of orifice diameter (*Df*) and orifice spacing (α) of the fluidization pipe [12, 14, 15]. The analysis revealed that the orifice spacing (α) and fluidization pressure (he) have a relationship that requires high fluidization pressure to maintain the perforation orifices from being blocked [24, 25]. The perforation orifices have a different proportional range of distance than in Table 2.

Table 2. Size of perforation orifice and spacing of fluidization pipe orifices

Years	Author's	Pipe Properties	
		Orifice Diameter (Df)	Orifice Spacing (α)
1977	Kelley [12]	3/32" (0.234 cm)	1" (2.54 cm)
1990	Ledwith [24]	1/8" – 3/16"	2" (5.08 cm)
1995	Lennon & Weisman [15]	1/8" (0.3125 cm)	2" (5.08 cm)
2006	Thaha [17]	1/8" (0.3125 cm)	2" (5.08 cm)

3.2. Experimental Setup

The research was conducted based on experimental variations designed for each parameter. There are 27 test variations for each fluidization pipe type, based on orifice distance (ɑ), that affect sediment type (d50), sediment thickness (db), and pump height (HP).

Table 3. An experimental scenario involving the hybrid system of fluidization and sediment flushing

Fluidization Pipe		**Sediment (d_{50}, ω, ρ, ε)**			**Suction Pump head (HP)**			**Sediment Thickness (db)**		
Orifice Diameter (Df)	Orifice Spaces (ɑ)	Coarse	Medium	Fine	HP 1	HP 2	HP 3	20 cm	30 cm	40 cm
5 mm	4 cm	√	√	√	√	√	√	√	√	√
5 mm	5 cm	√	√	√	√	√	√	√	√	√
5 mm	6 cm	√	√	√	√	√	√	√	√	√

The valve that connects the output pipe to the fluidization pipe can be opened by closing half of the valve opening (45°) located at the outlet pipe to the water tank (see Figure 2). The sediment layer experiences a horizontal jet during this stage due to the slow discharge of the fluidization pipe, which commences in the pre-fluidization phase.

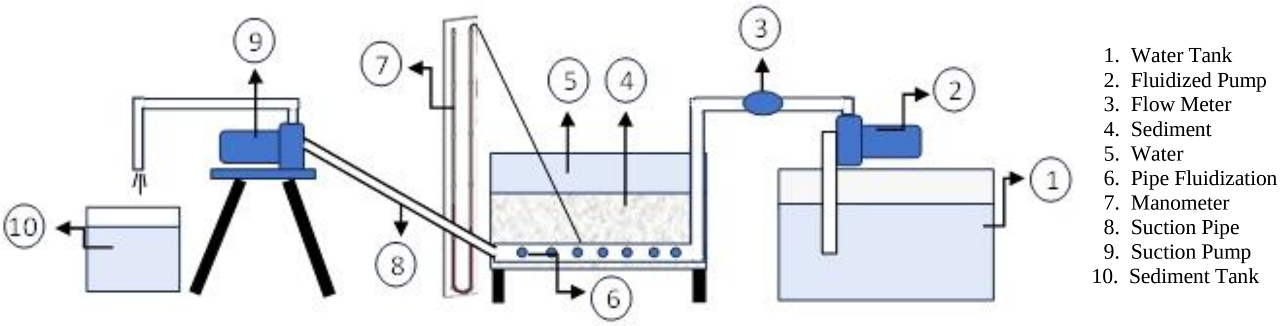


Figure 2. The setup of equipment in the laboratory for experiments

The initial fluidization phase is continued with the valve opening at 25° after the pre-fluidization phase has been completed. After that, the fluidization phase continued with the valve on the outlet pipe, resulting in the tank being completely closed.

The sediment suction stage is carried out in the initial fluidization phase by opening the valve on the suction pipe first to channel water from the fluidization pipe to the suction hose to avoid cavitation in the pump due to air in the suction hose. The shock wave system (water hammer) is used to open the valve in the suction hose after the flow fills it. The shock wave system's main purpose is to generate suction pressure.

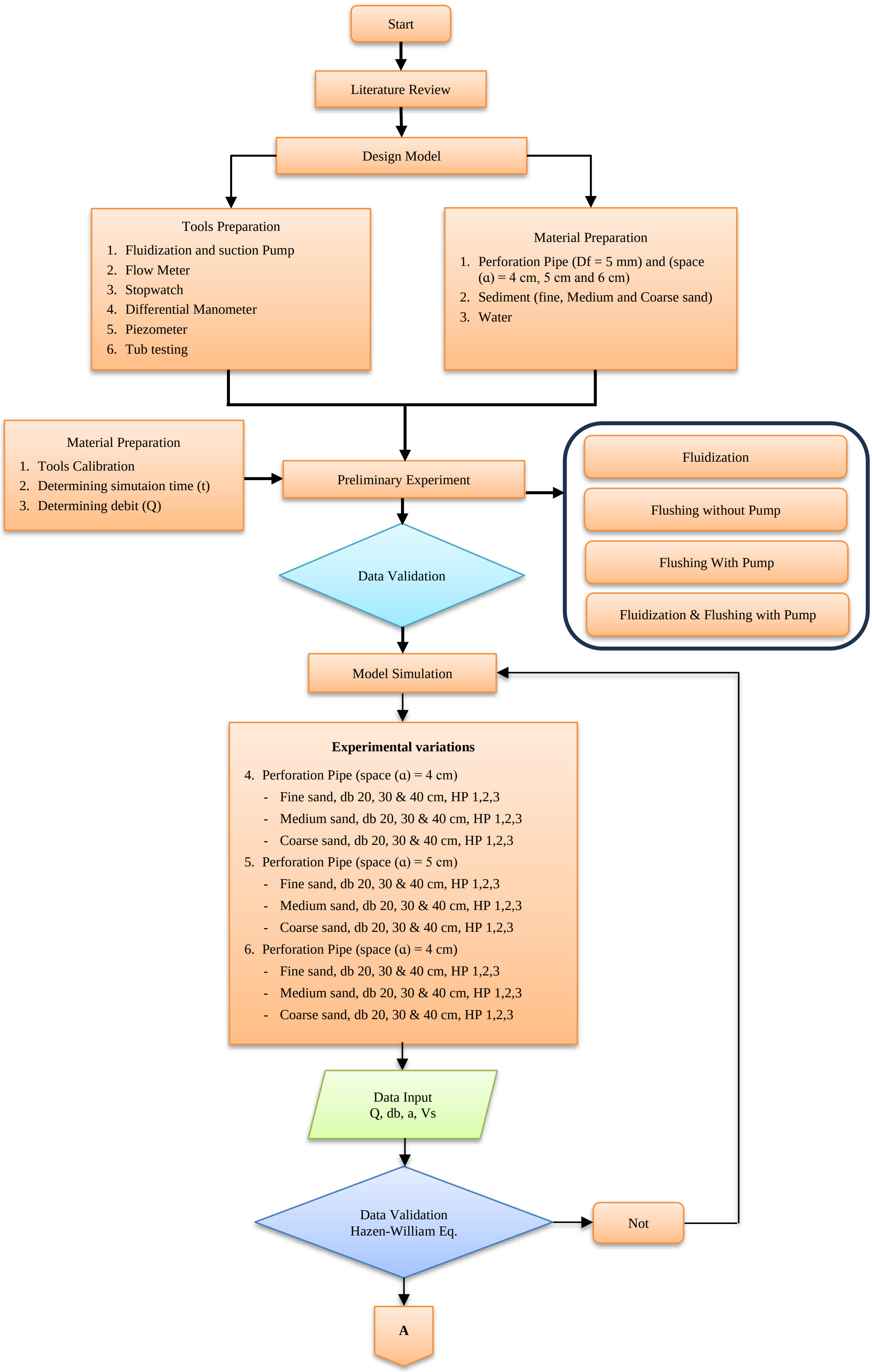
The valve that connects the output pipe to the fluidization pipe is closed while the valve that connects the output pipe to the water tank opens.

The suction process is carried out for approximately one minute, and the resultant sediment is measured using a measuring cup and scales.

The Pump Head position is determined by analyzing the variations of its head. (HP 1 = 0 cm above the sediment surface), (HP 2 = 10 cm above the sediment surface), and (HP 3 = 20 cm above the sediment surface).

3.3. Methodology

Figure 3 shows the flowchart of the research methodology through which the objectives of this study were achieved.


Start
Literature Review
Design Model
Tools Preparation
1. Fluidization and suction Pump
2. Flow Meter
3. Stopwatch
4. Differential Manometer
5. Piezometer
6. Tub testing
Material Preparation
1. Perforation Pipe (Df = 5 mm) and (space (α) = 4 cm, 5 cm and 6 cm)
2. Sediment (fine, Medium and Coarse sand)
3. Water
Material Preparation
1. Tools Calibration
2. Determining simutaion time (t)
3. Determining debit (Q)
Preliminary Experiment
Fluidization
Flushing without Pump
Flushing With Pump
Fluidization & Flushing with Pump
Data Validation
Model Simulation
Experimental variations
4. Perforation Pipe (space (α) = 4 cm)
- Fine sand, db 20, 30 & 40 cm, HP 1,2,3
- Medium sand, db 20, 30 & 40 cm, HP 1,2,3
- Coarse sand, db 20, 30 & 40 cm, HP 1,2,3
5. Perforation Pipe (space (α) = 5 cm)
- Fine sand, db 20, 30 & 40 cm, HP 1,2,3
- Medium sand, db 20, 30 & 40 cm, HP 1,2,3
- Coarse sand, db 20, 30 & 40 cm, HP 1,2,3
6. Perforation Pipe (space (α) = 4 cm)
- Fine sand, db 20, 30 & 40 cm, HP 1,2,3
- Medium sand, db 20, 30 & 40 cm, HP 1,2,3
- Coarse sand, db 20, 30 & 40 cm, HP 1,2,3
Data Input
Q, db, a, Vs
Data Validation
Hazen-William Eq.
Not
A

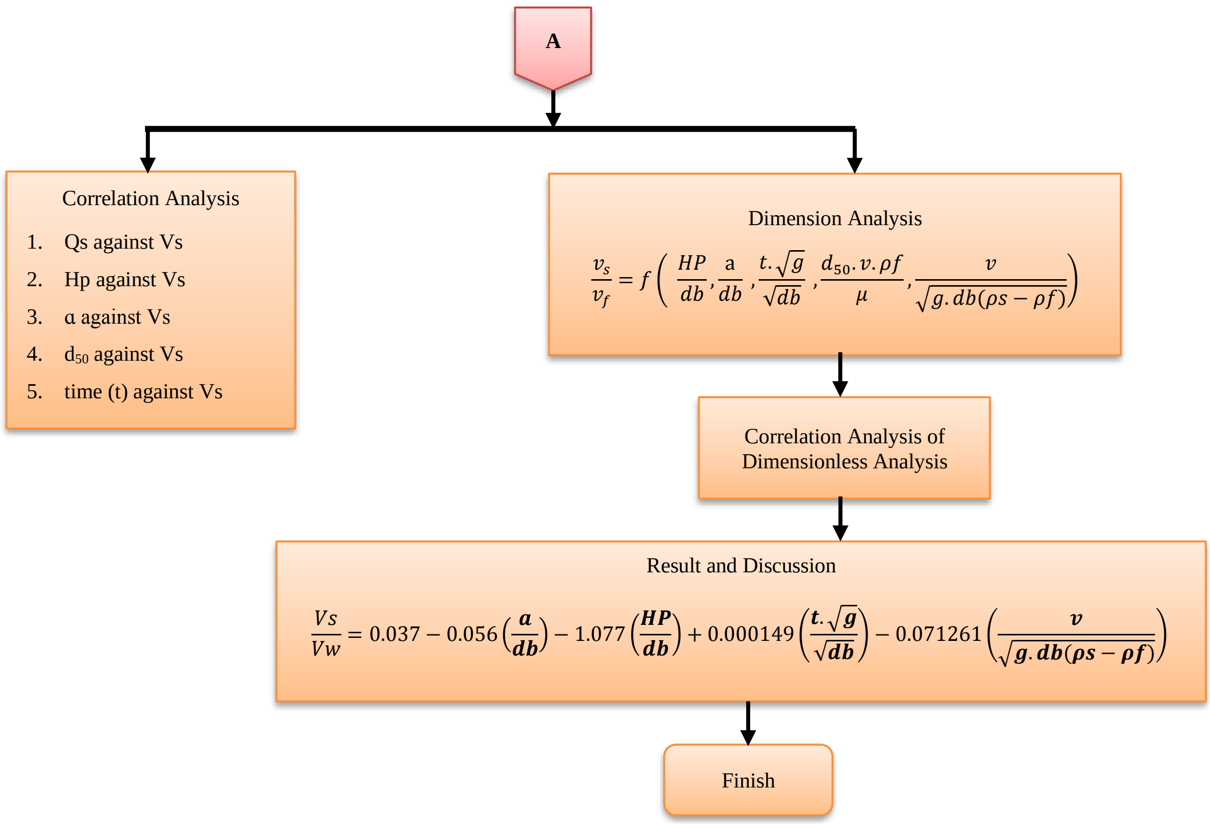


Figure 3. Flowchart of the research methodology

A literature review is the first step in Hybrid Fluidization research, which is a 2-dimensional experimental study. The experimental design is adjusted to the objectives of the observation so that the test tank model is designed to be limited to observing fluid motion in the fluidization phase and observing fluidization pressure in the perforated pipe as well as pressure distribution in the sediment layer. The flushing test is performed by referencing the fluidization test boundary as they are connected to the fluidization stage.

The instruments utilized to measure things include flow meters, stopwatches, differential manometers, and piezometers. The fluidization and suction pumps are used separately with a capacity of 14 liter/second. The tested materials consisted of perforated pipes with a perforation hole diameter (DF = 5 mm) that was varied in diameter (α) by 4 cm, 5 cm, and 5 cm. Sediment is composed of sand that has three grain sizes according to the Wentworth scale: fine, medium, and coarse sand.

The purpose of preliminary testing was to determine a system cooperation model between fluidization and flushing. The Hazen-William equation is used to validate the experimental results for resulting velocity and discharge data. The hybrid fluidization experiment is a prototype research, and this model has not been conducted on a field scale before. As explained in the introduction to this article, a fluidization method that does not require flushing has been developed. To develop a hybrid fluidization model, it is necessary to perform dimensional analysis and identify the necessary parameters.

The compatibility of the parameters to be tested was determined through a correlation analysis between independent parameters such as suction discharge (Qs), suction pump head (Hp), perforation hole spacing (α), sediment particle size (d50) and sediment flushing time (t) that were related to the volume of sucked sediment (Vs.).

All parameters are calculated using a 1:1 scale, with the length of the perforated pipe/fluidization pipe not taken into consideration. The Phi Buckingham analytical method is employed to generate a dimensional analysis, which is analyzed for suitability using a correlation analytical approach using a correlation analysis approach to obtain dimensionless numbers suitable for the hybrid fluidization model. The constraints of laboratory experiments:

- The research was conducted in a 2-dimensional experiment.
- The fluidization pipe with perforations can only be 40 cm in length.
- The capacity of the fluidization and suction pump is 14 liter/sec, depending on the type of pump available in the laboratory.
- River sand is utilized by sediment type (sand).

The suction hose can only be used with a diameter of 0.75 inches and a length of 120 cm (based on preliminary experimental results).

4. Analysis Result

4.1. Experiments on Fluidization are the Beginning of the Hybrid System of Fluidization and Sediment Flushing Mechanisms

Energy is necessary to penetrate the sedimentary layer when fluid flows out of a perforation hole (orifices) at a certain speed. Loss of power due to the perforation hole/orifices (hoc) and loss of energy in the sedimentary layer (hbc) are components of energy needed in the fluidization process, which is a function of thickness sediment (db), porosity (ε) and specific gravity (ρs). The amount of power necessary for fluidizing is equal to the amount of energy lost, and this can be expressed as:

$$h_e = (1 + K)\frac{V^2}{2g} + db\Delta\,(1 - \varepsilon) \tag{1}$$

Equation 1 is a theoretical equation that will test or validate the results of fluidization experiments both in a single horizontal jet and horizontal series. The theoretical equation is compared to experimental results in the laboratory in the graph that follows.

The fluid flow penetrates the surface layer with increased discharge during the initial phase of fluidization, which can result in a constant or decrease in fluidization pressure requirement from advanced full fluidization [15, 6, 26, 27]. Indications of Darcy flow are still visible in the pre-fluidization phase to initial fluidization with a tendency for the curve to move exponentially. The theoretical and experimental curves have been compared and the relationship between discharge and fluidization pressure remains consistent. where the direction of the experimental curve line is still following the path of the theoretical curve line.

The fluidization pressure obtained when medium and coarse sand are fluidized is slightly different, with coarse sand having a lower requirement for pressure compared to medium sand. Experimental results for both types of sediment still confirm the theory's relationship between discharge and fluidization pressure (see Figure 4).

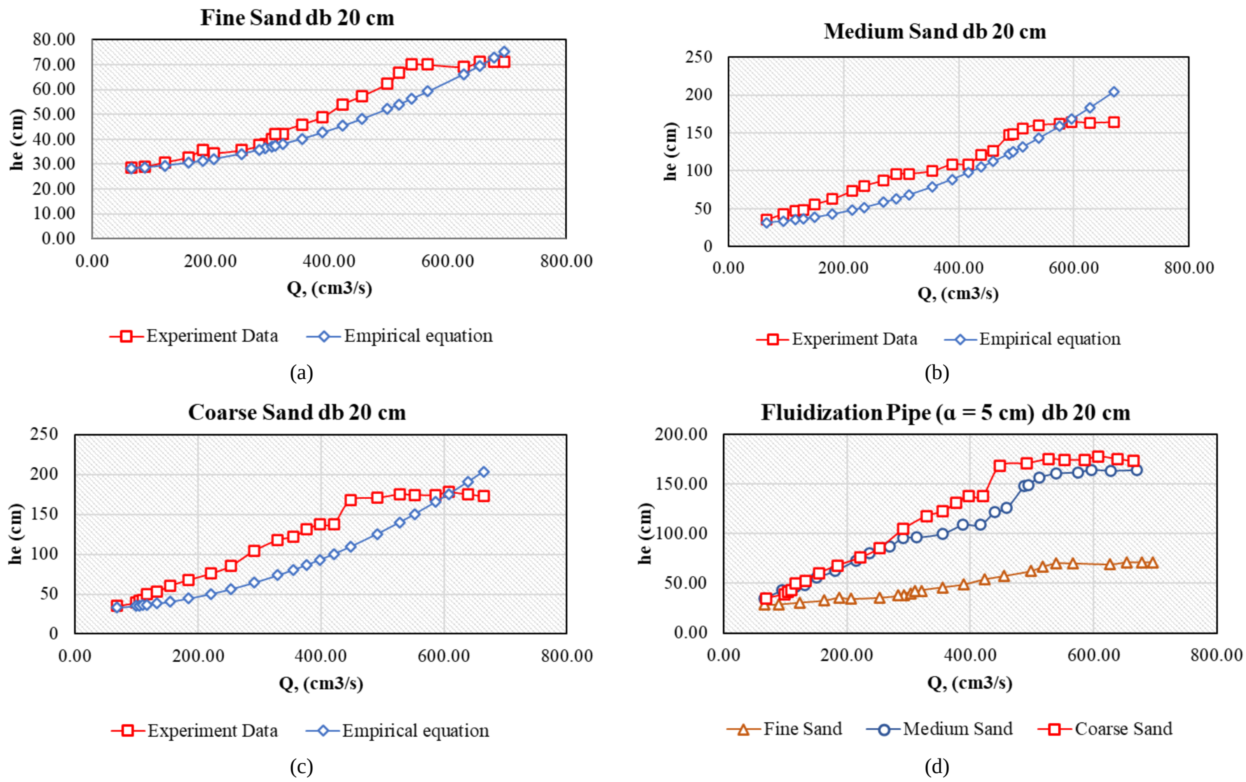
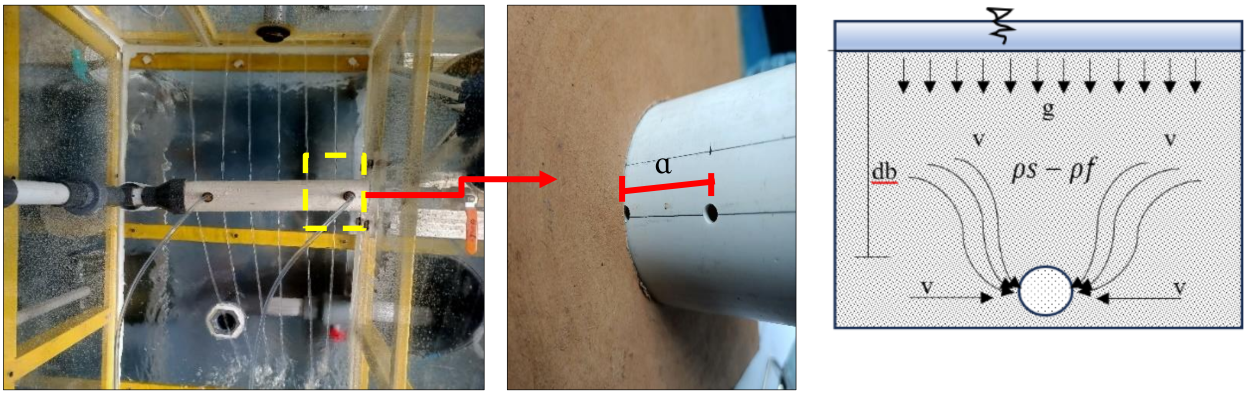


Figure 4. (a) Fluidization method on coarse sand db 20 cm, (b) 30 cm, (c) 40 cm, and (d) Comparison graph of fine, medium, and coarse sand for orifice space of fluidization pipe (α = 5 cm), db 20 cm

4.2. Investigating the Relationship Between the Spacing of Perforation Holes, Pump Head (HP), and the Volume of Flushed Sediment (Vs)

In addition to the orifice diameter and orientation direction, the perforation orifice spacing (ɑ) has a significant impact on determining the optimal operation. The results of experiments using 3 (three) variations in the distance/spacing of perforation orifices (ɑ) provide varied data that was tested on each type of sediment (Figure 5). A form of perforation hole performance test that expresses fluidization involves spray testing pure water for perforation holes (orifices). The fluidization experiment uses Newtonian fluid, but at the stage of the flushing experiment using the suction method, the fluid changes to non-Newtonian fluid. In the flow of non-Newtonian fluids, many problems become factors inhibiting the flow, such as drag and friction [28].



(a) (b) (c)

Figure 5. (a) Spray testing at Fluidization pipe, (b) Orifice Space (ɑ) at Fluidization pipe, (c) Sediment flushing scheme with fluidization pipe

The wide variety of orifices in the fluidization pipe is related to orifice spacing (ɑ), at the same time as the fluidization pipe temperature (L) stays consistent. The performance of orifice spacing is important for the hybrid fluidization-sediment flushing device concerning sediment flushing.

To see a comparison of all experimental results via taking one foremost orifice distance, an orifice spacing (ɑ) of 4 cm was selected because the common experimental results of the scale of the orifice distance have been greater most excellent than the orifice spacing of 5 cm and 6 cm. Apart from that, most beneficial flushing can be performed if the fluidization pipe is beneath 40 cm from the sediment surface with a suction pump head of 0 cm from the sediment surface (HP 1). The consequences may be seen within the graph showing every tester on 3 sorts of sand (Figures 6 to 8).

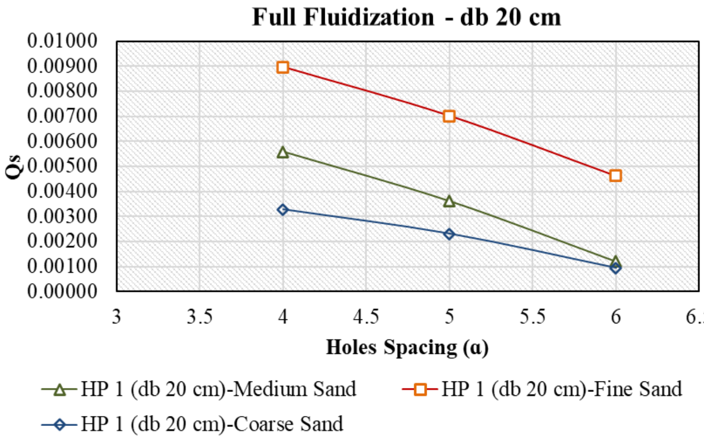


Figure 6. Comparison of Qs achievements in variations in orifice spacing (ɑ) below db 20 cm

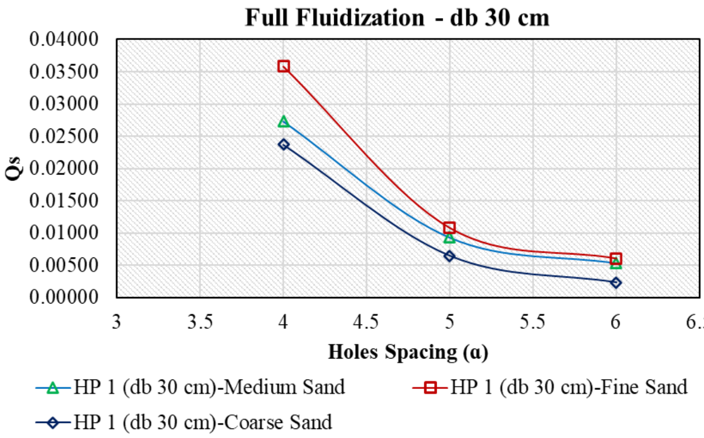


Figure 7. Comparison of Qs achievements in variations in orifice spacing (ɑ) below db 30 cm

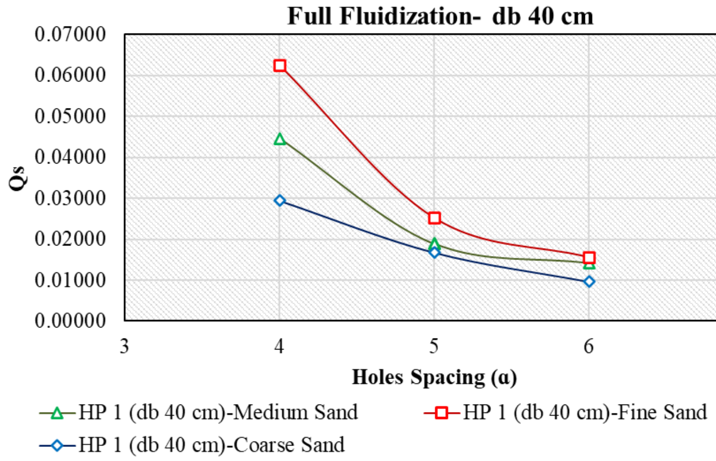


Figure 8. Comparison of Qs achievements in variations in orifice spacing (α) below db 40 cm

The overall experimental ratio of orifice spacing (α) to flushed sediment discharge (Qs) was optimally achieved by an orifice spacing of 4 cm, which means that the reduction in perforation orifice spacing is proportional to the increase in flushed sediment discharge (Qs). Flushing with a fluidization pipe installation below a thickness of 40 cm is more effective than with a thickness of 30 cm and 20 cm where the suction pump head (HP) is at one level with the sediment surface.

In the graph, the relationship between the distance of the perforation hole (a) to the volume of sediment (Vs) is quite complex because it is still reviewed against the relationship with the pump head (Hp) and sediment thickness (db). The graph will be explained exclusively for the relationship between hole spacing and sediment volume. At variations in sediment thickness (db) and pump head (HP), hole spacings of 4 cm lead to sediment volumes higher than those of hole spacings of 5 cm and 6 cm. The increase in sediment thickness (db) over the perforation pipe gives an advantage to the performance of hole spacing (a) where a significant increase in Vs in hole spacing of 4 cm respectively for db 20 cm of 0.18 liter, db 30 cm of 1.35 liter and db 40 cm of 1.65 liter. The sediment volume is obtained by utilizing HP 1, which is the top pump head (HP) and is 0 cm away from the sediment surface.

The pump height parameter or suction pump head (HP) is needed to determine the suction pressure requirement (hs) which can be expressed in the relationship between the pump head and the volume of sediment (Vs) flushed out (Figures 9 to 11). However, you need to know the suction pressure (hs) is a function of the velocity [16] produced by the suction pump.

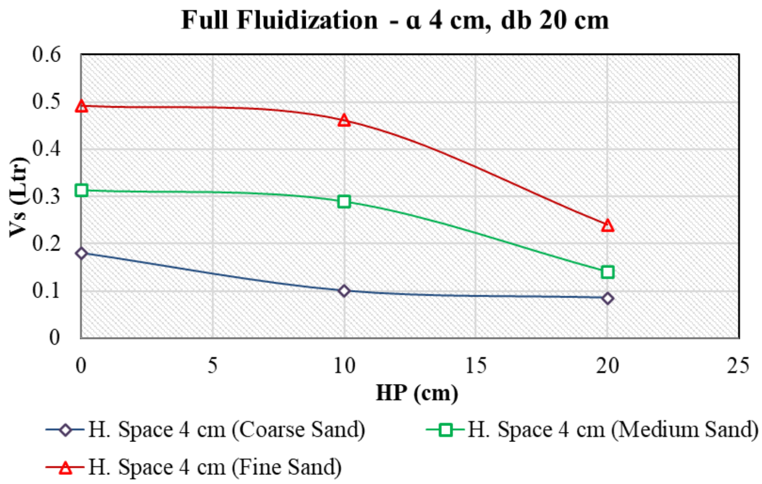


Figure 9. The relationship between the suction pump head (HP) and the volume of sediment flushed (Vs) in the orifice spacing (α) 4 cm at the Full Fluidization stage (db 20 cm)

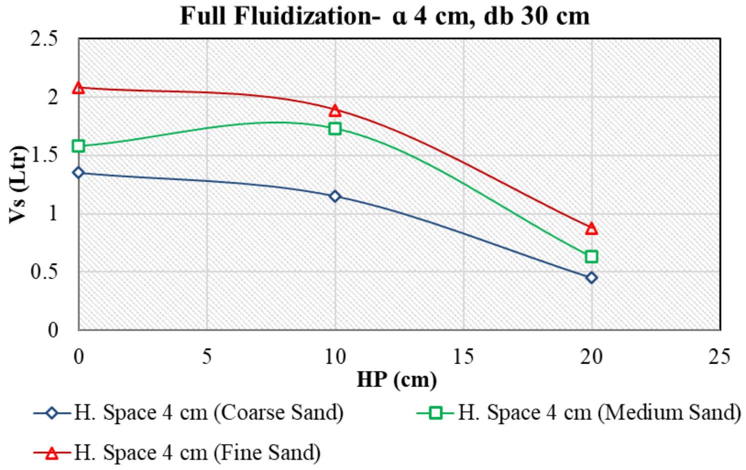


Figure 10. The relationship between the suction pump head (HP) and the volume of sediment flushed (Vs) in the orifice spacing (ɑ) 4 cm at the Full Fluidization stage (db 30 cm)

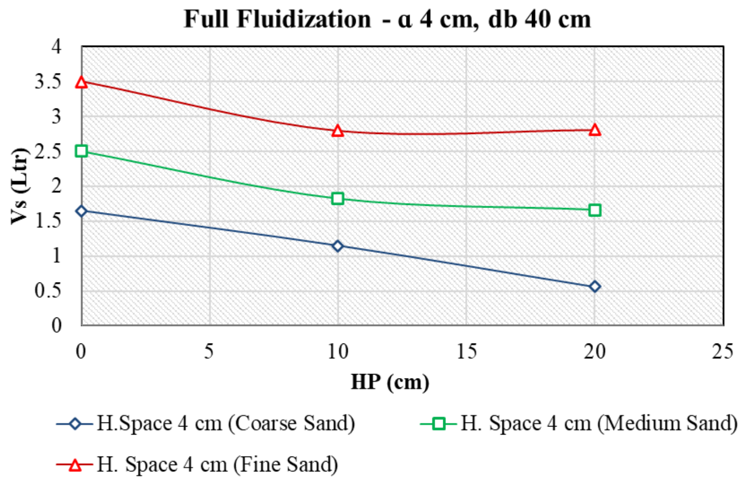


Figure 11. The relationship between the suction pump head (HP) and the volume of sediment flushed (Vs) in the orifice spacing (ɑ) 4 cm at the Full Fluidization stage (db 40 cm)

The suction pump head (HP) has a significant influence on the volume of sediment flushed (Vs) [8]. Based on experiments using variations in the perforation orifice distance (ɑ) and variations in sediment thickness (db) above the perforated pipe, the relationship shows the direction of change in the increase in pump head which tends to produce a smaller volume of sediment. The graph indicates that the fine and medium sand fractions are still more flushed than the coarse sand fractions. The thickness of the sediment (db) as a function of gravity (g) and the relative density of the sediment (S – 1) produces a difference in the volume value of the flushed sediment which varies quite widely from db 20 cm – 40 cm, namely in the fine sand fraction Vs = 0.493 liter (db 20 cm), Vs = 2.08 liter (db 30 cm) and Vs = 3.5 liter (db 40 cm). Fine sand contains an amount of Vs equal to 0.313 liter (db 20 cm), 1.58 liter (db 30 cm), and 2.5 liter (db 40 cm). The Vs produced by coarse sand is equivalent to 0.18 liter (Db 20 cm), 1.35 liter (Db 30 cm), and 1.65 liter (Db 40 cm).

The fine and medium sand experiments saw the most significant difference between pump head (HP) 1 and pump head (HP) 3, especially at sediment thicknesses of 20 cm and 30 cm. At a sediment thickness of 40 cm, the difference in Vs in fine sand is only a big difference in the Vs heads of pumps 1 and 2, whereas the Vs heads of pumps 2 and 3 are very close in value, namely Vs = 2.80 liter (HP 1), and Vs = 2.81 liter (HP 2). Pump head 3 is larger than pump head 2, but the quantity is not that significant, just a 0.01 liter difference. This difference indicates that equipment stability still has an impact on the data collection process in the experiment. The data trend suggests that the larger the pump head, the more sediment is flushed out.

4.3. 2-D experimental Dimensional Analysis of a Hybrid Fluidization and Sediment Flushing Model

The series of fluidization and sediment flushing systems in this study is made in one system which is operated on a fluidization pipe with a design determined based on the relationship between the parameters of orifice distance (ɑ), pump head (HP), and sediment thickness above the perforated pipe (db). Various literature has stated that fluidization and suction experiments are operated with a parallel system such as the self-sinking with orifices method [29]. So in this research, the combination of fluidization and suction functions for flushing sediment is a new system as a development of the fluidization method.

The hybrid system of fluidization and Sediment flushing requires an understanding that not all fluidization phases, namely pre-initial fluidization and full fluidization phases, are optimal for sediment flushing. So initial experiments on the mechanisms for the formation of fluidization zones and collapse zones are important because at that stage full fluidization is identified which is called the critical vortex dimension [30-32]. At the fluidization stage (full fluidization), the sediment particles do not have high cohesion, making it easier to flush with a suction pump. The optimal sediment volume (Vs/Vw) can only be produced in the hybrid model where maximum sediment agitation is achieved at the full fluidization stage (Figure 12).

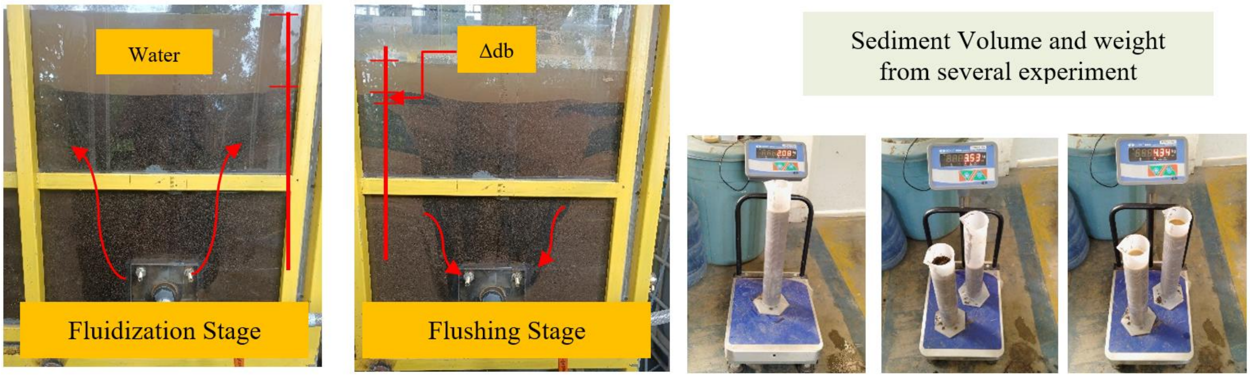


Figure 12. Overview of Sediment volume and weight from the hybrid system of fluidization and sediment flushing

The relationship between pump head parameters, sediment parameters, and perforated pipe parameters on the volume of sediment flushed out can be expressed through dimensionless parameter relationships. By using the Buckingham phi method for dimensional analysis, four dimensionless numbers can be found, making it easier to apply the approach to hybrid fluidization system models expressed in Figures 13 to 16.

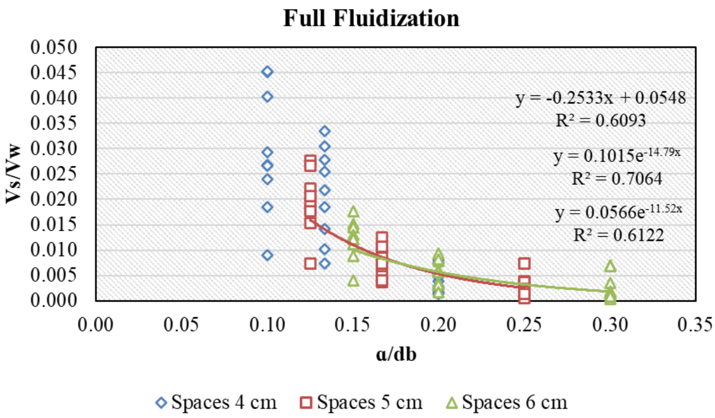


Figure 13. Graph the relationship between α/db and Vs/Vw

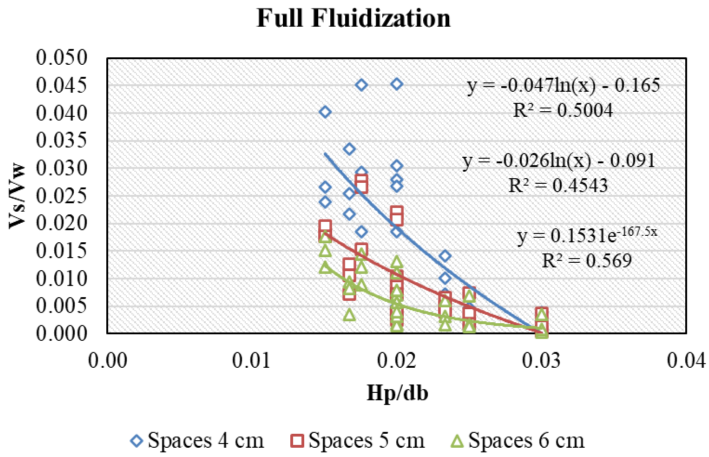


Figure 14. Graph of the relationship between HP/db and Vs/Vw

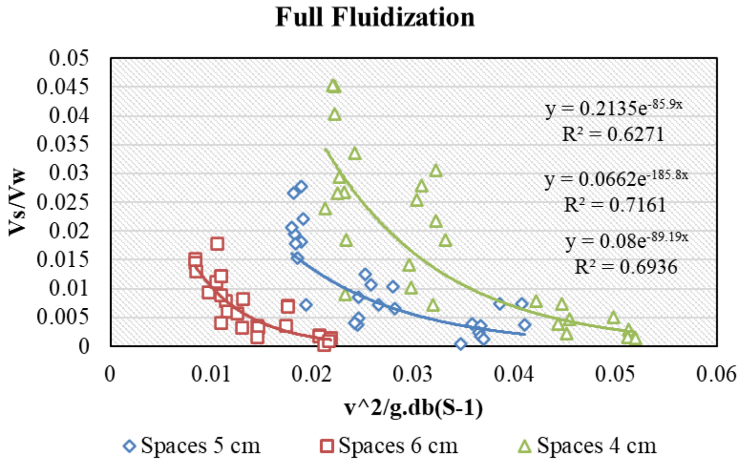


Figure 15. Graph of relationship between t.(g.db)$^{0.5}$ and Vs/Vw

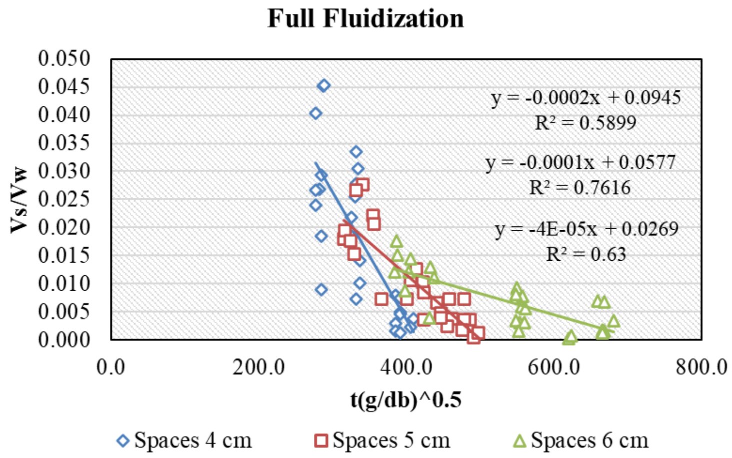


Figure 16. Graph of the relationship between v/(g.db(S-1)) and Vs/Vw

When orifice spacing (α) and sediment thickness (db) are increased, the relative volume of flushed sediment decreases by 0.2533 for every unit increase. The decrease in sediment volume caused by the exponential increase in the α/db ratio can be compared with a hole spacing of 5 and 6 cm. The α/db ratio is influenced by sediment thickness (db), and each increase in the α/db ratio coincides with a decrease in sediment thickness (db). Figure 13 shows that the correlation equation on the graph that has a significant impact on the relative volume (Vs/Vw) of flushed sediment is linear and has a hole spacing of 4 cm. According to the graph, the α/db relationship ratio is smaller when there is a larger sediment volume compared to when hole spacing is 5 cm and 6 cm.

The HP/db and Vs/Vw relationships show a logarithmic trend in their relationships at the full fluidization stage when the spacing between fluidization pipes is 4 and 5 cm, and at 6 cm spacing when they are separated by fluidization pipes. This means that lowering the HP/db number decreases the relative sediment volume (Vs/Vw) during the flushing process (Figure 14). The graph suggests that if the pump head (HP) is small and the sediment thickness is large, the volume of sediment produced is greater.

The dimensionless number of flushing time depends on sediment parameters (Figure 15). According to the dimensionless relationship ratio, the relative volume of sediment flushed through the suction pump increases as the dimensionless number of flushing times decreases. This also applies to the difference between the two fluidization stages where the time required for the full fluidization stage is shorter than the flushing time in the pre-initial fluidization stage. However, the volume of sediment flushed is greater during the full fluidization stage, which takes less time than during the pre-initial stage fluidization.

The flow velocity is less affected by sediment thickness while the hydrostatic pressure of the sediment layer is more affected. The Froude Particle number (Frp) for sediment movement indicates that hydrostatic pressure is the most important factor in determining the entry of sediment into the perforation hole. By comparing flow velocity through the perforated pipe to the pressure exerted on the sediment layer, the Frp decreases as sediment thickness increases.

The correlation between flushing time (t) and sediment characteristic (g/db) becomes more significant as the perforation hole distance decreases. Figure 16 shows that the flushing time value is greater when the hole spacing is (a) 5 cm compared to when the hole distance is (a) 6 cm. The influence of the hole spacing on the volume of sediment sucked in is the subject of discussion in this relationship.

Based on the results of dimensional analysis, it produces a dimensionless relationship between several parameters, which are estimated to influence the volume of sediment flushed (Vs).

$$\frac{Vs}{Vw} = f\left(\frac{a}{db}, \frac{HP}{db}, \frac{t.\sqrt{g}}{\sqrt{db}}, \frac{v}{\sqrt{g.db(\rho s-\rho f)}}\right) \tag{2}$$

Correlation analysis is used to analyze dimensionless relationships and obtain constants and coefficients of relationships with the relative volume parameters of flushed sediment (Vs/Vw).

$$\frac{Vs}{Vw} = 0.037 - 0.056\left(\frac{a}{db}\right) - 1.077\left(\frac{HP}{db}\right) + 0.000149\left(\frac{t.\sqrt{g}}{\sqrt{db}}\right) - 0.071261\left(\frac{v}{\sqrt{g.db(\rho s-\rho f)}}\right) \tag{3}$$

The correlation equation of the hybrid system resulting from regression analysis only produces four influential parameters (Equation 2), namely the ratio of perforation hole spacing to sediment thickness (ɑ/db) with a constant value of -0.056, the suction pump head ratio (HP/db) with a constant value of -1.077, the flushing time ratio to sediment thickness ((t.√g)/√db) with a constant value of 0.000149, and Froude Particle (Frp) v/√(g.db(ρs-ρf)) with a constant value of -0.071261 (Equation 3).

The correlation equation constant represents the diameter of the perforation hole (Df) set at k and is measured by 1/Df. This constant will contribute to the distance coefficient of the perforation hole (a), suction pump head (HP), flushing time (t), and suction speed in the perforation hole which is influenced by the force of the combined sediment expressed in the particle Froude (Frp).

5. Discussion

5.1. Experimental Results of 2-Dimensional of the Hybrid Fluidization-Flushing Sediment System

Based on experiments between the initial stage of fluidization and full fluidization, it can be concluded that effective results can be obtained on the volume of flushing sediment at the full fluidization stage. During full fluidization, the sediment becomes a slurry with a reduced level of cohesiveness after being agitated through the fluidization process. The suction pump, which is run simultaneously with the fluidization pump, helps produce the maximum sediment volume during the flushing process, comparable to hybrid fluidization in the pre-initial fluidization stage.

Based on dimensional analysis, there are limitations to facilitating understanding of the application of dimensionless relationships in the application of hybrid fluidization systems in field experiments, namely the diameter of the orifice (Df) is not more than 5 mm [22], the distance of the perforation hole (ɑ) is less than 5 cm (ɑ / db < 5 cm), the height of the suction pump (HP) is small, the thickness of sediment (db) can be larger. The flush volume achieved during flushing depends on the sediment concentration after the fluidization stage, which can be determined by the combination of geometric parameter relationships and flushing time (t).

The perforation holes should be spaced 4 cm apart for this 2-dimensional experiment to be effective. According to the experiment's results, the maximum pressure limit for the fluidization process is greater than that for the flushing process with a suction pump, which requires low pressure. To ensure continuity between the fluidization and flushing processes, the perforation hole's diameter of 5 mm must be 4 cm away from each other.

The dominant fraction of sediment that can be sucked through sediment holes tends to be fine and medium sand types. Coarse sand with a diameter of > 1 mm tends to be difficult to enter the perforation hole where it is tentatively estimated that the falling velocity of coarse sand particles is greater than the suction rate of sediment in the perforation pipe. However, the dimensionless relationship that produces the particle Froude number (Frp) gives the maximum portion for all types of sand in perforated holes spaced 4 cm apart. The Froude number of particles has an impact on the volume of sediment sucked in when the combined sediment characteristics are involved. Combined characteristics of sediment, such as sediment thickness (db), sand alternating density (S-1), and gravity (g), tend to increase sediment entry into the perforation hole compared to suction flow velocity.

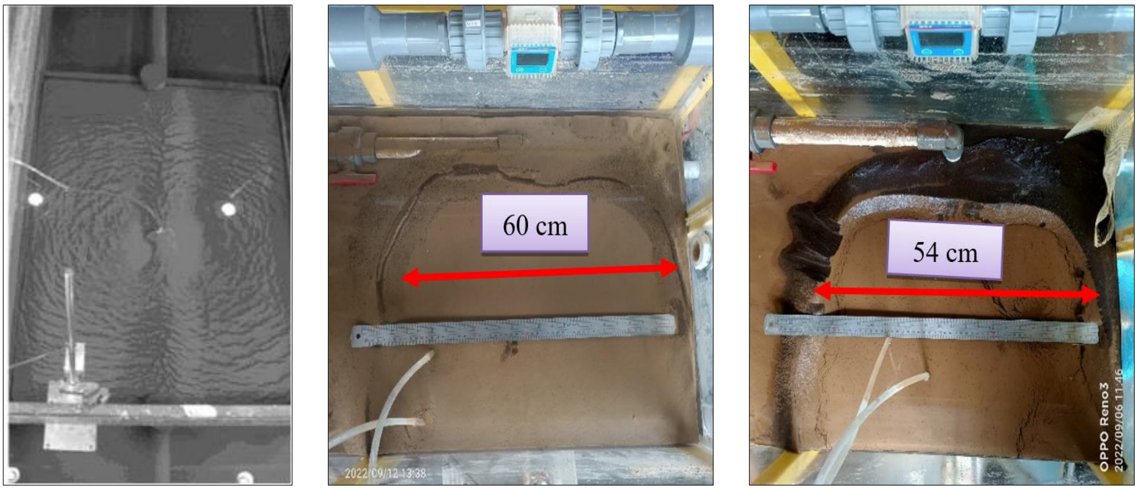
To enhance the suction speed of sediment, a suction pump is required. In the dimensionless relationship (Hp / db) there is a limit on the pump head (Hp) needed where the smaller (close to 0 cm) the pump head (m), the better it is at pouring sediment through the suction process. However, by increasing the pump head with high pumping power, the suction speed in the perforation hole can be increased to greater than the characteristics of the combined sediment.

5.2. Scour Profile Data Obtained from 2-Dimensional Experiments

The scour profile produced by the hybrid fluidization system is comparable to that produced by the hydro suction system of a suction pipe studied by Jaiswal et al. (2022) [33]. The use of hydro suction is not based on perforated pipes, but rather on pipes with a suction hole that is downward-oriented. Nakashima et al. (2005) [34] experimented with a Multi-Hole Suction Pipe (MHSP) in a laboratory setting with a flushing pipe that has many holes in a downward direction, which follows the hybrid fluidization model.

In the hydro suction research, 5 variations of suction pipe diameter were tested, and the results indicated that larger suction pipe diameters (0.127 and 0.152 m) did not impact scouring. The difference between this method and the hybrid fluidization system is in the size of the suction hole, which also affects the size of the scour formed. The hybrid fluidization system is designed to not only release sediment through the suction system but also to disturb the sediment in the system at the start of operation, allowing for the removal of grains of sediment (Figure 17). The fluidization pipe/perforated pipe used to suction continuously has a different scour profile than the hydro suction method due to its diameter, which is 0.05 m, and the suction hole, which is 0.005 m.

MHSP laboratory research was carried out at a depth of 0.7 m, pipe length of 8.5 m, suction hole diameter of 0.023 m, and suction hole distance (α) of 0.35 m [34].



(a) (b) (c)

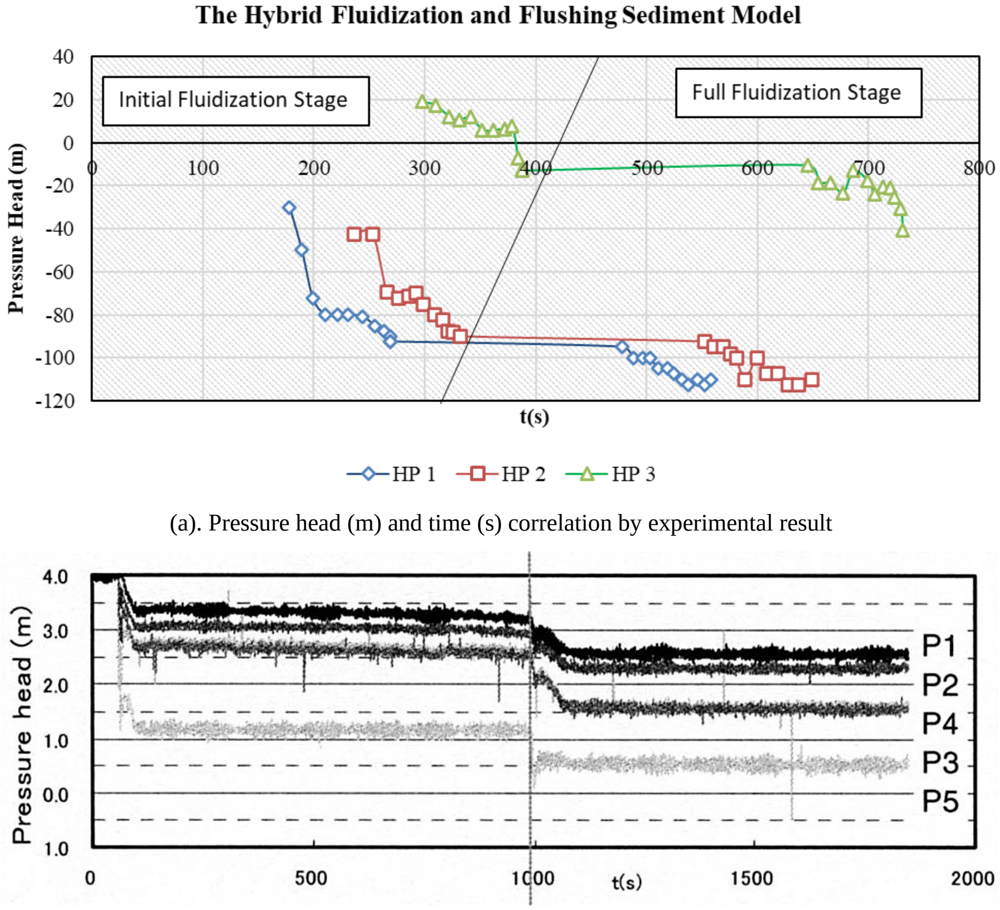
Figure 17. (a) MHSP experimental bed geometry, (b) and (c) The Hybrid Fluidization experimental bed geometry

The different suction pipe parameters result in the formation of different shapes and sizes in the scouring geometry. The experimental MHSP's pressure head (HS) has been in use for a long time but doesn't take into account the suction pump's position, which is expressed in the pump head (HP).

The pressure head (m) created by the experimental MHSP ranges from 4 m to 1.5 m and lasts for approximately 2000 seconds. The pressure head decreases as the suction time increases, as evidenced by hybrid fluidization research that shows a decrease in pressure over a short time. The fundamental difference between MHSP and the hybrid fluidization research on pressure readings throughout the flushing time is that at the Hybrid System of Fluidization and Sediment Flushing flushing stage, phase 1 is the initial fluidization stage, and phase 2 is the full fluidization stage which forms a long horizontal distance on the graph.

The high-pressure head in the MHSP experiment is caused by a greater contribution of incoming sediment to the suction hole while in the hybrid fluidization system, the pressure head is smaller because of the smaller volume of sediment through the small perforation hole. The flow speed along the flush in a Hybrid System of Fluidization and Sediment Flushing tends to increase when both the fluidization and suction pumps are operating simultaneously. The fluid supply in one pump drives the flow speed in the suction pipe in MHSP (see Figure 18).

Flushing sediment (suction) with one pump is not effective in the Hybrid System of Fluidization and Sediment Flushing. The fluidization pump (supply) and the suction pump must work together after the fluidization stage is completed, as based on preliminary experiments. The reason for this estimate is the suction hole's smaller diameter results in less effective flow capability along the fluidization pipe compared to MHSP in removing sediment from the suction pipe.



(a). Pressure head (m) and time (s) correlation by experimental result

(b). Pressure head (m) and time (s) correlation by MHSP technique

Figure 18. Comparison of pressure head (m) to flushing time (t(s)) experimental results and MHSP technique

5.3. The Development of a Hybrid Fluidization and Sediment Flushing Model for Field Use

Field conditions can simplify the dimensionless analysis results if the system is used in different locations. The sketch of the hybrid fluidization-sediment flushing system is shown in Figure 19.

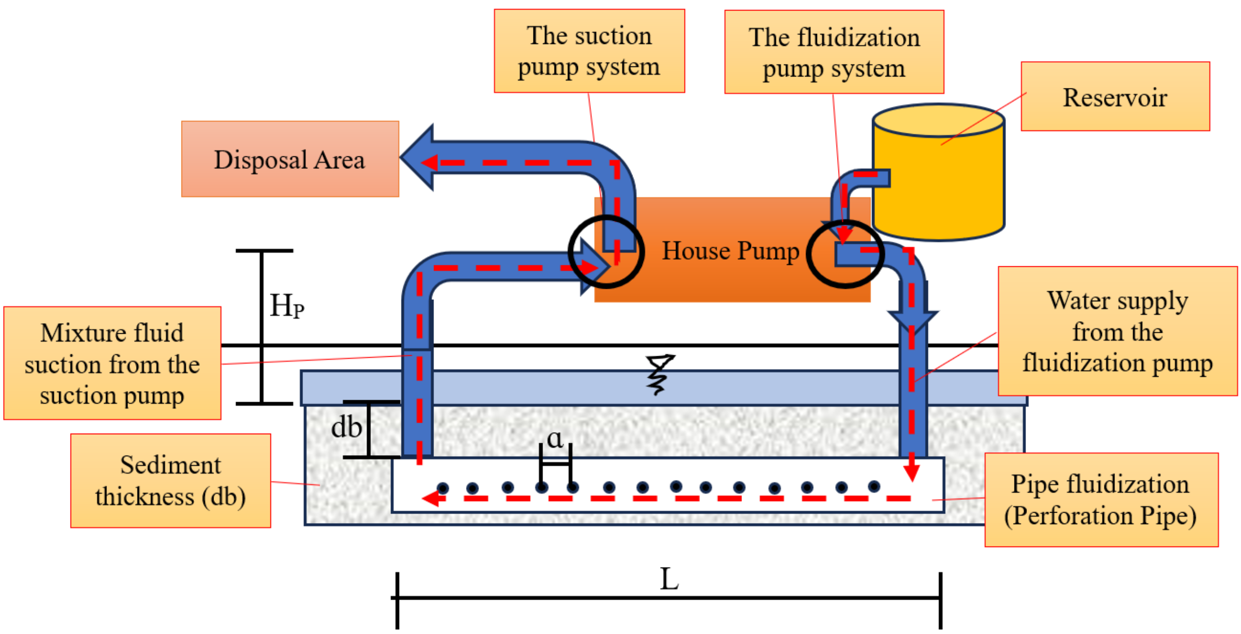


Figure 19. Sketch of a hybrid fluidization – sediment flushing system

The hybrid system of fluidization and sediment flushing installation scheme outlines dimensionless parameter components which can explain that the parameters of pump head (HP), perforation orifice spacing (α), and sediment thickness (db) are physical parameters or geometric parameters that can be directly changed according to site conditions. The prototype that was implemented has certain constraints:

- The perforation hole has a fixed diameter (Df = 5 mm)
- The suction pump heads (Hp) is dependent on the suction pump's capacity and the suction hose or pipe type.
- The perforation pipe's location below the sediment or the thickness of the sediment (db) must be adjusted depending on the elevation of the channel's bottom.
- The efficiency of the required flushing time has not been analyzed because it is limited to the experimental period in the laboratory.
- The Hybrid fluidization model is still requiring 3-dimensional testing with greater suction and fluidization pump capacities.

The advantages of the hybrid fluidization-flushing sediment method can be described in several parts. Installation requires the simplest fluidization pipes (perforations) planted on the base of the conduit (see Figure 19). Pump House installations can be mobile or cell and operated on the move to different hybrid fluidization installations. The usage of the hydraulic dredging approach is generally lower cost than mechanical dredging [35], similar to the hybrid fluidization method which may be classified into the hydraulic dredging method.

Several studies have contributed to the benefits of hydraulic dredging techniques on environmental impact such as water and sediment quality [36, 37]. The ratio of sediment volume (Vs) accumulated in one cycle (t) of limited hybrid fluidization implementation will provide benefits for the ecosystem where if fine sediment removal operations are performed controlling the SSC exceeding the limit SSC the downstream environmental impacts can be effectively limited [38]. The limited time wanted for the application of hybrid fluidization-flushing of sediment because of function elements of blended particles (sediments) which might be depositioned within a certain time after fluidization, so the time to breathe sediment is also limited.

6. Conclusion

The parameters that determine the volume of sediment flushed in a hybrid fluidization and sediment flushing system are pump head (HP), perforation orifice spacing (ɑ) and sediment thickness (db), flushing time (t), and a suction flow velocity ratio (vs). The parameter relationship is effective at the full fluidization stage where generally the sediment layer has become a slurry.

The results of the dimensional analysis produced four dimensionless relationships to determine the hybrid fluidization system model - Sediment flushing, namely relative perforation orifice spacing (ɑ/db), relative suction pump head (HP/db), relative flushing time ($t.(g0.5)/(db^{0.5})$) and the ratio of suction flow velocity to sediment particle friction stress or Particle Froude number ($v/(g.db\ (S-1))^{0.5}$). The correlation for the hybrid system model fluidization and sediment flushing is $Vs/Vw = 0.037 - 0.056(a/db) - 1.077(HP/db) + 0.000149\ (t.(g^{0.5})/(db^{0.5})) - 0.071261\ (v/(g.db\ (S-1))^{0.5})$ which has parameter limits, namely orifice diameter (*Df*) not more than 5 mm, orifice spacing (ɑ) less than 5 cm (a/db < 5 cm), pump head (HP) is small, the depth of the fluidization pipe/sediment thickness (db) can be greater.

This indicates that 1/*Df* can be used as a constant in the empirical equation that arises from the diameter of the perforation hole. The hybrid system of fluidization and sediment flushing can be more efficient compared to other sediment removal methods because it only requires a 2-inch diameter pipe with a fluidization pump and suction.

This study was limited to 2-dimensional experiments, the length of the fluidization pipe tested was only 40 cm long, the Fluidization Pump and Suction Pump were limited to a capacity of 14 liter/sec, non-cohesive sediment (sand) obtained from the river, the suction pipe used a hose measuring 0.75 inches in diameter and 120 cm long. The variation in suction pump height analyzed as a suction pump head (HP) is limited to a height of 20 cm above the sediment surface.

One of the advantages of the hybrid fluidization-flushing sediment (HSFF) system is its ease of use and lack of impact on the aquatic environment as a dredging technique. Dredging with the sediment fluidization-flushing hybrid method does not change the bottom of the channel but rather maintains the balance of the channel base. However, these environmental impact estimates are based only on classifying the type of dredging because there has been no field application for the system hybrid fluidization-flushing sediment models.

7. Declarations

7.1. Author Contributions

Conceptualization, R.A., F.M., M.A.T., and B.B.; methodology, F.M., M.A.T. and B.B.; validation R.A., F.M., M.A.T., and B.B.; formal analysis, R.A.; investigation, R.A.; resources, R.A.; data curation, R.A.; writing—original draft preparation, R.A.; writing—review and editing, R.A., F.M., M.A.T., and B.B.; visualization, R.A.; supervision, F.M., M.A.T., and B.B.; project administration, R.A.; funding acquisition, R.A. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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