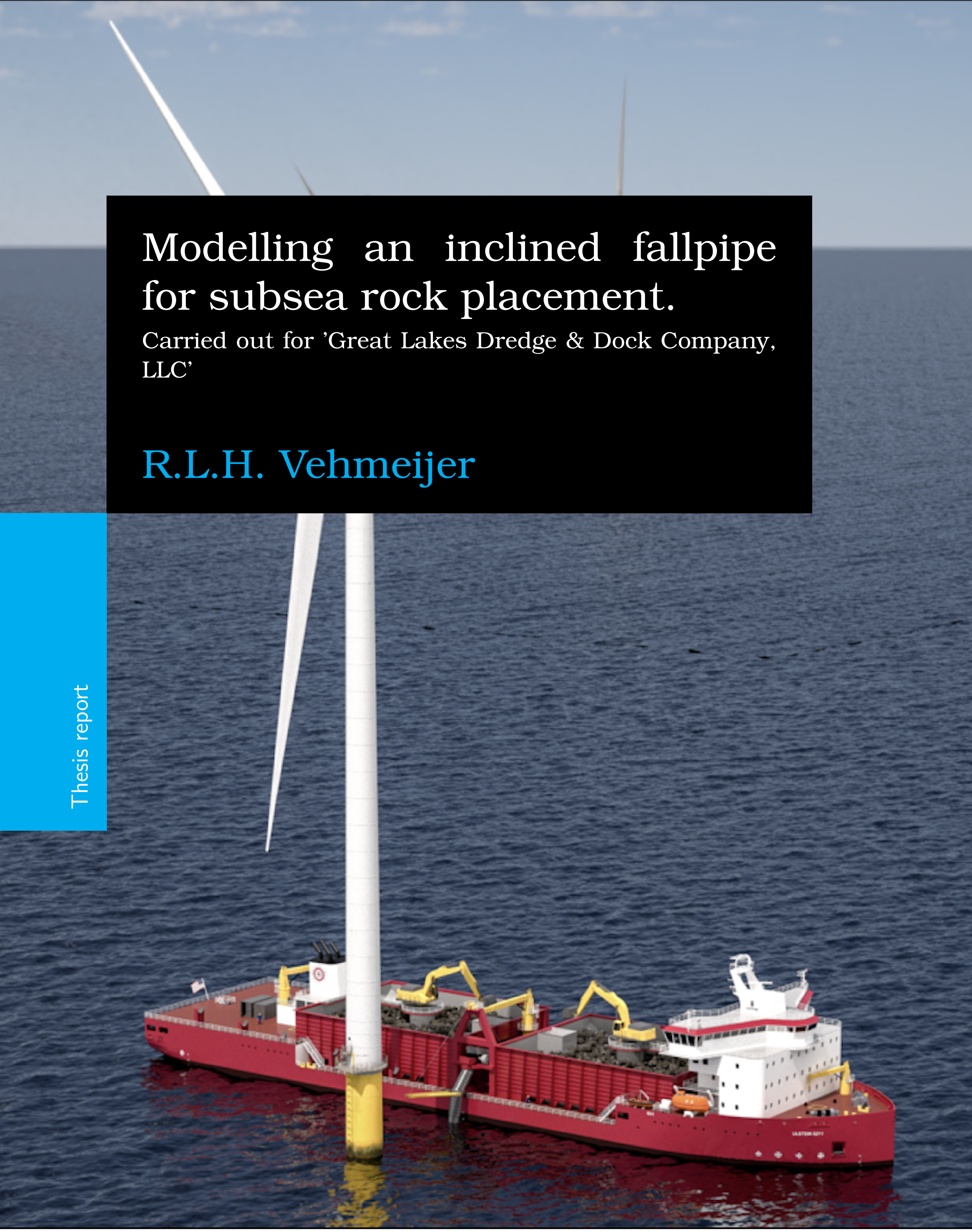
Modelling an inclined fallpipe for subsea rock placement.

Carried out for 'Great Lakes Dredge & Dock Company, LLC'

R.L.H. Vehmeijer

Thesis report



TU Delft Faculty of Mechanical, Maritime and Materials Engineering.

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R.L.H. Vehmeijer

November 14, 2025

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology

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Abstract

Subsea rock installation is a process in offshore engineering where rocks are placed on the seabed or subsea structures using a fallpipe. An example of a subsea structure could be a cable or pipeline that must be protected. In this research, the main scope is rock installation for scour protection of the foundation of offshore wind turbines. As the US government is planning to build 30 gigawatts of offshore wind capacity by 2030, many rock installation projects are planned. This is where GLDD wants to contribute by being part of a more sustainable future by building a subsea rock installation vessel. This vessel with a 20.000 ton rock capacity is placing rocks using a solid fallpipe.

Accurate knowledge of how rocks are placed using a fallpipe is necessary to plan, manage and estimate the costs of a project. The main focus of this thesis project is to establish an optimal computer model for an inclined fallpipe for subsea rock installation. This model can be used to calculate rock velocity during operating the inclined fall pipe (IFP). Additionally, the particle concentration and the distribution of particles over the pipe's cross-sectional area can be determined. The velocity of particles is essential for future models calculating where the rocks settle down after leaving the fallpipe. Based on the literature two models were made: Vertical fallpipe model 1 (VFM1) and Sliding bed model 1 (SBM1), these models are improved based on data and observations from lab research. These improvements lead to Vertical fallpipe model 2 (VFM2) and Sliding bed model 2 (SBM2).

In the lab research, a scale model of a fallpipe is made. This is done by placing a transparent fallpipe in a 5x2.5x2 meter tank of water. This fallpipe is attached to a conveyor belt, making it possible to precisely control the amount of rocks per second placed in the fallpipe.

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Chapter 1

introduction

Worldwide the demand for renewable energy rises, so is offshore wind energy becoming increasingly important in the US. On March 29 2021, the White House convened leaders from across the Administration and announced a set of bold actions that will catalyze offshore wind energy. In addition, the Biden Administration has recently set a goal of reaching 30 gigawatts of offshore wind capacity by 2030 in the USA[The White House, 2021]. To place an offshore wind farm, several offshore operations must be completed to fulfil the task. After the base of a monopile is installed, the seabed around its base is covered with a layer of rock to prevent scouring. The part of subsea rock installation is what Great Lakes Dredge & Dock Company, LLC (GLDD) wants to do with their new vessel. This thesis report is a sequel to the literature research that is done. This literature research provided knowledge about the physics behind this vessel's fallpipe system, by understanding this key part of the ship future operations can be better organised. Based on the literature research 2 models are made to predict the particle velocity in a fallpipe. After these models were made, the importance of making and testing a scale model became clear to verify these models.

The main question of this literature research is defined as 'How to model the production for an inclined fallpipe used for subsea rock installation?' To answer this main question the following sub-questions were determined:

- Is the designed fallpipe capable of discharging the required production at every operational relevant pipe angle?
- Which flow regimes are expected in an inclined fallpipe during rock placement?
- Does a backflow of water occur in an inclined fallpipe while operating it? If so, at what angles?
- At which fallpipe angle, do the particles reach the highest velocity?
- Is there a relation between pipe angle and bed density?
- How far do the rocks spread out after leaving the fallpipe? And what does this spreading pattern look like?
- What factors influence the spreading of rock after leaving the fallpipe?

In chapter 2 the flow regimes are explained to better understand how material transported in a pipe behaves. When flow regimes are clear, the physics behind a vertical fallpipe is discussed in chapter chapter 3 which will lead to Vertical fallpipe model 1 (VFM1).

Where-after in chapter 4, physics behind an inclined fallpipe is discussed, based on a sliding bed flow regime Sliding bed model 1 (SBM1) is made. This computer model will provide a production limit and velocity of the particles. Thereafter a scale model is made to validate and improve these theoretical models to match with the lab research. In chapter 5 the layout of this lab research is explained, followed by results in chapter 6. These results are compared with the models in chapter 7 whereafter the results are implemented in the final models: Vertical fallpipe model 2 (VFM2) Sliding bed model 2 (SBM2) shown in chapter 8.

Chapter 2

Flow regimes

In slurry transport, it is common to distinguish different flow patterns, which are so-called flow regimes. These regimes originate from slurry transport, where many different particle types are used. In case of sub-sea rock placement, it is clear that 'rocks' are used, not fine particles such as clay and sand. A typical characteristic in rock placement is that gravity is causing the movement of particles. In slurry transport, water is used as a carrier causing particles to move in the same direction true a pipe. In addition, most often, water is moving slower than the rocks, whereas in slurry transport water is moving faster than the particles in a pipe. This difference in velocity is called 'slip' [V_{sl}], which is defined as the difference between the velocity of mixture [V_m] and solids [V_s]. In this chapter eight flow regimes are discussed which occur for laboratory and real-life conditions [Miedema, b]. A visual display of how these eight different flow regimes look like is shown in 2-1. Every regime is visualised with two cross areas of a pipe, left with fine particles and right with coarse particles. These flow regimes are important to define the situation in a pipe and which equations can be applied to calculate friction forces in the pipe. With these friction forces, velocity of the particles can be determined.

2-1 The 8 flow regimes

1. **Fixed bed without suspension.**
A fixed bed with no suspension: all particles lay on the bed. This two-layer system where particles are settled at the bottom and above it is a flow of water, both layers usually have a different velocity. The bed slides due to friction between the two layers and the pressure working on the beds cross-section. A friction force between the layers occurs. This friction between the bed and fluid is expressed as the Darcy-Weisbach friction factor λ_{12}. This friction factor resulting in a force will be used in the sliding bed model and is expressed in equation

   Further friction force in this regime is the bed/pipe-wall friction, known as $F_{2,fr}$.

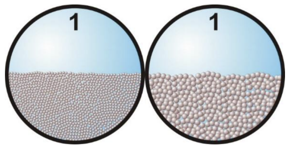

Figure 2-1: Flow regime 1

2. **Fixed bed with suspension.**
Flow regime 2 is a fixed bed with a suspension of particles that flow above the bed. The bed's density decreases to the top of the bed. The 'sheet flow' above the bed is similar to sliding bed but less dense, the sheet flow density also decreases.

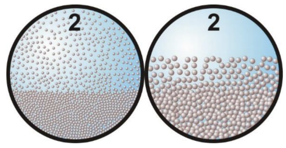

Figure 2-2: Flow regime 2

3. **Fixed bed with suspension or sliding bed with sheet flow Constant $\mathbf{C}_{vs}$.**
Under laboratory circumstances with a constant spatial volumetric concentration C_{vs}, for coarse particles the bed is sliding with sheet flow at the top, where the thickness of the sheet flow layer increases with an increasing velocity difference between the flow above the bed, while for fine particles the shear stress on the bed is not high enough to make it start sliding, but more and more particles will be in suspension as the line speed increases. For fine particles, the behaviour starts following the heterogeneous behaviour more and more with increasing line speed.

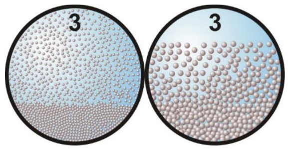

Figure 2-3: Flow regime 3

4. **Fixed bed with the suspension of coarse particles**. The bed is sliding with sheet flow. The thickness of the sheet flow layer increases at a higher particle velocity difference. For fine particles, the shear stress, between the bed and the mixture flow above it, is not high enough to create a sliding bed.

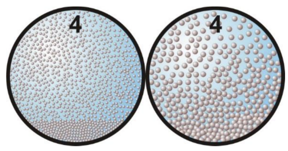

Figure 2-4: Flow regime 4

5. **Heterogeneous transport $\mathbf{C_{vt} \approx C_{vs}}$**
Line speed increased further, the difference between spatial and delivered concentration becomes smaller. Due to the turbulence of the flowing water, turbulent forces interacting with the particles are not strong enough to create a uniform particle distribution. In both cases, for coarse and fine particles, a concentration gradient occurs along the vertical axis of the pipe. Highest concentration at the top, the lowest concentration at the bottom.

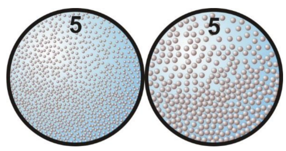

Figure 2-5: Flow regime 5

6. **Homogeneous transport $\mathbf{C_{vt}} \approx \mathbf{C_{vs}}$**
Similar to flow regime 5, even smaller difference between spatial and delivered concentration. For coarse and fine particles, the turbulent forces interacting with them are high enough to create a complete uniform distribution throughout the cross-section.

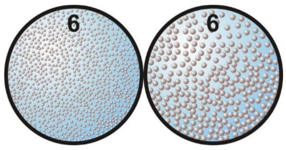

Figure 2-6: Flow regime 6

7. **Sliding Flow.**
For relative low concentrations and relatively small particle diameters, the sliding bed regime will transform into a heterogeneous regime at the intersection of the two regimes. This is caused by the lift forces not being large enough to lift particles from the bed. However, when particles are bigger and the lift forces are not large enough to lift the particles, a bed will form. This regime is called sliding flow, there is flow but the resistance on the bed is comparable with that of sliding bed friction.

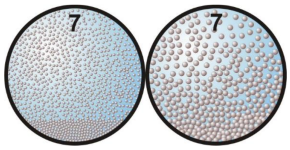

Figure 2-7: Flow regime 7

8. **Fixed bed with suspension, constant $\mathbf{C_{vt}}$.**
In this flow regime, constant volumetric transport concentration with decreasing line speed. An equilibrium arises between erosion and deposition of the bed. This equilibrium results in a certain bed height. This regime occurs if the relative excess hydraulic gradient is high enough to result in a sliding bed and so this will occur much more with small pipe diameters than with large pipe diameters.

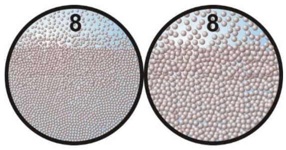

Figure 2-8: Flow regime 8

2-2 Applicable flow regimes

Much research has been done on flow regimes, however, this was for slurry transport and not for subsea rock installation(using an inclined fallpipe). The main difference is the driving force and grain size.

1. Driving force: for rock installation, this is gravity, for slurry transport, this is a pressure gradient. The pressure created by a pump creates a pressure difference causing water and particles to flow true the pipe. Water and particles are transported in the same direction. For a closed fallpipe where no water is added, this is not the case. Particles are moving down the pipe and water is staying in the pipe because it is not added. This is discussed in more detail in chapter 4.

2. Grain size: for rock installation relative large particles are used compared to slurry transport, this results in very large Reynolds numbers. A significant difference in grain size results in different behaviour of particles, making empirical and pseudo-scientific equations less applicable. With a particle diameter of 100 mm and higher

for rock placement the Reynolds number is far above 2000, so the particle will be in the turbulent region according to figure 4.3-2 in Miedema's book[Miedema, b].

These differences listed above make it difficult to predict which flow regime will occur in which situation. It is assumed that in the case of a vertical fallpipe, homogeneous transport applies. If the pipe is placed diagonally, it is assumed that a sliding bed or sliding flow occurs. The difference between a sliding bed and a sliding flow is that a bed is dense and a flow is not, a requirement of a bed is that it would be theoretically possible to walk on it[Miedema, b]. To determine which flow regime occurs in different situations, a scale model of a fallpipe is tested in a lab researchchapter 5.

Chapter 3

Rock placement using a vertical fallpipe

In this chapter the physiscs behind a vertical fallpipe is discussed to provide the information needed to make Vertical fallpipe model 1 (VFM1). The equations that are used for calculating the production of a vertical fallpipe is given in the first section 3-1. The different variables that are included in this equation will be further discussed in depth to give an insight in which variables influence the production of a fallpipe.

3-1 Vertical fallpipe production

In this section the production of a fallpipe will be discussed, it is expressed in kg/second or tons/hour. In this chapter it is assumed that water and stones will be added at the top (inlet section). The equation to calculate the production is given in Eq. (3-1).

$$P_o = \rho_s \cdot c \cdot u_p \cdot A_p \tag{3-1}$$

In Eq. (3-1) there are four variables that influence the production of a fall pipe. To maximise the production and increase the efficiency of a rock dumping process we look closer to this formula. The first variable is ρ_s, this is a material property of rock. This can differ depending on what kind of rock is used but is constant for a chosen rock type. The second variable is the volumetric concentration c. It is the ratio between rock and water that flows true the pipe, this ratio can be changed. This will be further discussed in section 3-2. Particle velocity u_p can be increased resulting in higher production, increasing u_p has its own pros and cons and will be discussed in the section 3-3. Finally, there is the fourth variable A_p, which is the crossectional surface area of the pipe, this will be discussed in section 3-4.

3-2 Volumetric concentration

As can be read from Eq. (3-1), increased Volumetric concentration of rocks in a fallpipe lead to higher production. However the concentration has its limits, when the concentration of rock in a fallpipe is too high it will clog and production will drop to zero. When a higher concentration of material is wanted in the fallpipe, more water should be added at the top to prevent clogging the system. A clear overview of concentration operating limits with various amounts of added water to the fallpipe (α), is shown in Figure 3-3

3-3 Particle velocity

Obviously, a higher particle velocity results in a higher fallpipe production. Despite striving for a maximum production, a particle velocity that is 'too high' is not desired. When rocks reach a high velocity and shoot out of the end of the fallpipe, this can lead to more rock penetration, damaging structures and rocks ending up in a different location than planned. More about the consequences of high particle velocity is discussed in the appendix. The particle velocity [u_p] in a fallpipe is relative to the velocity of the water around it[Van Rhee, 2018]. Therefore the water velocity [u_w] in the pipe is added to the settling velocity [w_s].

$$u_p = u_w + w_s \tag{3-2}$$

The velocity of the water can be expressed as:

$$u_w = \alpha \cdot w_{0,p} \tag{3-3}$$

u_w is the average water velocity due to added water at the inlet of the pipe based on α which is a dimensionless factor used to describe the amount of water added to the pipe. In the following subsections, different particle velocities will be discussed, it will depend on the situation which one to use. Eventually, Eq. (3-11) will be used to take into account hindered settlement and wall influences.

3-3-1 Single-particle velocity

In this part, only the single settling velocity of the sphere is discussed. This results in equation Eq. (3-4), this is a general equation of the one-dimensional settling velocity.

$$w_0 = \sqrt{\frac{4\Delta g d}{3C_D}} \tag{3-4}$$

Where C_D is dependent on the Reynolds number of a particle, in the case of subsea rock installation, where large rocks are used C_D is equal to 0.4. The settling velocity of a single particle is w_0 and can be calculated by Eq. (3-4).

However, if it is uncertain which flow regime is applicable, it can be determined by:

$$
\begin{aligned}
Re_p < 1 C_D &= \frac{24}{Re_p} \\
1 < Re_p < 2000 C_D &= \frac{24}{Re_p} + \frac{3}{\sqrt{Re_p}} + 0.34 \\
Re_p > 2000 C_D &= 0.4
\end{aligned} \tag{3-5}
$$

First one for the laminar, second for transition and the third for the turbulent regime. Reynolds number Re_p, is expressed in Eq. (3-8).

3-3-2 Hindered settling

When multiple particles settle in a confined space, the particles hinder each other due to the water flow around each particle influencing the other particles. [Richardson and Zaki, 1997]

$$w_s = w_0 \cdot (1 - c)^n \tag{3-6}$$

The exponent n in Eq. (3-6) is dependent on the Reynolds number and can be expressed as:

$$n = \frac{4.7 + 0.41 \cdot Re_p^{0.75}}{1 + 0.175 \cdot Re_p^{0.75}} \tag{3-7}$$

In the case of coarse particles this results in 'high' Reynolds numbers: 2000+ then n in Eq. (3-7) is 2.4 and for fine particles, it is 4.65 [Rowe, 1987].

The Reynolds number can be expressed as:

$$Re_p = \frac{w_0 \cdot d}{\nu} \tag{3-8}$$

The plot in figure 3-1 shows the particle Reynolds number as a function of the particle diameter for sands and gravels, using the Ruby & Zanke(1977) equation.

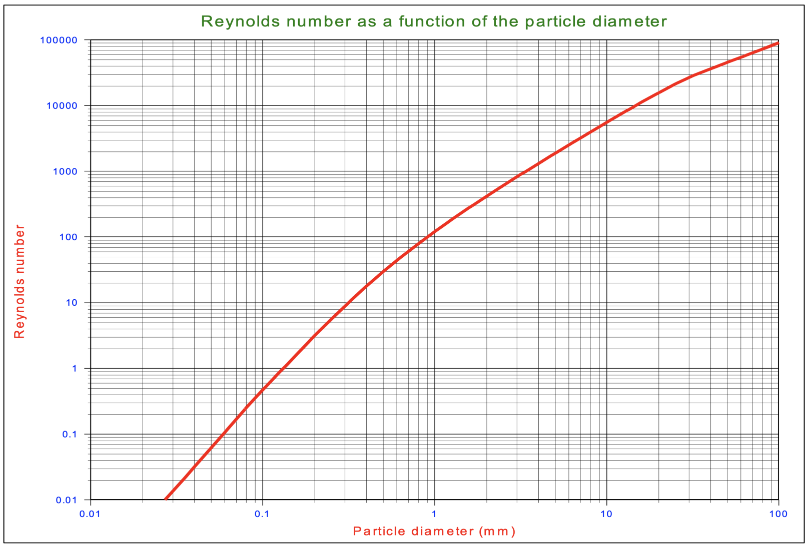

Figure 3-1: The Reynolds number as a function of the particle diameter

3-3-3 Wall influenced settling velocity

The velocity reduction of a material that flows true a pipe and is influenced by the pipe wall is given in equation Eq. (3-9).

$$\frac{w_{0,p}}{w_0} = \left(1 - \lambda_w^2\right) \cdot \sqrt{1 - 0.5\lambda_w} \tag{3-9}$$

When a large particle falls true a pipe filled with water, the water that flows around the object causes friction. This friction slows down the falling object, when the object has nearly the same diameter as the pipe the effect becomes large and the velocity approaches zero. In that case the particle behaves almost like a piston. The equation for hindered settling velocity shows that λ_w, the ratio between the particle and pipe diameter, has a significant influence on the settling velocity and thereby on the production. In figure 3-2 this relation between relative particle size and reduction in velocity is shown.

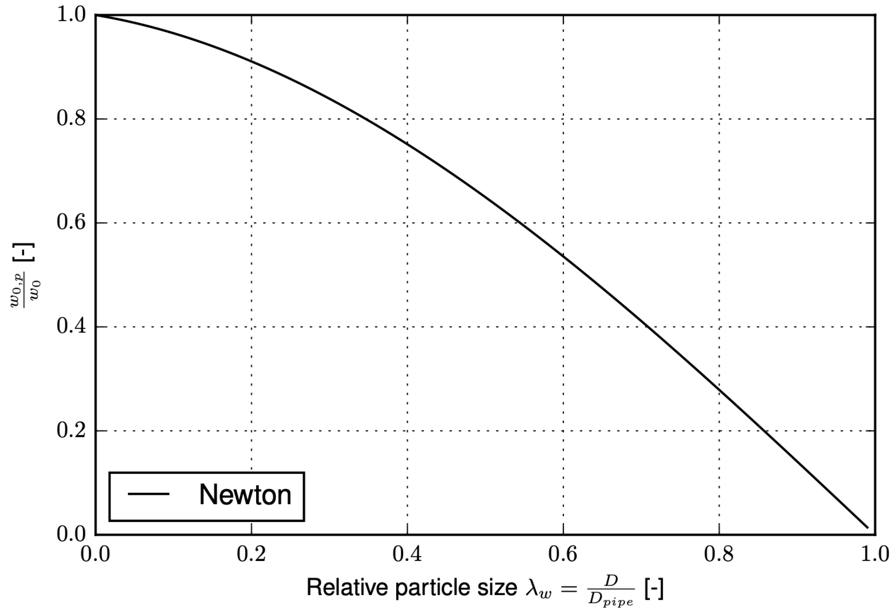

Figure 3-2: Relative particle size

3-4 Influence of fallpipe diameter

Increasing the fallpipe diameter increases production in two ways. A larger diameter results in a larger surface area of the pipe A_p as shown in Equation 3-10 the production of material that can flow true the pipe.

$$A_p = \frac{\pi}{4} \cdot D \tag{3-10}$$

Another influence of pipe diameter is the wall influence of a particle and the pipe Figure 3-2. As shown in Eq. (3-9), the ratio between rock diameter and pipe diameter λ_w influences the settling velocity in a pipe.

3-5 Normalized production with hindered settling

Assuming that water, together with the rocks is added to the fallpipe, Equation 3-11 can be written based on Eq. (3-2), Eq. (3-9) and Eq. (3-3).

$$P_s = c \cdot (\alpha + (1-c)^n) \cdot (\rho_s \cdot A_p \cdot w_{0,p}) \tag{3-11}$$

In the equation Eq. (3-11) the hindered settling exponent n is set on 2.4 based on high Reynolds numbers applied in Eq. (3-7). This value is chosen for relative large rock particles with high Reynolds numbers. With this value set, the production of the fallpipe can be determined based on particle concentration c and different values for α. The production curve for α= 0, 0.1, 0.28, 0.4 is given by graph in Figure 3-3. This graph clearly shows how to achieve maximum production for a fallpipe in different circumstances. When no water is added to the fallipipe and α is zero, maximum production can be achieved at a concentration around 30%. A higher or lower concentration leads to lower production. When the concentration passes the critical value of about 30/35%, the flow velocity will drop at that point in the pipe. When the local flow velocity drops the local concentration will rise and can eventually block the fallpipe.

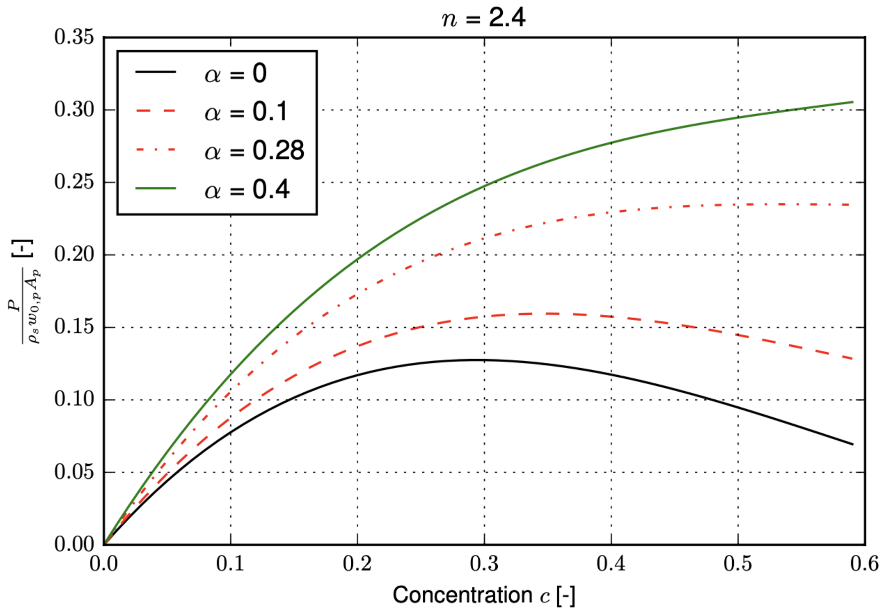

Figure 3-3: Normalized rock production

When no water is added to the inlet of the fallpipe the situation can become unstable, as local concentration in the pipe can fluctuate. When the concentration exceed 28% the pipe can be blocked. Therefore, when no water can be added caution is needed and the concentration must be kept under the maximum to prevent the pipe from clogging.

3-5-1 Maximum concentration for given α

When equation 3-11 is derived over the concentration the maximum production can be found by setting the normalized rock production equal to zero for different values of α.

$$\frac{d\tilde{P}_s}{dc} = \alpha + (1-c)^n - c \cdot n(1-c)^{n-1} \tag{3-12}$$

Where The value chosen for the hindered settling exponent n = 2.4, which is a value for high particle Reynolds numbers [Van Rhee, 2018] When assuming $n = 2.4$, the maximum concentration can be found by setting equation 3-12 equal to zero. Plotting α and the maximum concentration results in the following graph:

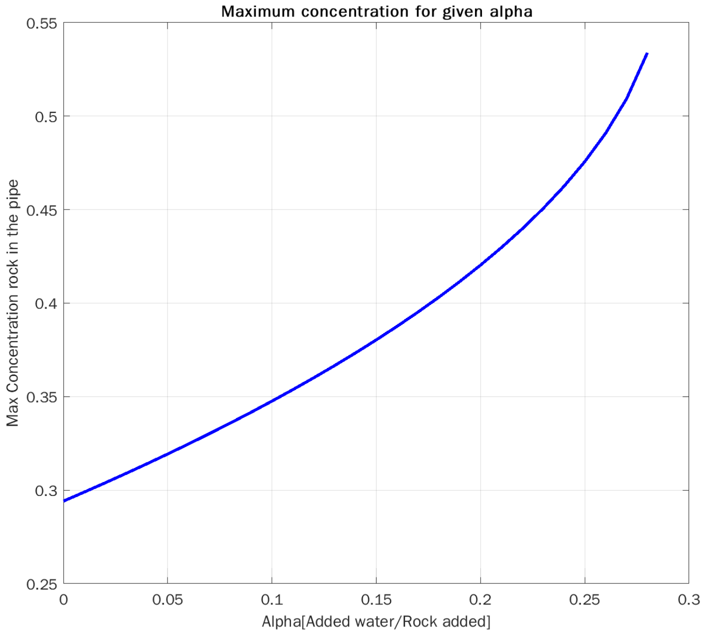

Figure 3-4: Maximum concentration for given α

3-6 Matlab model vertical fallpipe 1

Combining concentration hindered settling and wall influences the VFM1 is setup, the code for it can be found in the Appendix F. Aswell as in the Sliding bed model 1 (SBM1), the equation for calculating production of the fallpipe must be rewritten to have production as an input instead of an output of the model. The main output of the model is concentration, which can be judged as acceptable according to Figure 3-3. As long as there no water added to the fallpipe, it is advised to keep the concentration below 0.2 to prevent the change of blocking the pipe. This concentration is eventually used to calculate the hindered settling velocity of the particles.

Figure 3-5: VFM1:input output

The following velocities are calculated using the VFM1 shown Table 3-6. The concentration (c) shown in the table is set based on the production that is required, in this case, production of 0.48 was used because that was the production that was used in the lab research, scaled from the desired production on full-scale operational vessel.

Batch #	d_{50}	c	$w_0[m/s]$	$w_{0,p}[m/s]$	w_c $[m/s]$
1	0.008 [m]	0.072	0.46	0.44	0.37
2	0.015 [m]	0.052	0.63	0.59	0.52
3	0.022 [m]	0.039	0.76	0.67	0.60

Constant properties: ρ_s= 2600 $[kg/m^3]$ α= 90 [°] D_p=0.094 [m]

Table 3-1: Vertical fallpipe model 1 input

As shown in the table above, the velocity difference between single particle- and wall-influenced velocity is larger as the particle diameter increases. For small, medium and large particles the velocity decreases 4%, 6% and 12% due to interaction with the pipe-wall. When adding the influence of particles hindering each-other the settling velocity drops again with 16%, 12% and 10%, despite the low concentrations it makes a significant difference.

Chapter 4

Rock placement using an inclined fallpipe

In chapter 2, different flow regimes are distinguished. One of them, sliding bed, is being explained in more depth in this chapter. For a sliding bed regime, it is common to use the Wilson method [K.C.Wilson et al., 1992], this is what Miedema has applied when modelling a sliding bed regime at low line speeds [Miedema, a]. In this chapter, this method is adjusted and applied for Sliding bed model 1 (SBM1)

4-0-1 The limit deposit velocity

To form a 'sliding bed' the particles in the pipe must settle and not be in suspension. In Hydraulic Engineering it is assumed that particles stay in suspension when the so-called shear velocity equals the settling velocity of the particles:

$$U_* \geq w_c \tag{4-1}$$

Where w_c is the hindered settling velocity and U_* can be determined with :

$$U_* = \sqrt{\frac{\tau_{2,fl}}{\rho_l}} \tag{4-2}$$

Where $\tau_{2,fl}$ is the shear stress between bed and pipewall, further described in Equation 4-8 [Miedema, 2013]

Furthermore, there is the limit deposit velocity, this is the velocity below which the first particles start to settle and a bed will be formed at the bottom of the pipe[Miedema, b]. This bed can be fixed, fixed with suspension or sliding as a whole. This is described in the subsection about flow regimes 2-1. The limit deposit velocity is calculated by equation 4-3

$$V_{ls,ldv} = F_L \cdot \sqrt{2 \cdot g \cdot D_p \cdot R_{sd}} \tag{4-3}$$

Where $F_L = 1.34$ to 2.2 for coarse particles and R_{sd} is relative submerged density.

$$R_{sd} = \frac{\rho_s - \rho_l}{\rho_s} \tag{4-4}$$

The equations 4-1 & 4-3 are applicable when a material is transported in a horizontal pipe, where a liquid is flowing and a direction force between the liquid and the particles is created.

4-1 Sliding bed model

In a vertical placed fallpipe, rocks discharged at the inlet of the pipe will settle down vertically. The vertical pipe situation is previously discussed in chapter 3. When the pipe is placed at a steep angle, close to vertical, particles are still 'falling' and not sliding. In this chapter, the physics behind a 'sliding bed' will be discussed. At which angle this transition takes place is not clear and will be estimated. For future research it is useful to investigate this in more depth.

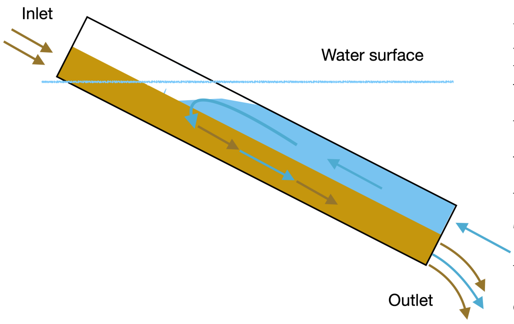

Figure 4-1: Flow directions in pipe, no added water.

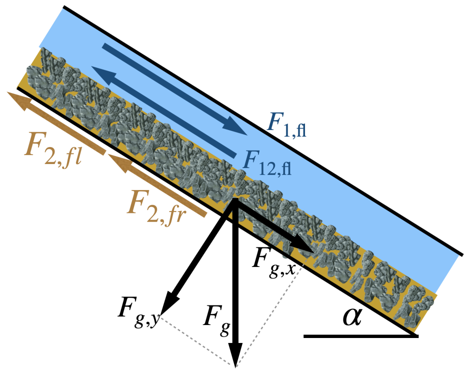

Figure 4-2: Force equilibrium sliding bed.

As rocks and water mix together at the inlet of the pipe, the water filling the pores is dragged with the water out of the pipe. The water needed to 'fill' the pores between rocks must come from somewhere, as the opening of the pipe is above water, the water comes from the other side of the pipe. The rocks dragging the water out the pipe cause the water level in the pipe to drop. This water drop causes a pressure difference between the inside and the outside of the pipe. This pressure difference causes water to come from the outlet of the pipe causing a flow in the opposite direction of the sliding bed movement. This flow of water is named the 'backflow'.

Figure 4-1 visualizes what happens. The forces acting on the system will create an equilibrium where a certain velocity is reached. In an inclined fallpipe, gravity is the driving force to make particles slide down; gravity force is straight down. Therefore it must be factorised to be parallel to the direction of the pipe, this vector is defined as $F_{g,x}$. The other four forces created by friction between the bed, the pipe and water are:

1. $F_{12,fl}$: Friction force bed-fluid.
2. $F_{2,fr}$: Friction force bed-pipewall.
3. $F_{1,fl}$: Friction force water-pipewall.
4. $F_{2,fl}$: Friction force water, in between bed, and pipewall.

This gravity force and the four friction forces will reach an equilibrium at a certain velocity which is the average particle velocity in the pipe.

In the following subsections, the relevant forces are discussed which lead to the equilibrium of forces in the pipe. Therefore the basic dimension of the pipe must be clear, following as shown in figure 4-3:

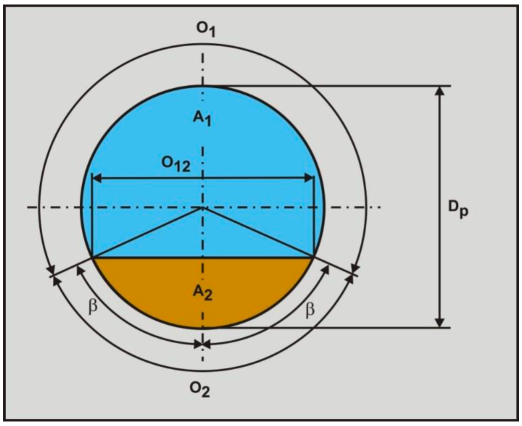

Figure 4-3: Schematic view cross section pipe

Table 4-1: Variables sliding bed.

Parameter	Description	Equation
β	Angle of the bed height $[Rad]$	[-]
O_1	Contact arc-length water and pipe $[m]$	$O_1 = D_p \cdot (\pi - \beta)$
O_2	Contact arc-length bed and pipe $[m]$	$O_2 = D_p \cdot \beta$
O_{12}	Width contact bed and water in pipe $[m]$	$O_{12} = D_p \cdot sin(\beta)$
A_p	Cross sectional area pipe $[m^2]$	$A_p = \frac{\pi}{4} \cdot D_p^2$
A_2	Cross sectional area bed $[m^2]$	$A_2 = \frac{D_p^2}{4} \cdot (\beta - sin(\beta) * cos(\beta)$
A_1	Cross sectional area water above bed $[m^2]$	$A_1 = A_p - A_2$
V_1	Velocity of water above bed $[m^2]$	$V_1 = \frac{A2 \cdot (1-C_{vb}) \cdot V_2}{A1}$
V_2	Velocity of sliding bed $[m^2]$	See Figure 4-4

4-1-1 Gravity force

In the sliding bed, gravity, F_g is the driving force. It can be vectorized in two forces: one force parallel and one perpendicular to the pipe. The gravity force vector parallel to the pipe is given by:

$$F_{gx} = F_g \cdot \sin(\alpha) \tag{4-5}$$

Where F_g, the submerged weight of the bed is given by calculating the volume of the bed multiplied by the relative density:

$$F_g = \rho_{fl} \cdot g \cdot L_{pipe} \cdot R_{sd} \cdot C_{vb} \cdot A_2 \tag{4-6}$$

Where ρ_{fl} is the liquid density, R_{sd} relative submerged density and $C_v b$ the volumetric bed density.

4-1-2 Friction force bed-fluid

The friction between water in the pipe and the sliding bed is given as $F_{12,fl}$. The shear stress between the sliding bed and water in the pipe is described as $\tau_{12,fl}$.

$$F_{12,fl} = \tau_{12,fl} \cdot L_{pipe} \cdot O_{12} \tag{4-7}$$

$$\tau_{12,fl} = \frac{\lambda_{12}}{4} \cdot \frac{1}{2} \cdot \rho_{fl} \cdot (V_1 + V_2)^2 \tag{4-8}$$

In the equation above, the velocity V_1 and V_2 are added instead of subtracted because the direction is opposite increasing the relative velocity between bed and fluid.

With:

$$\lambda_{12} = \frac{\alpha_{Wilson} \cdot 1.325}{\left(\ln\left(\frac{0.27 \cdot d_{50}}{D_H} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \tag{4-9}$$

Where $\alpha_w ilson$ is 2.75 as described in Wilsons latest book [K.C.Wilson et al., 1992].

$$Re = \frac{V_1 \cdot D_H}{\nu_{fl}} \tag{4-10}$$

Where ν_{fl} is the fluid viscosity. In the equation, previously mentioned V_1 can be extracted from the equation which can be used to determine the production of the fallpipe.

4-1-3 Friction force bed-pipewall

Friction forces between the bed and the pipe wall are caused by the shear stress; $\tau_{2,fr}$

$$F_{2,fr} = \tau_{2,fr} \cdot O_2 \cdot L_{pipe} \tag{4-11}$$

Where $\tau_{2,fr}$ exists of

$$\tau_{2,fr} = \frac{\mu_{\text{fr}} \cdot \rho_{\text{fl}} \cdot g \cdot cos(\alpha) \cdot R_{sd} \cdot C_{vb} \cdot A_p}{\beta \cdot D_p} \cdot \frac{(\beta - \sin(\beta) \cdot \cos(\beta))}{\pi} \tag{4-12}$$

Where μ_{fr} is the sliding friction factor between the pipe wall and particles. Miedema uses a value of +/- 0.4 for a sliding bed, this could vary depending on type and shape of rocks[Miedema, b].

4-1-4 Friction force water-pipewall

Friction forces between water in the pipe and the pipe wall are caused by the 'backflow'. This force is given by:

$$F_{1,fl} = \tau_{1,\text{fl}} \cdot O_1 \cdot L_{pipe} \tag{4-13}$$

Where the shear stress is given by:

$$\tau_{1,fl} = \frac{1}{8} \cdot \lambda_1 \cdot \rho_{fl} \cdot V_1^2 \tag{4-14}$$

In this shear stress, the Moody friction factor is given by λ_1. This factor is necessary to define the shear stress between water flow and the pipe wall. In this equation ϵ is the absolute roughness of the pipe material, divide this by the hydraulic diameter D_H and the relative roughness is obtained.

Where λ_1 is the well-known Darcy Weisbach equation[Miedema, a]. Over the whole range of Reynolds numbers above 2320 the Swamee Jain equation gives a good approximation for the friction coefficient:

$$\lambda_1 = \frac{1.325}{\left(\ln\left(\frac{0.27 \cdot \varepsilon}{D_H} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \tag{4-15}$$

4-1-5 Friction force water, in between bed, and pipewall

As the sliding bed exists of rock and water, which slide over the wall of the pipe, both create a shear stress between the pipe and the bed. In this part, the water in the bed sliding over the wall of the pipe is modelled.

Where $F_{2,fl}$ is given by

$$F_{2,fl} = \tau_{2,fl} * O_2 * L_{pipe} \tag{4-16}$$

Where $\tau_{2,fl}$:

$$\tau_{2,fl} = \frac{\lambda_2}{4} \cdot \frac{1}{2} \cdot \rho_{fl} \cdot V_2^2 \tag{4-17}$$

$$\lambda_2 = \frac{1.325}{\left(\ln\left(\frac{0.27 \cdot \varepsilon}{d} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \tag{4-18}$$

4-1-6 Solving the equilibrium of forces

When material in the pipe moves at constant speed, the previous mentioned forces are in equilibrium and 4-19 can be used.

$$F_{gx} = F_{12,fl} + F_{1,fl} + F_{2,fr} + F_{2,fl} \tag{4-19}$$

By elaborating the equation and rewriting it, the production of the fallpipe is given in equation/figure 4-4. How this simplification and rewriting is done can be found in section A-3.

This equation seems very complex, that is because it is written in its most detailed form. Every variable such as O_1, O_{12}, O_2 etc is expressed in β, resulting in:

$$V_2 = \sqrt{\frac{g \cdot sin(\alpha) \cdot R_{sd} \cdot C_{vb} \cdot A_2 - \frac{\mu_{fr} \cdot g \cdot cos(\alpha) \cdot R_{sd} \cdot C_{vb} \cdot A_p}{\beta \cdot D_p} \cdot \frac{(\beta - \sin(\beta) \cdot \cos(\beta))}{\pi} \cdot \beta \cdot D_p}{\frac{1}{8} \cdot D_p \cdot \left(\frac{\alpha_{Wilson} \cdot 1.325}{\left(\ln\left(\frac{0.27 \cdot d}{D_H} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \cdot \left(\frac{A2 * (1 - C_{vb})}{A1} + 1\right)^2 \cdot sin(\beta) + \frac{1.325}{\left(\ln\left(\frac{0.27 \cdot \varepsilon}{D_H} + \frac{5.75}{Re^{0.9}}\right)\right)^2} \cdot \left(\frac{A2 \cdot (1 - C_{vb})}{A1}\right)^2 \cdot (\pi - \beta) + \frac{1.325}{\left(\ln\left(\frac{0.27 \cdot \varepsilon}{d} + \frac{5.75}{(Re)^{0.9}}\right)\right)^2} \cdot \beta \cdot (1 - c_{vb}) \right)}}$$

Figure 4-4: Velocity sliding bed

When the velocity of the bed is known, the production of the fallpipe can be determined with:

$$P_o = V_2 \cdot A_2 \cdot C_{vb} \cdot \rho_s \tag{4-20}$$

4-1-7 Applying model, with known inputs

The equilibrium of forces that result in a particle velocity Figure 4-4, is theoretically correct but cannot be used with the known input variables. During a subsea rock installation project, the Pipe-angle (α), production in/out (P_i/P_o), particle diameter (d_{50}) and other variables concerning viscosity and further rock properties are assumed to be fairly constant. What should be determined using the model is whether the pipe can cope with the production by calculating the volumetric concentration in the pipe. Therefore P_i must equal P_o otherwise the pipe gets blocked. Furthermore, the model must provide the velocity of particles sliding/falling true the pipe and the height of the sliding bed or flow.

To achieve this, Equation 4-21 is setup.

$$V_2 = \frac{P_i}{A_2 \cdot C_{vb} \cdot \rho_s} \tag{4-21}$$

This function can be solved by a program such as Matlab using 'vpasolve' function, finding the β that provides an equilibrium. When β is known, it can be used to calculate V_2 with Equation 4-21, (the adjusted code of SBM1 is shown in Appendix C)

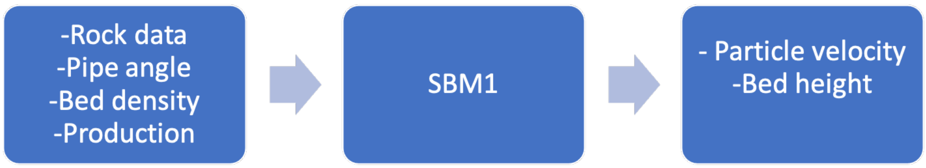

Figure 4-5: SBM1R:input output

4-2 Results sliding bed model 1

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4-3 Discussion of results

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Chapter 5

Lab research

In the chapter 2 flow regimes are discussed, where-after two models are made in Matlab: a vertical fallpipe in chapter 3 and in chapter 4 a sliding bed model. In the upcoming chapters, the main focus will be to validate these models based on a scale model that is built and tested in a lab research. In this chapter, the research questions are stated and the layout of the lab-research will be discussed. Then in 6 the results are discussed which are compared with the two models in 7. Finally, the results and observation gathered from the lab research is used to improve the models and bring them in line with reality in chapter 8.

5-1 Aim of lab test

Based on the results of this lab research the following research questions are answered:

- Does a backflow of water occur in a closed inclined fallpipe during underwater rock installation?
- What is the influence of fallpipe angle, on particle velocity, bed height and bed density?
- Which flow regime occurs in a fallpipe?
- Can the Sliding bed model 1 (SBM1) be used to calculate the bed height and particle velocity?
- How do the results of SBM1 compare to the labtest results?
- Is the model reliable for larger scale? What must be changed to be so?
- What does the spread of rocks look like after leaving the fallpipe? What is the influence of fallheight on that dispersion?

5-2 Lab test setup and method

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5-3 Scaling

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5-4 Method lab research

During the lab test, 3 batches of rock sizes are used; small: (5.8-10 mm), medium: 10-20 and large: 20-25 mm. These different batches are tested for at least four different pipe angles, 48°, 59°, 70° and 80°. After these test are done, some additional test are done to determine the spread of particles.

- Step 1: Rocks are placed on a conveyor belt.
- Step 2: Minimum of 1 slow-motion and one standard video camera is set in place. One for filming the entire pipe and one for a detailed view of a part, see A-7 for the camera views.
- Step 3: Conveyor belt feeds the rocks to a funnel which the rocks in a transparent pipe.
- Step 4: The pipe will be placed at an angle varying from 48 to 90 degrees in steps of +/- 10 degrees.
- Step 5: Measure particle velocity and bed height using video analysis software 'Tracker'.
- Step 6: Calculate bed density from bed height, production and velocity.
- Step 7: Additionally, the dispersion of the rocks is determined using the steel grid with containers.

5-4-1 Measuring dispersion setup

In this section, the setup for measuring the dispersion of rocks will be discussed. Rocks that will flow out of the pipe and spread out, and how this dispersion of rocks happens will be measured with a steel grid filled with containers. By catching the rocks in a container, afterwards can be determined how the dispersion is distributed by weighing the content of each container

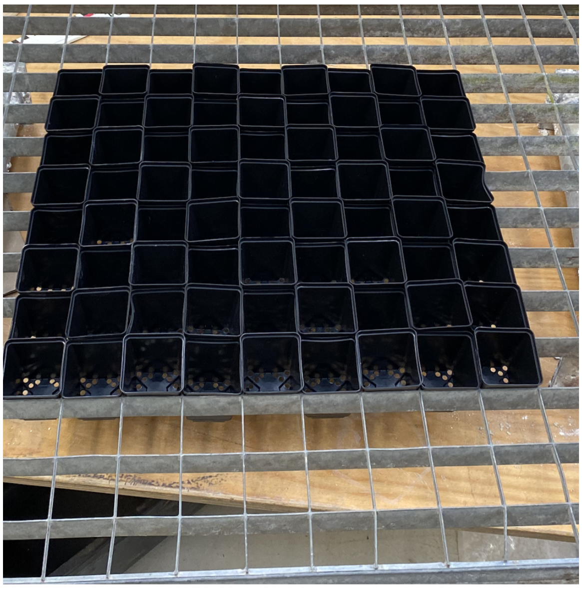


Figure 5-1: Rock collector

Chapter 6

Results lab research

In this chapter, the measured data and observations from the labtest will be discussed. First will be explained how the lab test was recorded, thereafter will be explained how the video footage was processed with video analysis software to measure particle velocity. After that the bed height of rocks in the pipe was measured manually. In addition to measuring velocity and bed height, particle dispersion was measured after leaving the fallpipe.

6-1 Result gathering

Every 'run' is filmed with 2 or 3 cameras, two of them being a GoPro HERO 9 on linear lens mode. According to the manufacturer, *this leads to 'Linear field of view (referred to as "lens" on HERO 9 captures a straight horizon with a more natural perspective. This mode eliminates the barrel distortion (fish-eye effect) typically captured by your GoPro's wide-angle lens, without compromising image quality.*

The resolution was set at $4K$ (2160x3840 pixels) with 240 frames per second. This high resolution and many frames per second were desired for having the best possible quality for analysing of the footage. During the lab test, the pipe angle, particle size, added water and input of rocks [kg/s] is varied, the data obtained from the video footage is particle velocity, bed height and observation of particle behaviour. Based on these measurements bed concentration can be calculated and based on visual observation flow regime can be determined.

Production First step is to determine production, this is done by weighing the amount of rocks placed on the conveyor belt divided by the time it took to empty it, providing kilogram rock going true the pipe per second.

6-1-1 Velocity

Velocity of the particles is measured using 'Tracker', which is a video analysis and modeling tool built on the Open Source Physics (OSP) Java framework. It is designed to be used in physics education. Tracker video modeling is a powerful way to combine videos with computer modeling.

How to use this program is explained by the following eight steps:

Step 1: Upload video file in tracker Step (1), Simply drag a video in the program, in this research mp4 files are used.

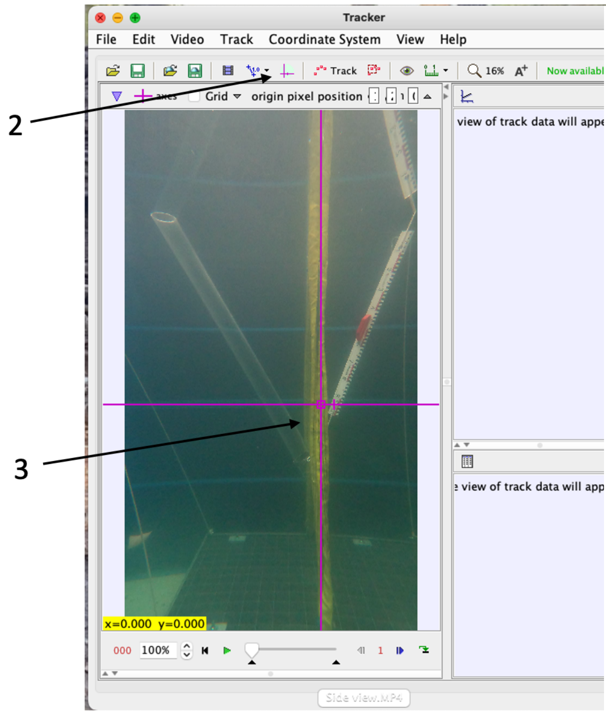
Step 2 & 3: Create x-y axis Step (2) adding x/y axis, this makes it possible for the program to define the position of a particle, difference in position from frame to frame is used to determine velocity and acceleration. The camera filming the setup is placed outside the tank, this causes the light refract and deform the image slightly. Therefore middle-point of the x/y axis is placed near the centre of the image where deformation is minimal(step 2). The axes are aligned with the horizontal and vertical beams in the tank, assuming these are placed in a 90° angle.

Step 4& 5: Create calibration stick A calibration stick is used to define length in the program, the 1 meter ruler is used to define 1 meter in the program. It is important that this calibration stick is in the same plane as the the movement of particle.

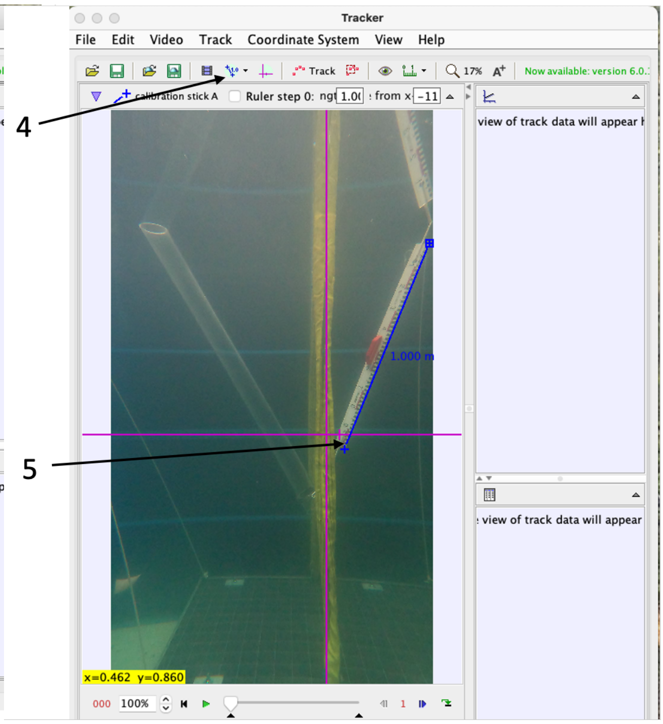
Step 6: Define a point mass Define a point mass to start tracking, in this case particles are so small that point mass is best suited. When zoomed in to one particle, it becomes blurry therefore an outstanding particle is chosen to make it easier to track it every frame. An odd coloured particle is mostly chosen, very dark, very light for example.

Step 7 & 8: start tracking frame by frame Now the file is ready to start tracking a particle, select a particle and select it in the middle holding shift, automatically the next frame will be shown and the particle has moved. Select the particle in the next frame, and continue this process. Every step, automatically the x/y coordinate is reported of the selected point. As the frame-rate is 60 frames per seconds, the program automatically calculated the particle velocity based on the difference in its position. Velocity is calculated and shown on the right of Figure 6-1d, these values can be exported and average velocity can be calculated from all values.

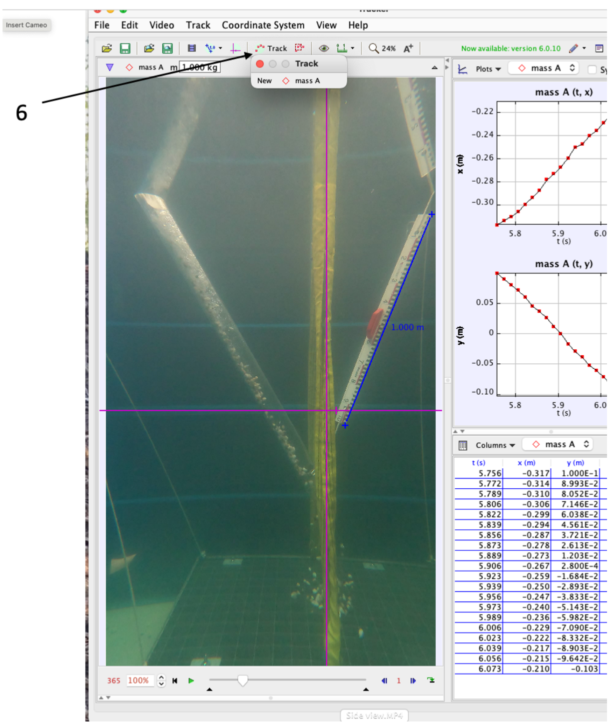
To determine the average particle velocity of a 'run' the following steps are repeated at least 5 times to receive an accurate average velocity.



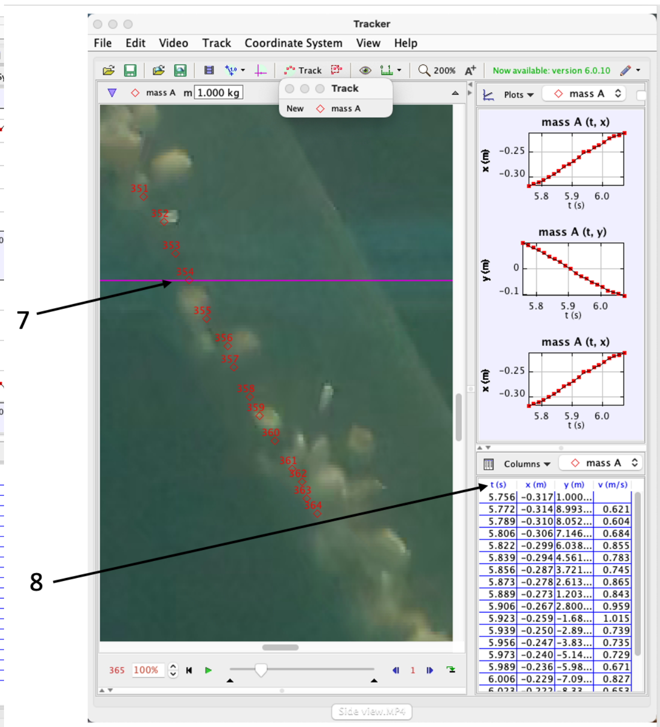
(a) Tracker step 2 and 3



(b) Tracker step 4 and 5



(c) Tracker step 6



(d) Step 7 & 8

Figure 6-1: Explanation using 'Tracker' video analysis software

6-1-2 Calculating remaining variables

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6-1-3 Dispersion results labtest

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6-2 Conclusion of lab research

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6-2-1 Backflow

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6-2-2 Concentration bed or flow is not constant

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6-2-3 Influence of high concentration

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6-2-4 Dispersion of rock

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6-3 Discussion of lab research results

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Chapter 7

Validating models with labtest results

In this chapter, the results from the lab test are compared with the original models in Matlab. First, the sliding bed model is compared. Comparing the results will provides an indication of how far the models are off from reality and eventually implement results to calibrate the models.

7-1 Validation sliding bed model

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7-2 Validation vertical pipe model

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Chapter 8

Model improvement based on lab research

8-1 Sliding bed model 2

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8-2 Vertical fallpipe model 2

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Chapter 9

Conclusion

The main objective of this research is to develop a model that can simulate the most efficient production levels of an inclined fallpipe, used for subsea rock installations.

After initial literature study two models have been developed that model a fallpipe, one simulating a diagonal fallpipe and one simulating a vertical fallpipe. These are the Sliding bed model 1 (SBM1) and Vertical fallpipe model 1 (VFM1). Where Model VFM1 was not designed to be used in other situations than completely vertical flow regimes, model SBM1 assumes particles to operate in the flow regime 'sliding flow' and 'sliding bed'. The use of model VFM1 showed a limitation due to the assumption of only a vertical situation, a fully suspended flow regime. On the other side, it was not clear under which flow angles the SBM1 model would be most accurate.

To gather information about the occurring flow regimes and particle velocity a scale model of a fallpipe was tested in a lab. The measurements and observations of these tests have been used to validate and calibrate the models which had to follow the operating limits and requirements of Great Lakes Dredge & Dock Company, LLC (GLDD). Based on the results of these tests the models were calibrated and Sliding bed model 2 (SBM2) and Vertical fallpipe model 2 (VFM2) have been made.

These final models are able to predict average particle velocity, the SBM2 model can provide particle velocity in 5% accurate from pipe angle 48° up to 86% for rock sizes from 10-25 mm. Smaller diameters that were tested seem to result in a larger deviation. This is best explained by a combination of inaccurate velocity measurements from the video footage due to small particle size and an overestimation of particle density that have thereafter been used in SBM2. The VFM2 provides results within 10% range accurate for a vertical pipe(90°) down to +/- 70°.

Remarkable is the influence of concentration in a vertical fallpipe model, as long as the fallpipe is completely vertical a higher concentration lowers the settling velocity. However, when the pipe is placed in an angle, starting at 87% a higher concentration increases the average particle velocity. When the pipe angle decreases even more, the particles start sliding over the pipe wall. Eventually, at a pipe angle below 60°, the friction force between the pipe and the particles becomes significant slowing it down. The highest velocity is reached at a pipe angle of 60% using 'medium-sized particles. At this angle medium particles still move in a sliding flow regime but are not slowed down significant by wall-friction, resulting in the maximum velocity measured. Furthermore, a reassuring confirmation is that the dimensions of the fallpipes provided by GLDD are large enough to cope with the estimated production limits. The scale model was mostly tested with a production of 0.48 [kg/s] which is comparable with 1850 ton/hour on full scale. Despite being not being validated, using the models SBM2 and VFM2 on lower productions, a credible output is given by the models, both providing a velocity close to single the settling velocity.

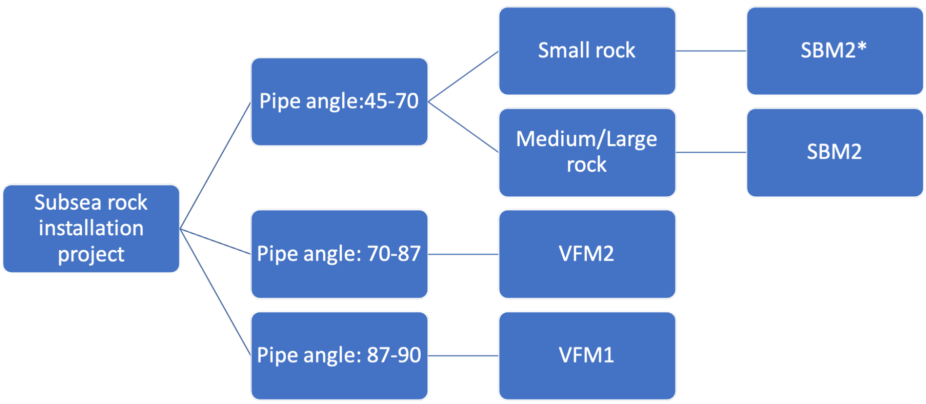
Concluding, this report shows that both the SBM2 and the VFM2 model can provide a good estimation of production levels for a fallpipe (used for subsea rock installations) when used in the correct and representative flow regime. Therefore, these results provide insights that can be used for future subsea rock operations by GLDD.

Chapter 10

Discussion and recommendation

10-1 When to use which model

After comparing the two final models Sliding bed model 2 (SBM2) and Vertical fallpipe model 2 (VFM2) with the results from the experiment done in the lab research, it became clear that each model operates optimally in certain situations. To decide which model to use at which pipe angle for which particle size, the flowchart in Figure 10-1 provides an overview.



* Using small rocks in SBM2 is not accurate and not validated

Figure 10-1: Model advise flowchart

10-2 Different production

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10-3 Scaling models to full scale

It is expected that VFM2 can be scaled without problems as it is built based on the single particle settling velocity. In this equation, particle size is used in the equation for a single settling velocity. Variables that need attention before scaling VFM2: Drag coefficient (C_D) 1-2 for gravel $\rightarrow$ if using rough mined rock this value would be around 2[Miedema, b].

In contrast to SBM2, where particle size does not play a significant role in calculating particle velocity. Also, it can be that a drag force must be added to SBM2, as the particles are scaled, so does the velocity. Due to the low concentrations in the fallpipe that Great Lakes Dredge & Dock Company, LLC (GLDD) will probably using, a sliding bed does not occur. Therefore the rocks falling/rolling true the pipe will experience frontal drag force. These forces are not taken intoo account. As this force increases to a 2nd power as velocity increases($F_{drag} = 0.5 \cdot C_D \cdot A \cdot V^2$), it can be that this did not play a role in a scale model but does have significant influences at full scale.

Appendix A

The back of the thesis

A-1 Settling velocity in more detail

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A-2 Sliding bed formulas derived

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A-3 Rewriting the equilibrium

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A-4 Additional images lab research setup

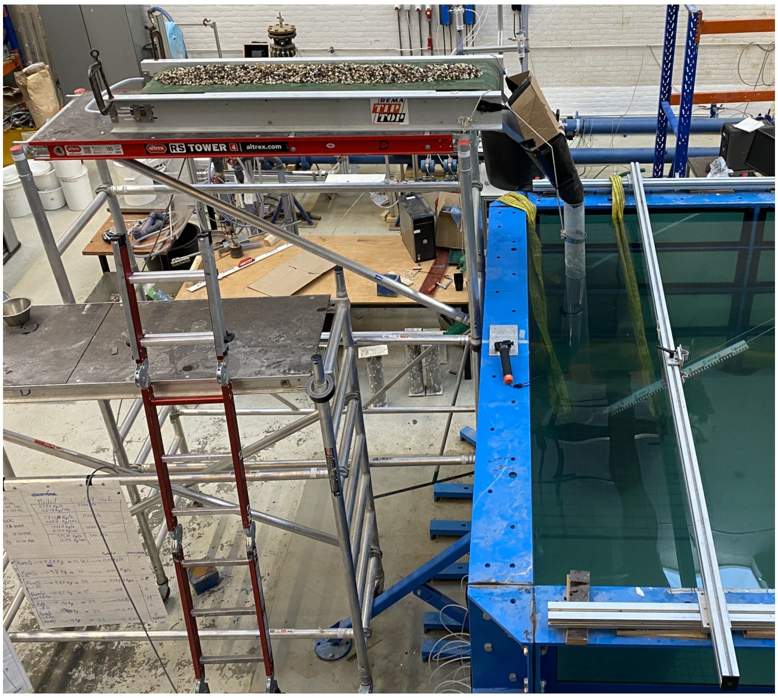

Figure A-1: Lab setup scaffolding with conveyor belt

Figure A-2: Lab setup conveyorbelt

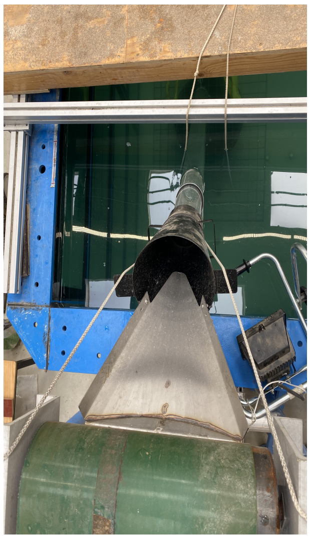

Figure A-3: Lab setup funnel feeding the fallpipe

A-5 Remarkable observations lab research

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A-6 Spread of rock

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A-7 Observation of flow regime labresearch

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Appendix B

Sliding bed model 1 code

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Appendix C

Sliding bed model 1 code: rewritten

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Appendix D

Sliding bed model 2 code

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Appendix E

Sliding bed model 2 code:rewritten

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Appendix F

Vertical model fallpipe code 1

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Appendix G

Vertical model fallpipe code 2

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. Glossary

List of Acronyms

IFP	inclined fall pipe
GLDD	Great Lakes Dredge & Dock Company, LLC
SBM1	Sliding bed model 1
SBM2	Sliding bed model 2
VFM1	Vertical fallpipe model 1
VFM2	Vertical fallpipe model 2

List of Symbols

A_1	Cross-section surface water in pipe $[m^2]$
A_2	Cross-section surface bed pipe $[m^2]$
c_{vb}	volumetric concentration of bed[-]
i	Hydraulic gradient [-]
c	volumetric concentration[-]
F_l	Durand and Condolios Limit Deposit Velocity coefficient
L_{pipe}	Length pipe [m]
n	Hindered settling exponent
F_W	Weight bed [KN]
$F_{1,fl}$	Force between fluid and pipe wall [KN]
$F_{12,fl}$	Force between fluid and bed [KN]
$F_{2,fl}$	Force on bed due to pore fluid [KN]
$F_{2,fr}$	Force on bed due to friction[KN]
F_W	Weight bed KN
O_{12}	Width contact bed/water in pipe $[m]$
O_1	Contact arc-length water and pipe $[m]$
O_2	Contact arc-length water and pipe $[m]$
P_i	Production in fallpipe$[kg/s]$

P_o	Production out fallpipe $[kg/s]$
V_m	Mixture velocity
V_{sl}	Slip
V_s	Solid velocity
c_{vs}	Spatial volumetric Concentration [-]
c_{vt}	Delivered (transport)volumetric Concentration [-]
d_{50}	Mass median diameter [m]
u_ω	Velocity of water $[m/s]$
u_p	Velocity of Particle $[m/s]$
u_*	Friction velocity $[m/s]$
β	Angle of the bed $[rad]$
λ_w	Ratio diameter rock and pipe [-]
λ_{12}	Moody friction factor on bed [-]
λ_2	Moody friction factor on pipe wall [-]
ν	Kinematic viscosity water $[m^2/sec]$
ω_s	Hindered settling velocity of particle $[m/s]$
ρ_l	Density of liquid$[kg/m^3]$
ρ_s	Density of solid $[kg/m^3]$
$\tau_{1,fl}$	Shear stress from between fluid and pipe wall above bed [kPa]
$\tau_{12,fl}$	Shear stress bed-fluid [kPa]
$\tau_{2,fl}$	Shear stress from fluid in between bed and pipe wall [kPa]
$\tau_{2,fr}$	Shear stress from sliding friction bed and pipe wall [kPa]
ε	Pipe wall roughness [m]
w_0	Single particle settling velocity $[m/s]$
$w_{0,p}$	Hindered by wall fallpipe settling velocity$[m/s]$