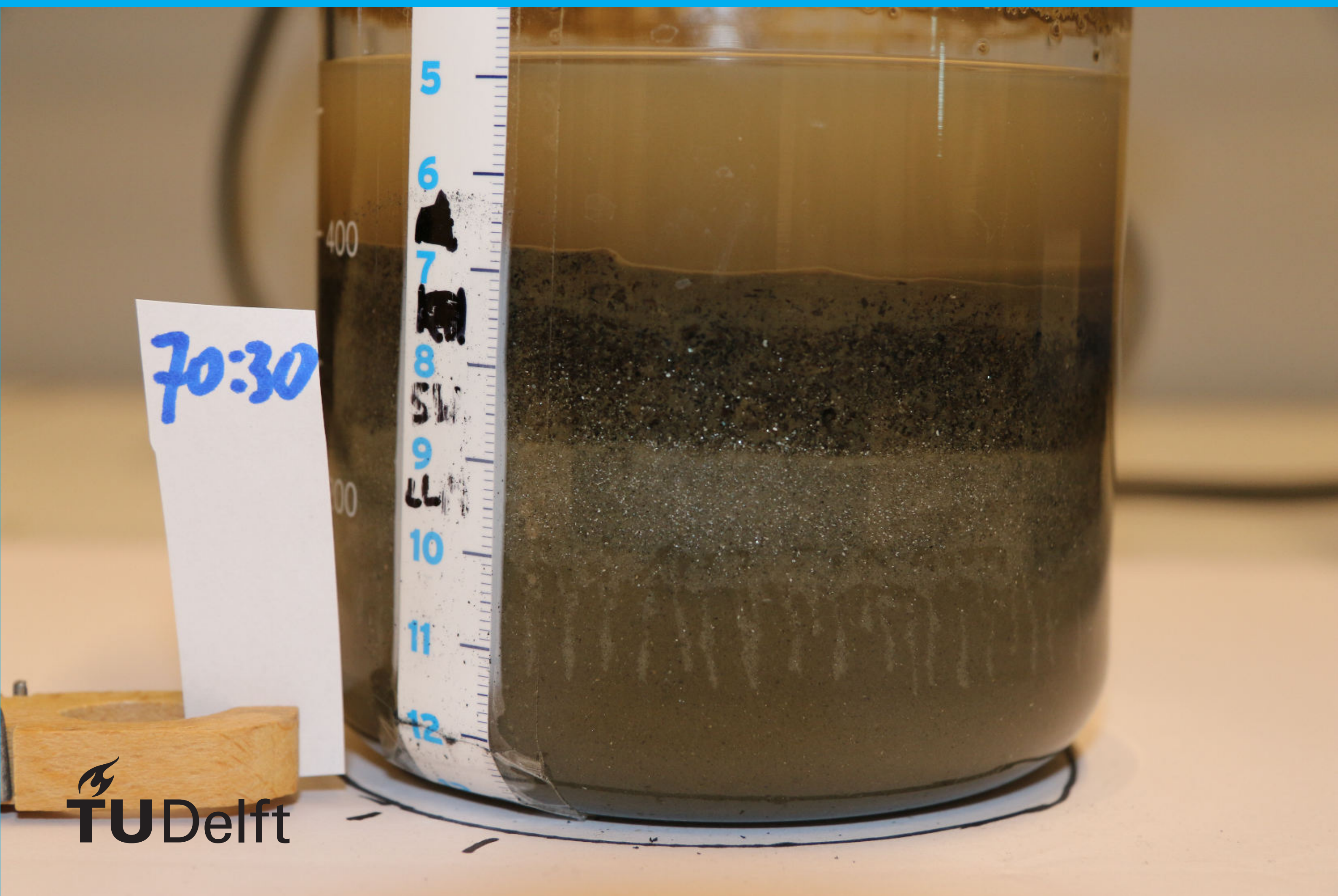
Effect of movement on the settlement of fluid mud

A bachelor end project

L. Pleij



TU Delft

Effect of movement on the settlement of fluid mud

A bachelor end project

by

L. Pleij

to obtain the degree of Bachelor of Science
at the Delft University of Technology,
to be defended publicly on Monday May 20, 2019 at 09:30.

Student number:	4333217	
Project duration:	March 11, 2019 – May 20, 2019	
Thesis committee:	Dr. J. Gebert,	TU Delft, supervisor
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	Florian Zander,	TU Delft
	Ahmad Shakeel,	TU Delft
Acknowledgements:	Deltares,	For making their lab available

TU Delft

Contents

1 Introduction

The Port of Rotterdam in the Netherlands had channel depths of 9.8 m in the 1940s. With the rapid pace of growth in vessel size in the 1960s and 1970s, the least depth was increased to 24 m and it developed into the biggest port in the world. The annual need for mud maintenance dredging was 20 million t/year by 1970.[4] Dredging is an ongoing process in ports and canals and it is very expensive. For example, fluid mud occurs in ports and channels along the total U.S. coastlines and it accounts for a significant portion of the United States' $1 billion dredging expense.[4] Still it must be done because ships that have more cargo lie deeper and will need a deeper canal. But researches have shown that sometimes dredging is done unnecessarily.

A physical density up to 1.25 t/m3 allows ships to manoeuvre without difficulty in the Harbour of Emden.[6] Other investigations (Vantorre, 1994) have shown that ships can sail through mud layers with densities varying between 1.15kg/l and 1.24kg/l to 1.3kg/l [2]. So apparently the nautical depth is not defined by the beginning of a layer of sediment or its density.

1.1. Nautical depth

According to PIANC (1997) the nautical depth can be defined as 'the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and manoeuvrability.' Accordingly, nautical depth can be defined as: the instantaneous and local vertical distance between the nautical bottom and the undisturbed free water surface. [2]

This ”nautical depth” used to be determined with a lead line. With this method, the depth was recorded to the fairly solid bottom and any overlying mud layer was usually not detected. By introducing echo sounders, the water-mud interface was not always clearly defined. [2]

The case is that ships are able to sail through fluid mud since its physical properties do not reach the critical limits to damage the ship's keel or make the ship uncontrollable. Researchers are still investigating these critical limits and when fluid mud is safe and unsafe to sail through. According to the latest investigations, the nautical depth can best be defined by a physical parameter as the yield point (yield stress). [2] This means that the nautical depth is in a lot of cases not well determined when using echo sounding methods. Since it only takes density into account. Research shows that echo soundings with 12-5 kHz come closest to nautical bottom defined with rheological parameters. While other echo sounding methods are defined as not suited.[6] It can be concluded that echo sounding methods are not suited for finding the nautical bottom since they do not give information about the yield point of the mud. In most cases ships cannot sail through mud because its yield point and density is too high. There is a type of mud that is an exeption. This type of mud is called ”fluid mud”.

1.2. Fluid mud

Very often (depending on the season) fluid mud can be found on the bottom of water bodies. Fluid mud contains a lot of organic material that creates microbial slime. This slime separates the particles which reduces the friction between particles and causes the particles to stay into suspension longer. Because the slime has a lower density, it also reduces the density of the fluid mud as a whole. [6] Fluid mud will settle over time. This causes the density and yield point to grow and after a certain time the fluid mud will not be navigable any longer.

To increase the nautical depth, or to prevent the nautical depth from decreasing, ports can prevent the need of dredging. Fluid mud has such properties that it settles slower than other types of sediments. These properties can be used to keep the fluid mud suspended, or resuspend the material after it has settled. It is expected that kinetic energy could keep fluid mud suspended. The purpose of my research is to find the amount and type of kinetic energy that is needed to keep fluid mud suspended. This knowledge could also tell port authority's somethings about how fluid mud is formed.

1.3. Research question

How does kinetic energy have an influence on fluid mud?

1.3.1. Hypothesis

Fluid mud that contains kinetic energy will settle at a slower rate than fluid mud that contains no or less kinetic energy.

1.4. Subquestion

1. How much kinetic energy must the fluid mud have to stay suspended?
2. How does the density of fluid mud effect its settling rate?

1.4.1. Hypothesis

1. The fluid mud settles very slow. The presumption is that the fluid mud will need very little kinetic energy to stay suspended.
2. A lower density will cause the fluid mud to settle faster.

2
Materials and Method

In this section the main experiment is described. All the foundings and results of pre-research 1 and pre-research 2 have been used to develop this method. Pre-research 1 and pre-research 2 can be found in the Appendix.

2.1. Materials

- Measuring beaker 1L
- Shaker
- Good quality camera
- Measuring tape
- Tape
- Beater
- Ladle
- Silicone spatula
- Cooling cell
- Plastic foil
- Rubber bands
- At least 6 L of sample
- Pincers
- Pen
- Paper
- Density meter
- Particle size meter (mastersizer 2000)
- Metal stirring stick

Figure 2.1: Sample locations. Source: Hamburg Port Autorities (HPA).

2.2. Samples

The samples have been obtained from the port of Hamburg. SW and KH both stand for a specific place in that port. See figure 2.1.

The samples have been obtained by HPA in collaboration with Julia Gebert and Florian Zander. HPA goes by boat to the locations. With the help of GPS they are able to choose a location with an accuracy of several centimetres. HPA is able to obtain sample material from the exact same location every time.

When the boat has arrived at the location a sample is taken out of the bottom of the canal using a cylindrical container. On the bottom of the container is a metal plate that can be opened and closed. When the container is filled the sample material is separated manually. On top of the sample material is water. This is extracted with a pump. Afterwards the metal plate on the bottom of the container is opened and closed to drop a part of the sample material into a bucket. The sample material is divided over several buckets. These buckets are sealed air tight and can later be used for experimenting. Because sedimentation can be different every day, the sample material will almost never be the same.

For the main research, fluid mud of locations SW and KH have been used. The fluid mud is the upper most layer of the sample material that is extracted from the bottom of the canal. Because the sample is distributed immediately, the mud is still in suspension. This causes the sample to resemble as much as possible the fluid mud that can be found in the canal.

2.3. Preparation of the samples

The samples have been obtained from the port of Hamburg. The locations were KH and SW (see figure 2.1). To be sure that the samples are the same for every experiment, they have been homogenised for several minutes with a beater and spatula. When the samples are fully fluid and smooth, they are poured into buckets with a ladle. The ladle is used to stir the sample continuously while being poured. In this way the sample stays homogenized during the process. The sample material from KH is divided over 4 buckets and the material from SW is divided over 3 buckets. The material from KH contained about 10,5 L of fluid mud and the material from SW contained about 5,5 L of fluid mud. The samples have been preserved below 10° Celcius. Every day one bucket of material had to be taken out of the frigidaire to set up the experiment. Most of the sample material has been in the firigidaire for most of the 4 weeks time. The homogenization process of the sample was always the same. First the sample was homogenized with a beater and spatula until it was entirely smooth. Then a ladle was used to keep the fluid mud turbulent and to scoop it into the designated container.

2.4. The experiment

Measuring tape is stuck on the side of the measuring beaker. On the tape a code is written that explains the type of experiment. First the sample area is noted, then the dilution type and then the shaking frequency. For example KH N LLM stands for area KH dilution type Normal (not diluted or thickened) and Low Low Medium. Every time a picture is taken, a note on the side indicates the time that has passed.

During the day a picture is made every half hour. The reason why half an hour is chosen is that the sample has to be taken out of the shaker every time a picture is taken. The sample has to be placed on the table so that the picture can be taken. Taking a picture in this way disturbs the movement of the sample. The last picture is taken at around 19:00 in the evening just before the lab closes. The next morning the last result is documented. A sample is taken from every layer and the experiment will be repeated with a different kinetic energy.

2.5. Density, particle size, Rheology and loss of ignition (LOI)

The sample of a certain layer will be homogenised by intensive stirring with a metal stirring stick. When the sample is smooth and homogenized the density will be measured with a density meter. The density meter extracts a tiny amount of fluid mud for its measurement.
When the density has been measured the sample will be put dropwise into the measuring beaker of the mastersizer. The mastersizer is used to measure the particle size. When the particle size has been measured the mastersizer is rinsed at least 4 times. The density meter is cleaned after every measurement by rinsing it with tap water 3 times and then with demi water 3 times.
At the end of the research the thickness, density and mean particle size of every layer has been measured. Of all layers of one experiment the LOI and Rheology has been measured.

3

Results

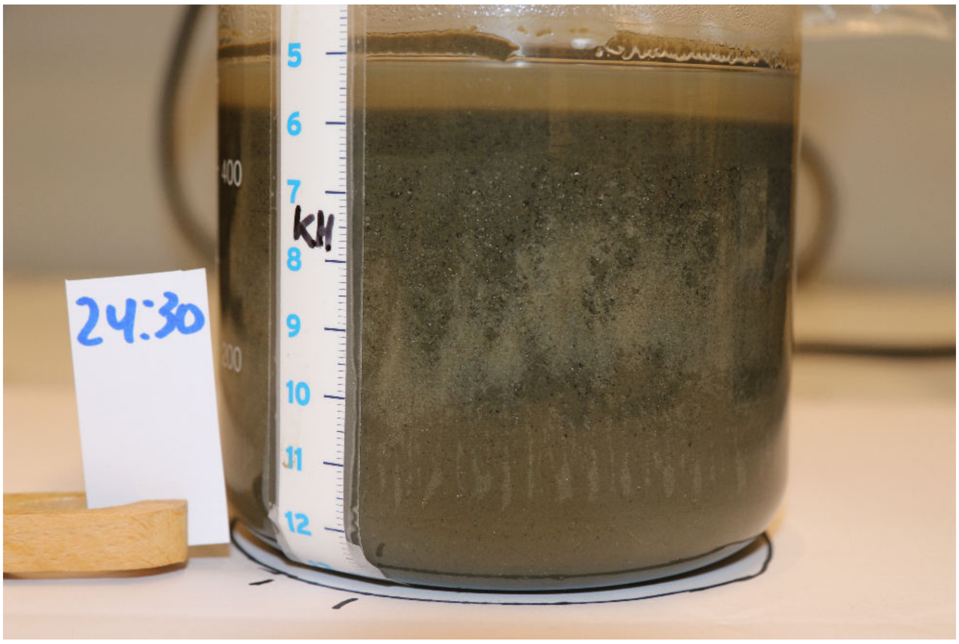

Figure 3.1: A sample from site KH after it experienced the lowest level of kinetic energy for 24.5 hours

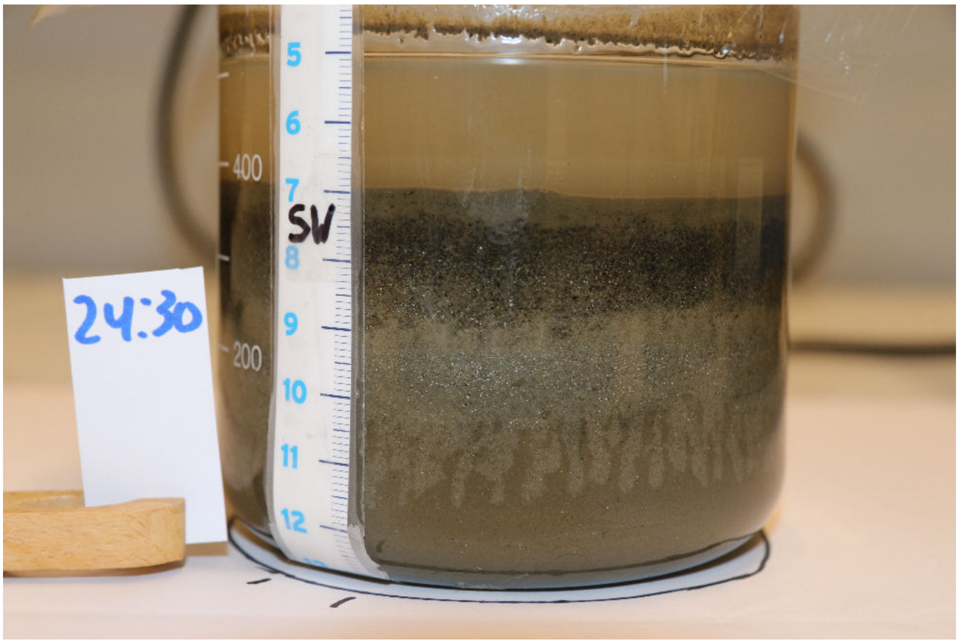

Figure 3.2: A sample from site SW after it experienced the lowest level of kinetic energy for 24.5 hours

3.1. Rate of settlement

Picture 3.3 and 3.4 show the amount of settlement over time. Each code represents an experiment. The first part is the sample material, the second part is the dilution type and the third part is the kinetic energy level. For example KH N L(1) is the sample material from site KH. It was undiluted so the density was normal (N) and the kinetic energy was low, which I abbreviated with an L. I added a number for every kinetic energy level to make that part more clear. Level 0 had no kinetic energy and level 6 had the highest kinetic energy.

Table 3.1: This table describes the meaning of the first two parts of the code that has been written on the samples

Location	N	LD
SW	As received $1.1717\ g/cm^3$	Diluted with supernatant water $1.08\ g/cm^3$
KH	As received $1.1467\ g/cm^3$	Diluted with supernatant water $1.08\ g/cm^3$

Table 3.2: This table describes the meaning of the last part of the code that has been written on the samples

Energy level	0	1	2	3	4	5	6
	control sample, no energy input	Amplitude ~2 mm, frequency ~95 rpm	Amplitude ~4 mm, frequency ~98 rpm	Amplitude ~7 mm, frequency ~99 rpm	Amplitude ~8 mm, frequency ~100 rpm	Amplitude ~10 mm, frequency ~102 rpm	Amplitude ~15 mm, frequency ~105 rpm
name	C	L	LLM	LLLMM	LLMM	LM	M

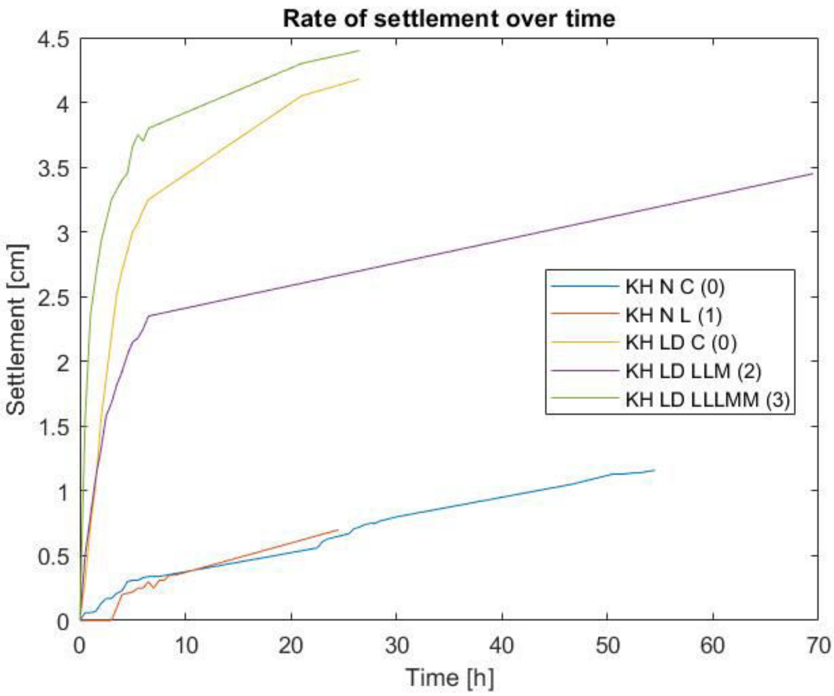

Figure 3.3: Amount of settlement over time of the samples from site KH

Figure 3.3 shows 3 things:
Normal density: Kinetic energy does not influence the amount of settlement over time.
Lower dilution: Kinetic energy influences the amount of settlement over time, but there is no pattern.
A lower diluted sample will have a greater settlement over time than a undiluted sample.

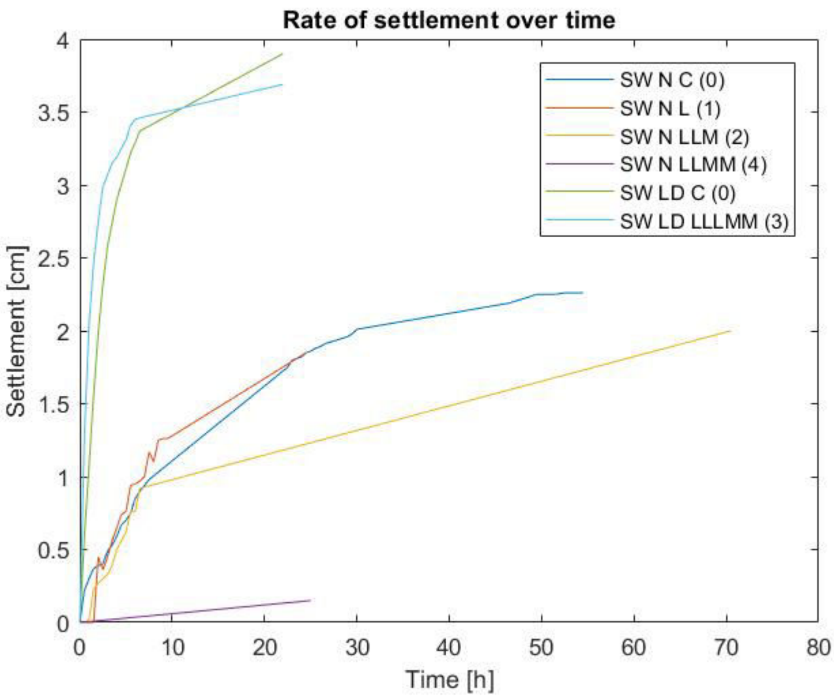

Figure 3.4: Amount of settlement over time of the samples from site SW

Figure 3.4 shows 3 things:
Normal density: Kinetic energy does not influence the amount of settlement over time.
Lower dilution: Kinetic energy influences the amount of settlement over time.
A lower diluted sample will have a greater settlement over time than a undiluted sample.

SW N LLMM (4) is the sample that just settled. Energy level 4 was the least amount of kinetic energy needed to keep the sample material suspended for 24 hours.

The density of the sample from site KH is 1.1467 g/cm^3 and the density of the sample from site SW is 1.1717 g/cm^3. The density of the sample from site KH is lower and its settlement was slower.

Figure 3.5 and 3.6 show the settlement velocity of site KH and SW respectively. The data from the first part of the experience has been used to create this graph so that the influence of compaction could be neglected. The graphs show that the settlement velocity of all the undiluted sample material is about the same. The settlement velocity of diluted sample materials will change when kinetic energy in the form of shaking is applied.

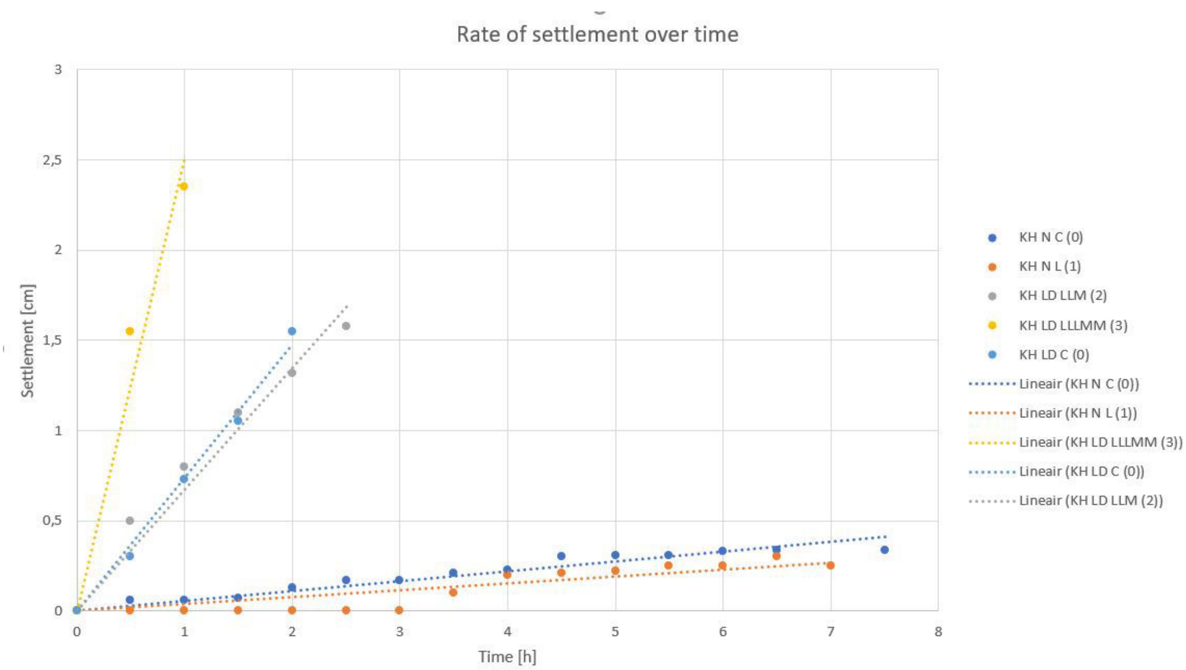

Figure 3.5: Velocity of settlement during sedimentation from site KH. The data of the first part of the experiment was used so that compaction would not have an influence yet.

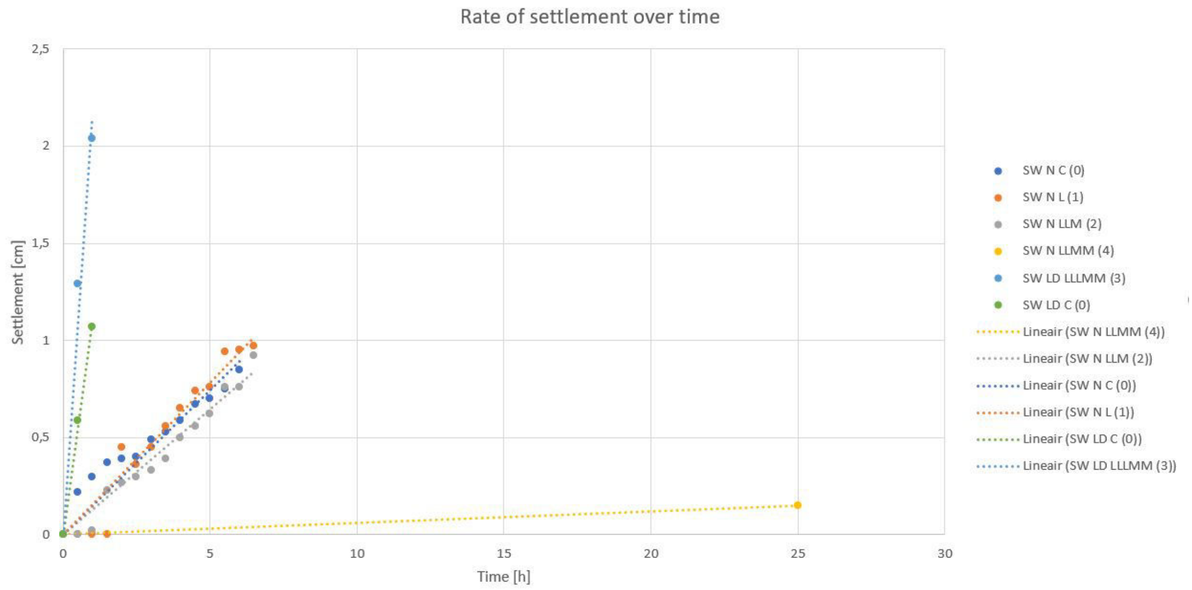

Figure 3.6: Velocity of settlement during sedimentation from site SW. The data of the first part of the experiment was used so that compaction would not have an influence yet.

3.2. Fingers

On the lower part of the sample material, there is a formation of “fingers”. Two different type of sediments form finger shaped vertical pipes. The formation of fingers is stronger in the samples that experienced lower kinetic energy.

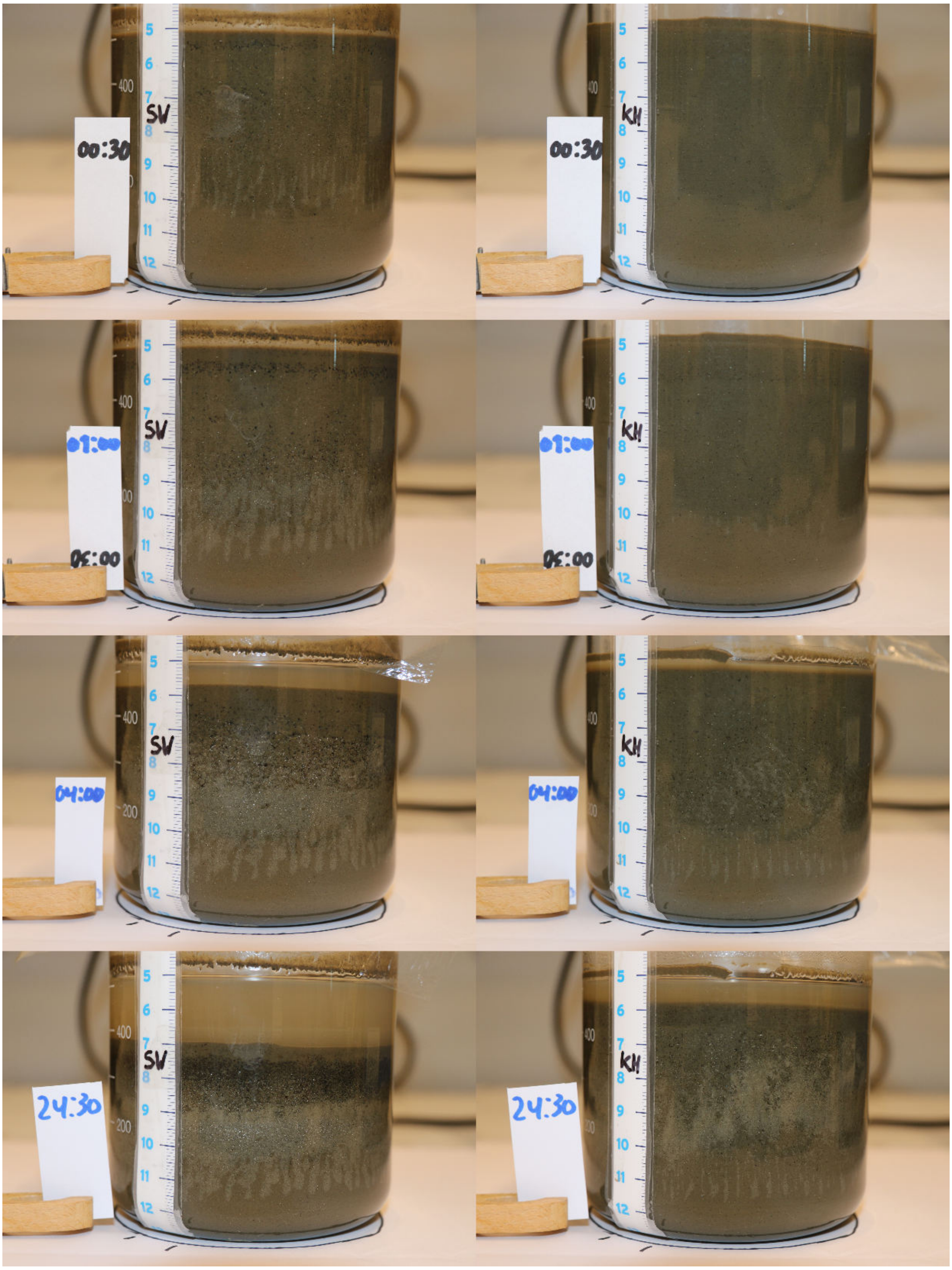

Figure 3.7: A small timelapse of how these “fingers” form when the sample experienced the lowest kinetic energy level, which was level 1. On the left, the time is noted with a marker on a paper.

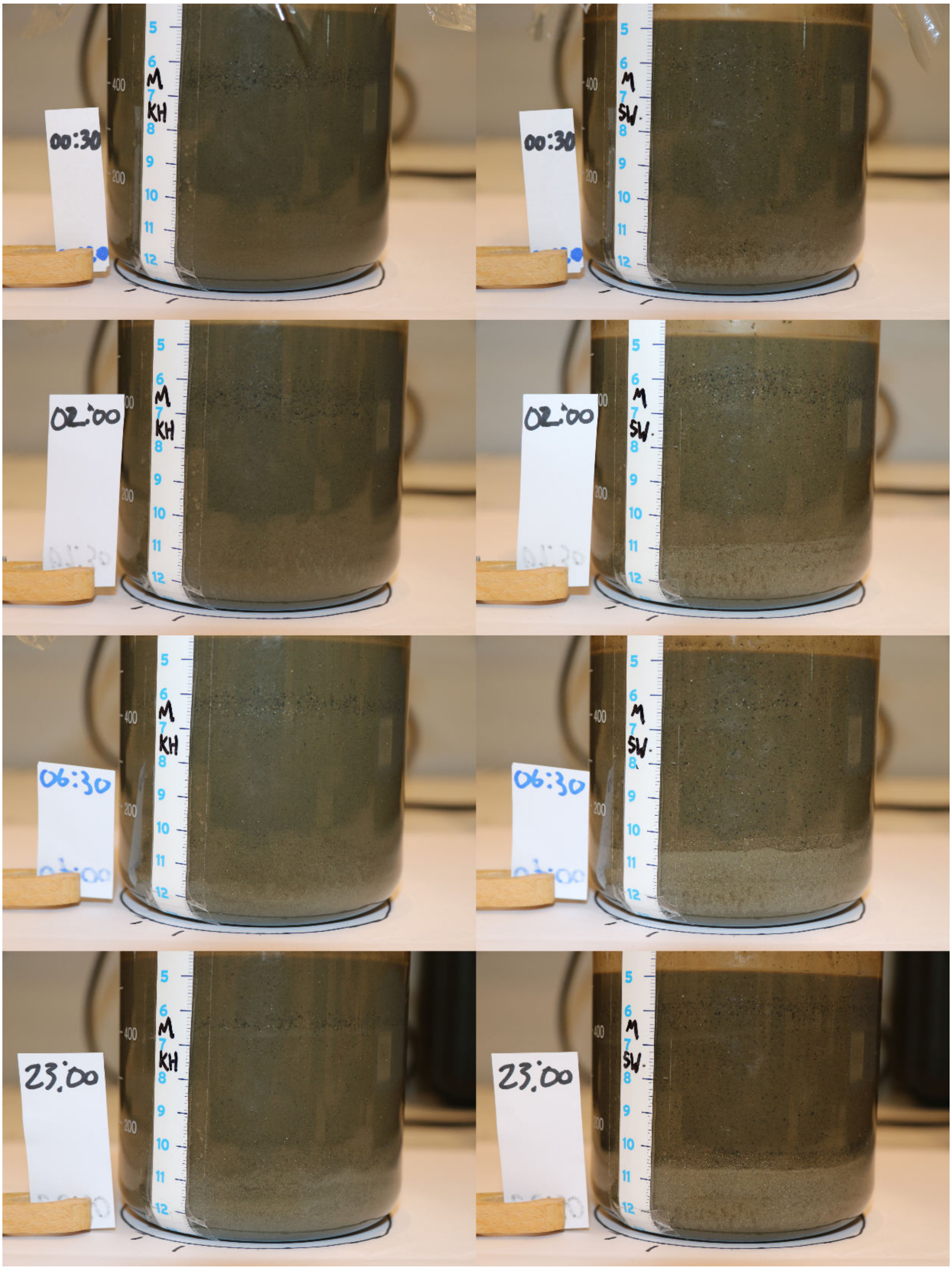

Figure 3.8: A small timelapse of how these “fingers” form when the sample experienced the highest kinetic energy level, which was level 6. On the left, the time is noted with a marker on a paper.

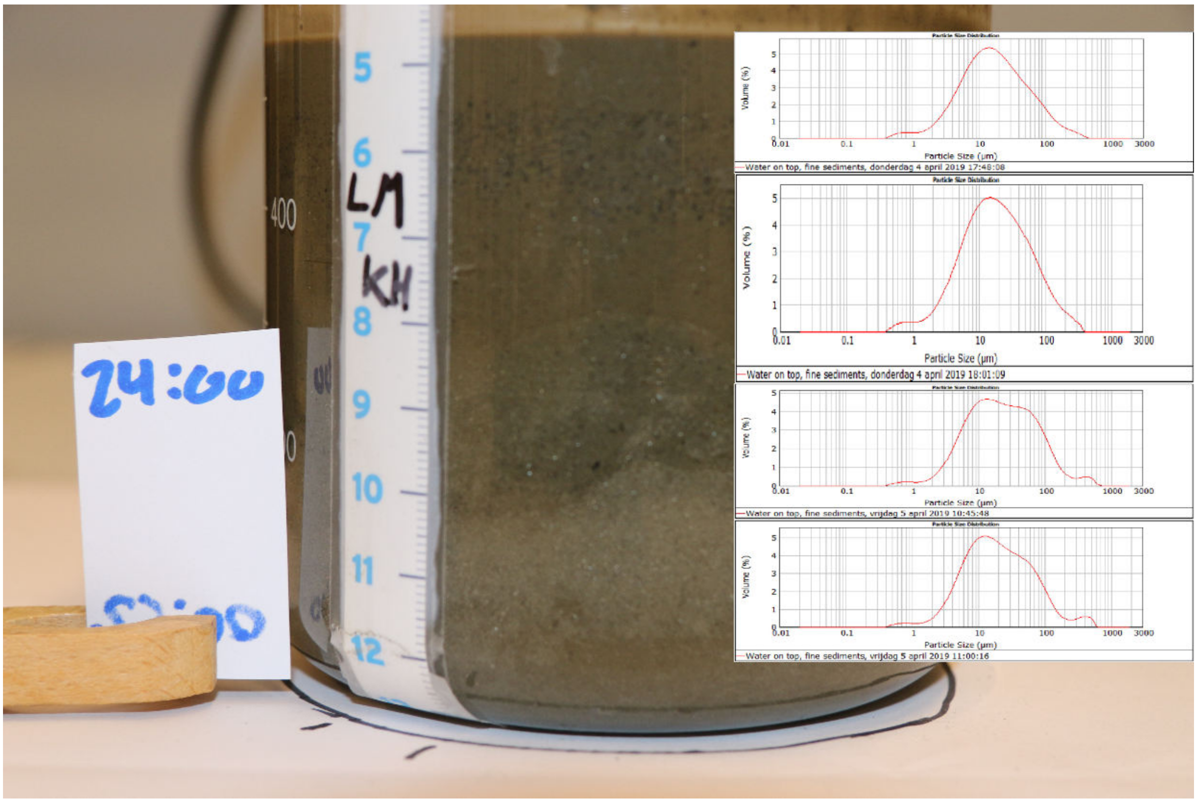

Figure 3.9: A photo of a sample from site KH (KH N LM (5) after it experienced kinetic energy level 5 for 24 hours. The particle size plots of every depth have been added on the right. The sample that is extracted for this particle size analyzation is extracted at the same height as where the plot is shown.

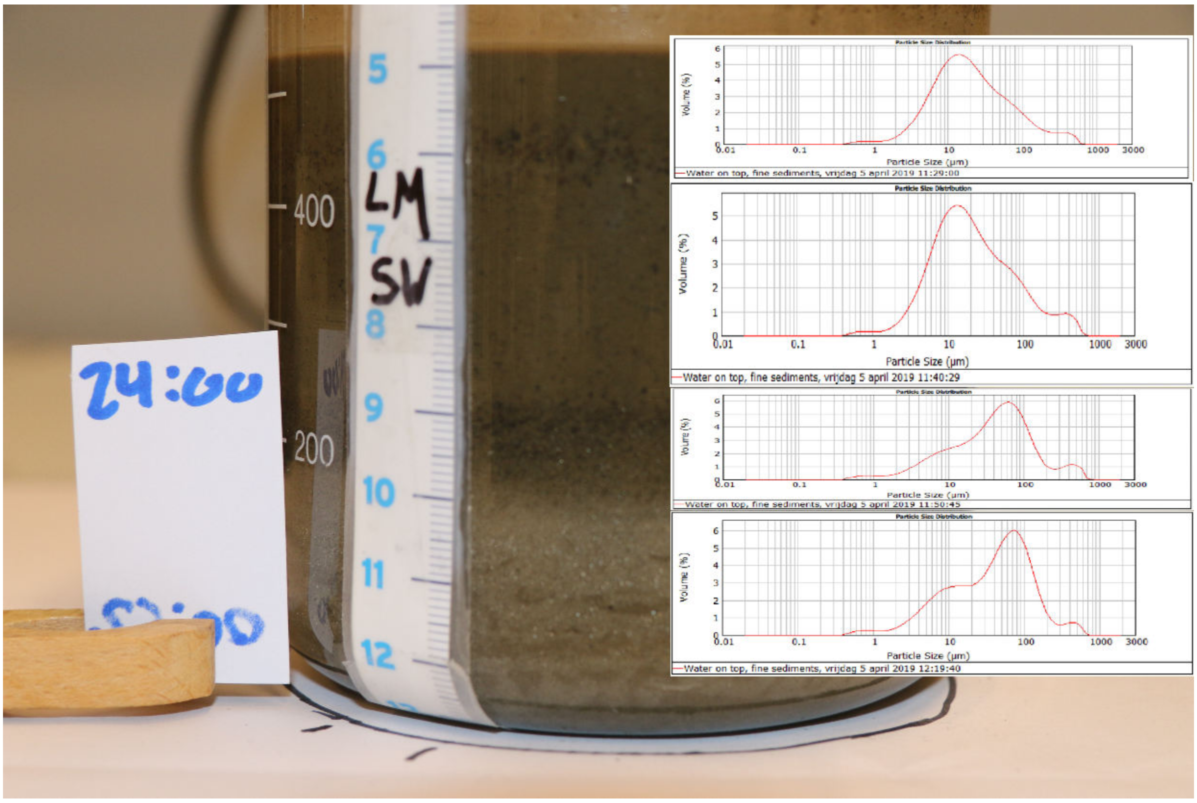

Figure 3.10: A photo of a sample from site SW (SW N LM (5) after it experienced kinetic energy level 5 for 24 hours. The particle size plots of every depth have been added on the right. The sample that is extracted for this particle size analyzation is extracted at the same height as where the plot is shown.

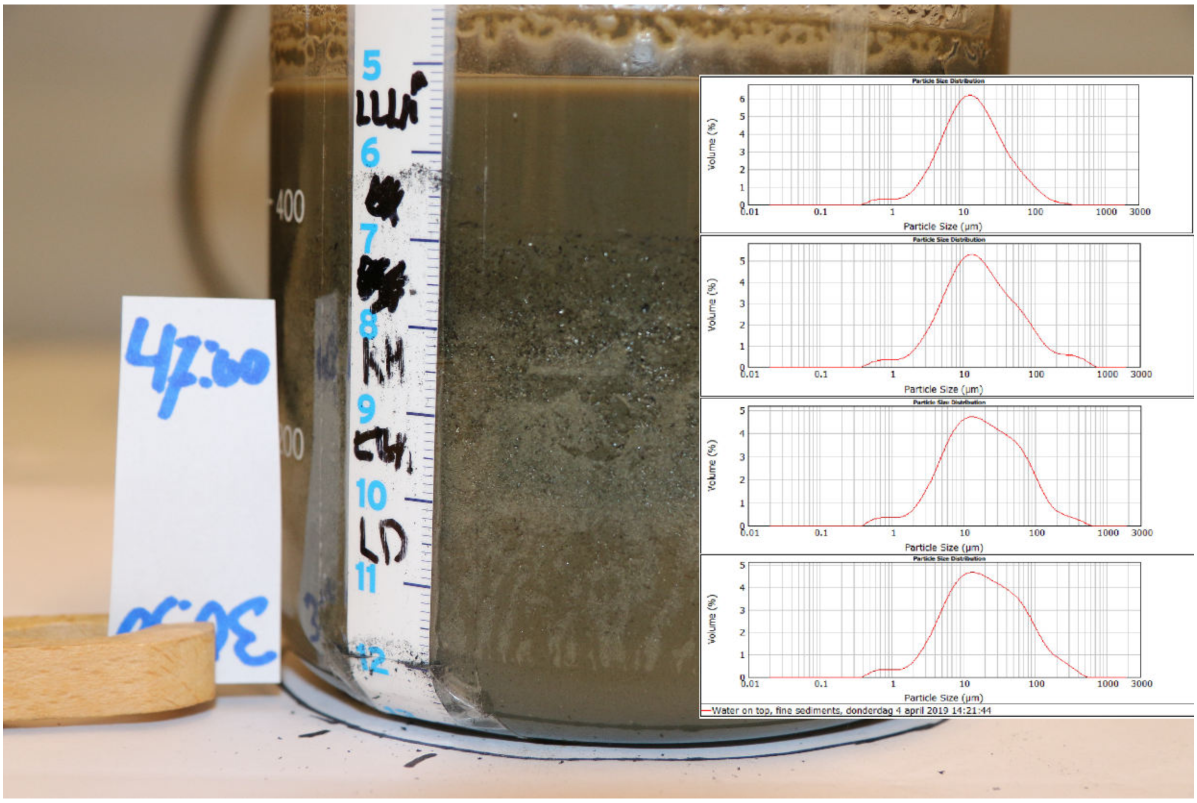

Figure 3.11: A photo of a sample from site KH (KH N LLLMM (3) after it experienced kinetic energy level 3 for 47 hours. The particle size plots of every depth have been added on the right. The sample that is extracted for this particle size analyzation is extracted at the same height as where the plot is shown.

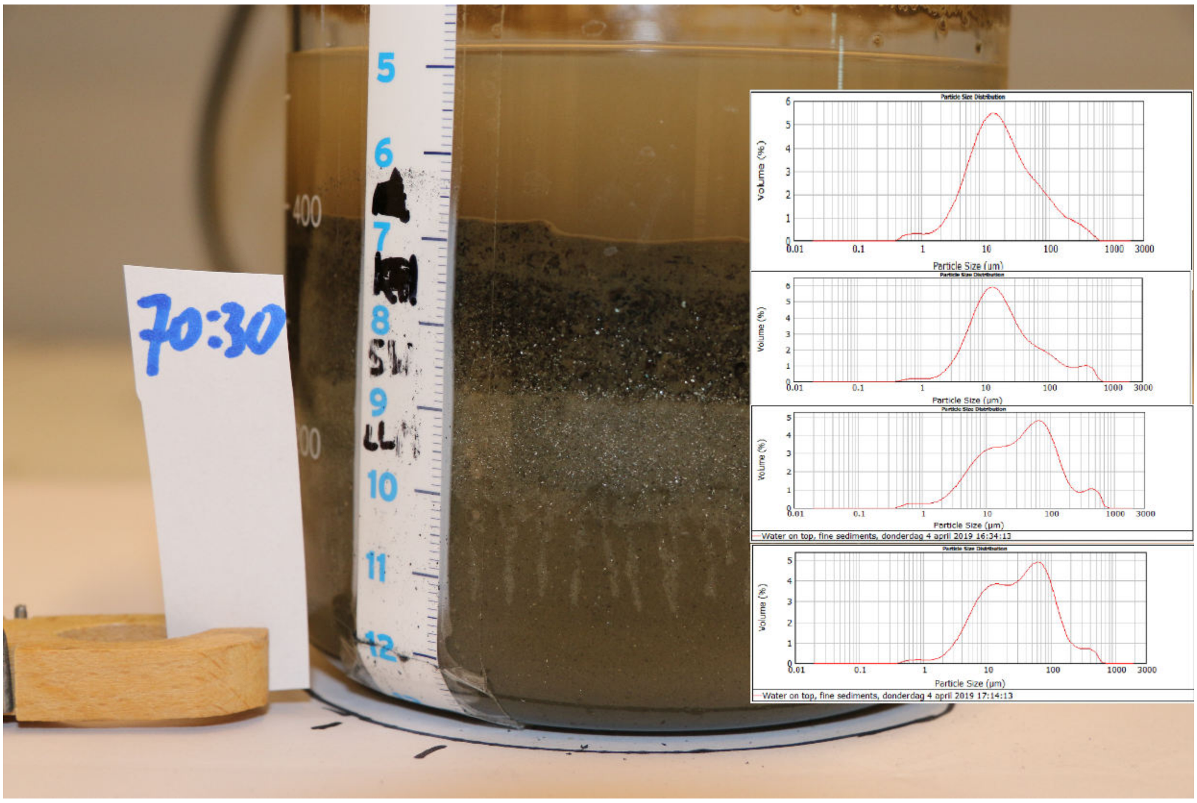

Figure 3.12: A photo of a sample from site SW (SW N LLM (2) after it experienced kinetic energy level 2 for 70.5 hours. The particle size plots of every depth have been added on the right. The sample that is extracted for this particle size analyzation is extracted at the same height as where the plot is shown.

3.3. Density and particle size plots

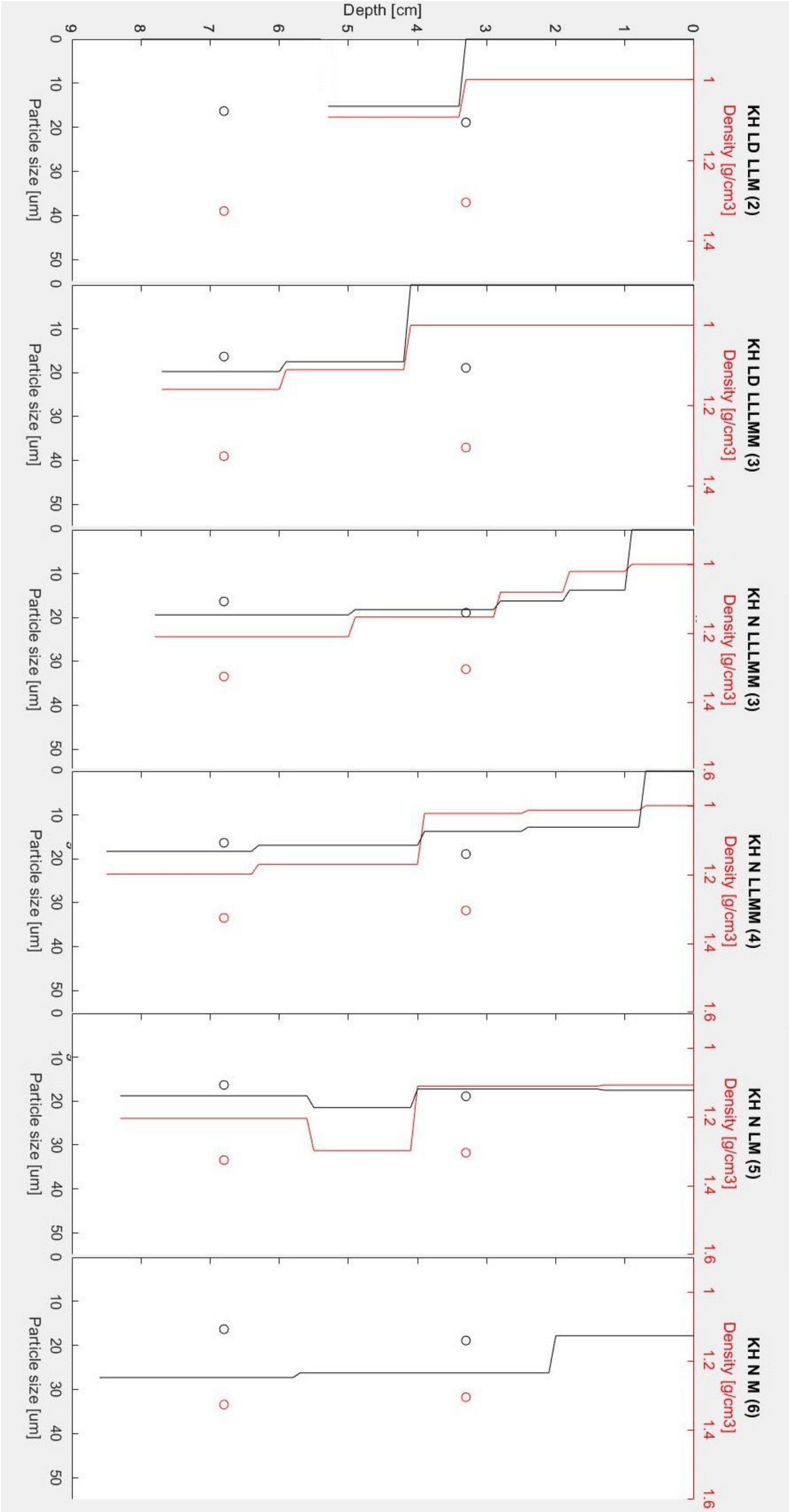

Figure 3.13: Density and particle size plot of the samples from site KH. These plots show the density and mean particle size of the sample over its depth. The small circles show the mean particle size and density of the control sample.

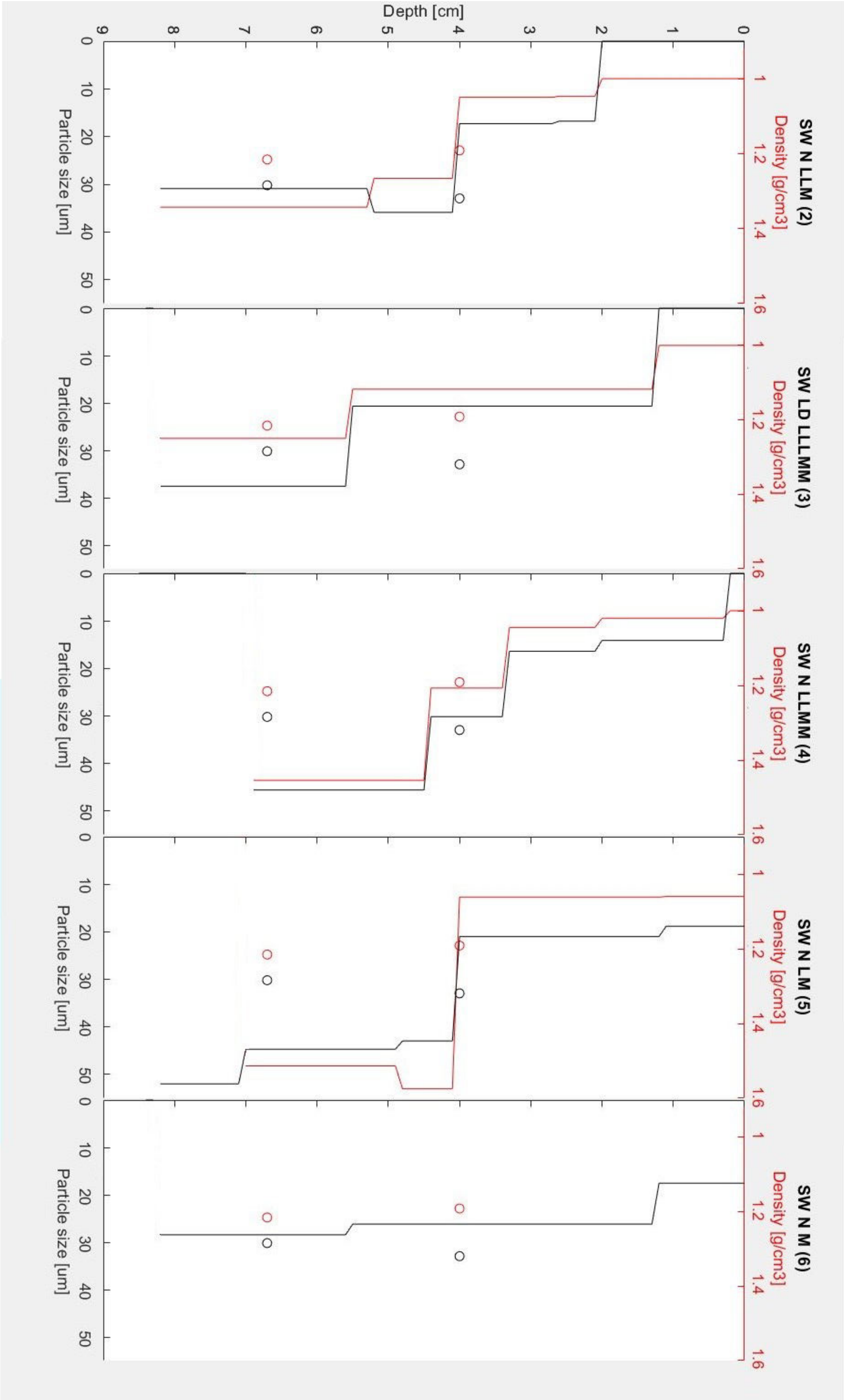

Figure 3.14: Density and particle size plot of the samples from site SW. These plots show the density and mean particle size of the sample over its depth. The small circles show the mean particle size and density of the control sample.

Figure 7.1 and 7.2 show that the mean particle size and density of the samples, from both sites SW and KH, increase over depth after exposure to kinetic energy. The density and particle sizes were measured from the layers of the sample material that had formed after the exposure to kinetic energy. More information about these layers can be found in the appendix.

The control samples, of both KH and SW, show that when a sample has settled unexposed to kinetic energy, the mean particle size and density do not vary significantly over depth.

3.4. Loss on ignition

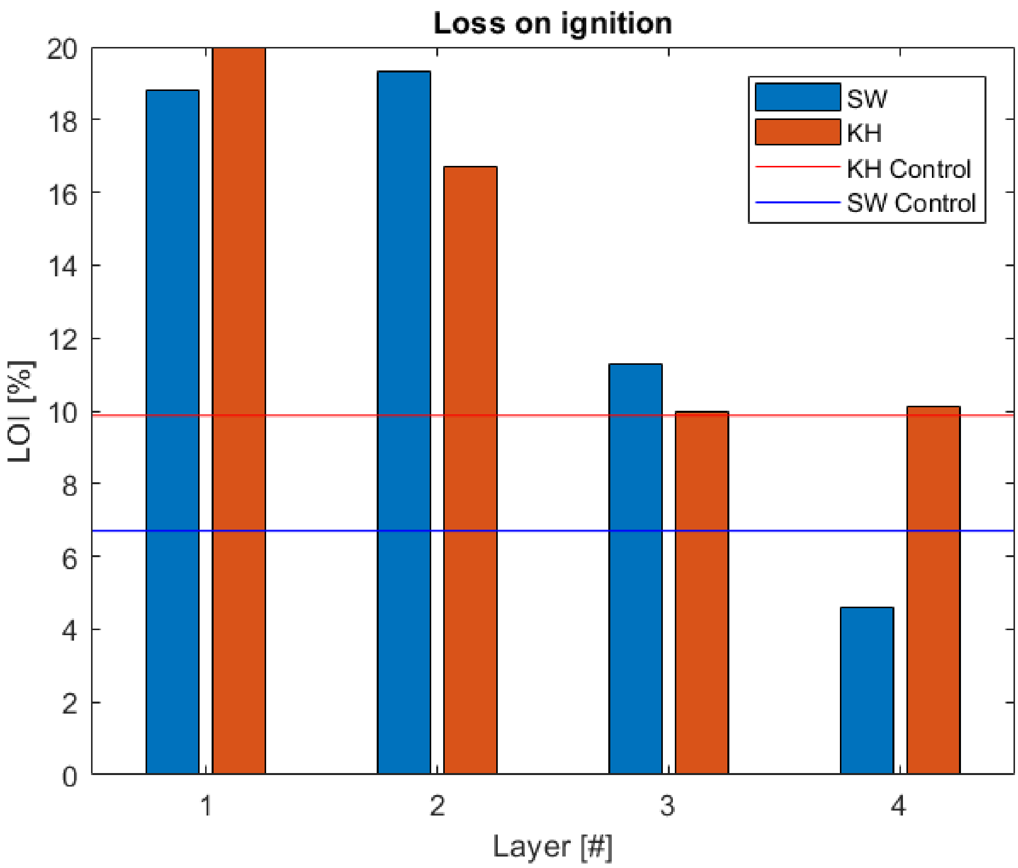

Figure 3.15: Loss on ignition of layer 1 to 4 of the samples that experienced kinetic energy compared with a homogenised control sample that experienced no kinetic energy

The loss on ignition (LOI) is a test that shows the percentage of mass of the sample that is organic. The two bars in the middle are the control samples. As can be seen, there is more organic material in the top layers of the sample, than there is organic material in the bottom layers.

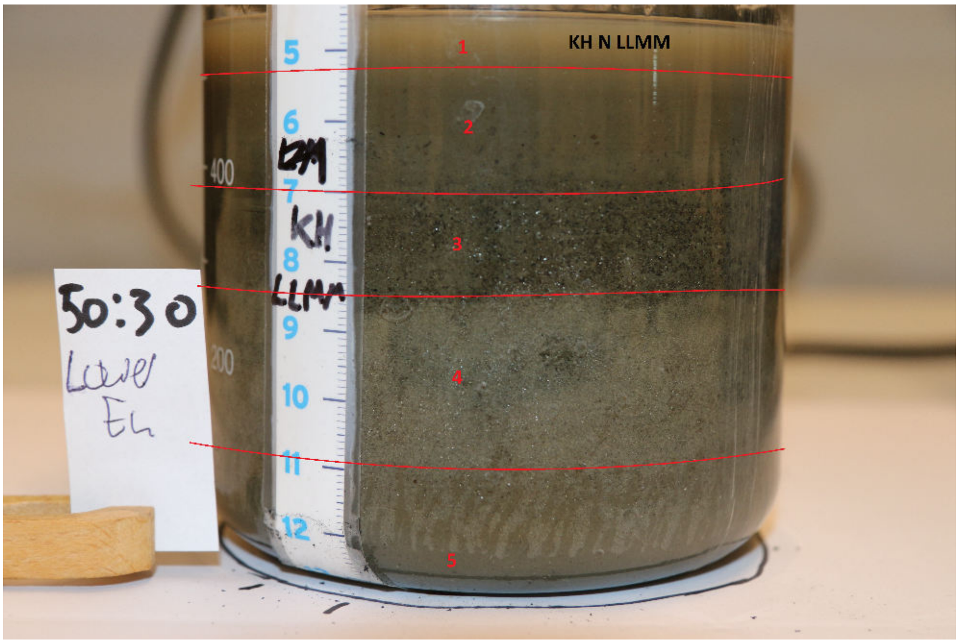

Figure 3.16: KH N LLMM: Layer 3 is a black layer. This could be organic material. Note that this sample is not the sample on which the LOI has been done.

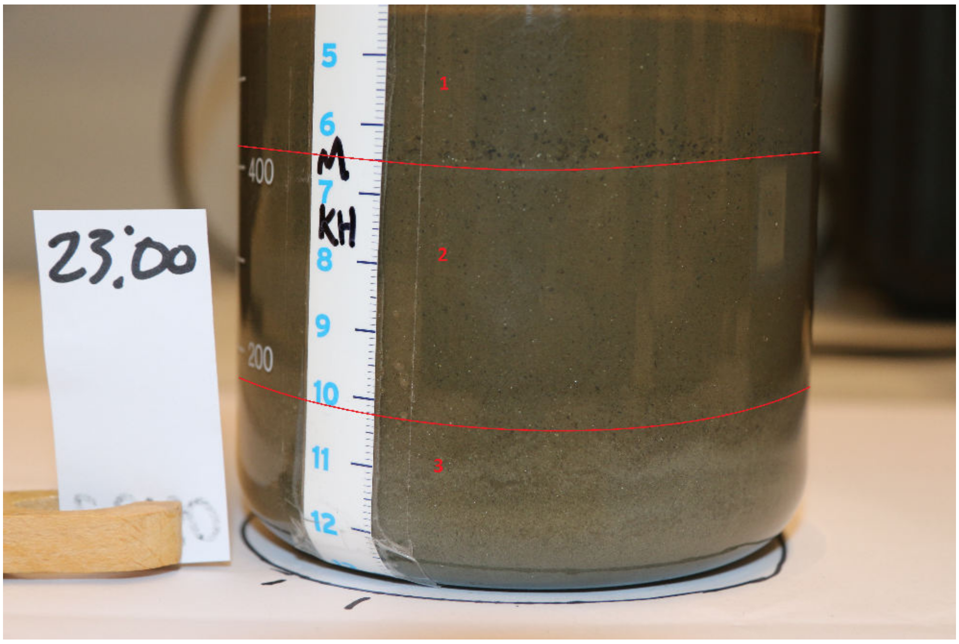

Figure 3.17: KH N M: Along the red line that separates layer 1 and 2 is a line with black grains. This line was in every unsettled sample at the bottom of the amplitude of the waves.

4 Discussion

Kinetic energy did not influence the settling velocity compared to the control sample. The sample material from site KH did not settle when they experienced an energy level higher than level 3. And the sample material from site SW did not settle when they experienced an energy level higher than level 4. But when the samples did settle, the settling velocity was the same as the control sample. See figure 3.3 and 3.4. This contradicts the hypothesis that was made. It was expected that the sample material would have a gradation in the velocity of settlement. The results from the experiments show that there is no gradation, but two settling velocities. Either the settling velocity would be 0, or the settling velocity would be the same of the sample that experienced no kinetic energy.

Also, kinetic energy had an unexpected effect on the sample material. When a sample experienced kinetic energy, layering formed. The sample material would arrange itself over its depth depending on its properties like density and particle size. The highest density can be found at the bottom of the sample and the lowest density can be found at the top. The samples from site KH that did settle had densities that went up to $1.17\,g/cm^3$. This is higher than the homogenised control samples from site KH. HPA has made logs with information about the fluid mud on 14 sites, those logs show that a lot of sites had fluid mud with densities higher than $1.2\,g/cm^3$. Also, the Dutch Rijkswaterstaat uses a maximum density of $1.2\,g/cm^3$ for nautical depth[3].
The layers of samples from site SW however, had a much higher density in the lower layers compared to the settled control samples. The densities could go up to $1.5\,g/cm^3$ in the case of SW N LM (5). The density of the control sample from site SW was $1.17\,g/cm^3$. In the 14 sites where the density was measured by HPA, a maximum density of $1.35\,g/cm^3$ was found. Also, the densities of the lower layers of the samples from site SW are way above the density criteria shown in figure 4.1. When the layers of the samples were taken apart, it was also noticed that the mud was a lot thicker on the bottom.

Table 1. Density Criteria for Navigable Depth

Country	Port	Density tonnes m^{-3}
The Netherlands	Rotterdam	1.2
Thailand	Bangkok	1.2
Surinam	Paramaribo	1.23
Belgium	Zeebrugge	1.151–1.347
China	Yangtze	1.25
China	Liang Yungang	1.25–1.30
China	Yianjing Xingang	1.2–1.3
UK	Avonmouth	1.2
France	Dunkirk	1.2
France	Bordeaux	1.2
France	Nantes–Saint Nazaire	1.2

Figure 4.1: Density criteria from Mcanally et al.-2016-[4]

Considering the results from the LOI and mean particle size over the depth of the sample, a lot of kinetic energy is needed to keep fluid mud suspended. This contradicts the hypothesis which stated that very little kinetic energy would be needed to keep fluid mud suspended. When the samples were exposed to kinetic energy, the Particles would arrange in size so that the largest particles could be found at the bottom of the sample and the smallest particles can be found at the top. If a sample is well mixed, a particle size plot like figures 7.1 and 7.2 should show a straight vertical line. The results shown in figure 7.1 and 7.2 do not show a vertical line. They show instead, that the mean particle size would differ significantly over the depth of the sample. Even the highest kinetic energy level (6) gave a difference of 10 micro meters in mean particle size between the top part and the bottom part of the sample. The frequency of the waves was about 3 to 4 waves per second with an amplitude of 1.5 cm. This would be the very least amount of kinetic energy needed to keep fluid mud suspended. There is no data about the yield stress that the samples had, so it is not sure if the mud would be navigable. The LOI showed that there is more organic material in the top part of the sample (18.8% of the total mass in site SW and 20.0% of the total mass in site KH) than in the bottom part of the sample (4.59% of the total mass in site SW and 10.1% of the total mass in site KH). This is due to the fact that organic material has a lower density than sand and silt particles. Since organic material has a major influence on the cohesiveness of sediments, because the organic material increases the viscosity and lowers the inner friction of the mud[1], it is expected that the lower parts of the samples will become less suitable for navigation over time. See 7.22 and the appendix for more data.

The results shown in figure 3.4 and 3.3 indicate that a lower density sample will settle faster than higher density sample. The samples from site KH had a density of 1.1467 g/cm^3 and the samples from site SW had a density of 1.1717 g/cm^3. The samples from SW settled faster than the samples from site KH. According to these results fluid mud with a higher density will settle faster than fluid mud with a lower density. This is in line with the hypothesis. This could be explained due to the fact that more dense particles will sink faster. But also by a phenomena called “hindered settling”. When figure 3.1 and 3.2 are compared, it can be seen that SW has a lower volume of particles. Silt particles have a sheet like form[5]. When there is a higher concentration of particles in the sample, there will be more internal friction between these silt particles. Also, it could be that the fluid mud appears to settle faster since it has less grains. This would make the bed of sediments thinner. This causes the distance from the top of the water to the top of the sediment layer to be greater. Therefore the settling velocity could appear greater in diluted samples. There are results of a rheology test that could show why lower diluted samples have a higher velocity, only these are not discussed in this article. The lower diluted samples had a greater settling velocity too. It is expected that this is caused by the same phenomena as described before.

An unexpected result was the formation of fingers in the lower part of the sample. These formations can be seen in figures 3.11 and 3.12. The formation of these fingers is stronger when low kinetic energy is applied than when high kinetic energy is applied. The formation of these fingers was also stronger in the samples from site SW than in the samples from site KH.

5
Conclusion

When fluid mud is exposed to kinetic energy of the type used in this experiment, particles will arrange themselves. Dense material and larger particles can be found lower than less dense material and smaller particles. The amount of kinetic energy has no effect on the settling velocity once fluid mud settles. In this research energy level 6 created waves with a frequency of about 3 to 4 waves per second with an amplitude of 1.5 cm. This is the least amount of kinetic energy needed to keep the fluid mud homogenised. A lower density fluid mud will settle faster than a higher density fluid mud. It is not yet clear if this is caused by the density, or that the relation of the difference in density and settling velocity is coincidental.

6

Reccomendations for future research

6.0.1. Movement

Since this research considers the effect of kinetic energy on fluid mud, further research should have to start with one question: ”what type of movement does fluid mud have at the bottom of the canal?”
This could be researched in many different ways. For example, simulations could be made or it could be investigated by placing sensors at the bottom of the canal.
Afterwards, the effect of different types of movement on fluid mud should be investigated. Experiment 1 and 2 from this research have shown that different types of movement had different effect on the fluid mud. It could be seen that the layering was different. The movements used in this research was limited to shaking. This created small waves in the sample material. It can be expected that these waves do not occur at a depth of 24 m. It is more likely that the movement of the fluid mud layer will be mainly laminar flow and turbulence caused by flow.

6.0.2. Layers

The results of this research show that layering will form in fluid mud when the fluid mud is shaken. It is concluded in the discussion that this separation of particles is caused by the difference in density and particle size. It should be researched what the parameters are of these layers. Is it true that this layering is formed because of the density of particles? Or are there other properties of the fluid mud that cause this effect? Also, this research was not made to investigate these layers. The research is not executed in duplo, which makes the results unreliable. It is not possible to exclude human errors. If the formation of layering is interesting, a whole new research should be done to investigate its properties. Also the long term effect of layering should be investigated. Organic material makes the fluid mud ”alive”. This material changes the properties of the mud over time. The results have shown that the presence of organic material is not evenly distributed over the depth of the sample after the sample has been exposed to the specific type of kinetic energy used in these experiments. Future research could show interesting results about the effect of this occurrence.
The effect of temperature on the settlement with and without kinetic energy should also be investigated. These experiments were conducted during temperature change from 10 degrees Celsius to 20 degrees Celsius. In-situ, the temperature is seasonal bounded and more constant.

7 Appendix

In this chapter are the results represented. Figure 7.1 shows the densities and particle sizes of sample KH after a certain time of exposure to kinetic energy. Figure 7.2 shows the same as figure 7.1 but for sample SW. The coloured "o" in the graphs are the measured values of the control samples. Those values are measured from a sample taken from the middle of the settled mud layer.
All the results are shown in tables. The frequency of the shaker that has been chosen for the experiments could not be clearly distinguished. The frequency was around 100 rounds per minute. after every experiment the frequency would be enlarged or lowered based on whether the sample had settled or not. Numbers are used to give a better indication of the amount of kinetic energy that has been given to the sample. 0 is the lowest frequency or kinetic energy. Energy level 0 is given to the control samples that had no kinetic energy. Energy level 6 is the highest energy level.

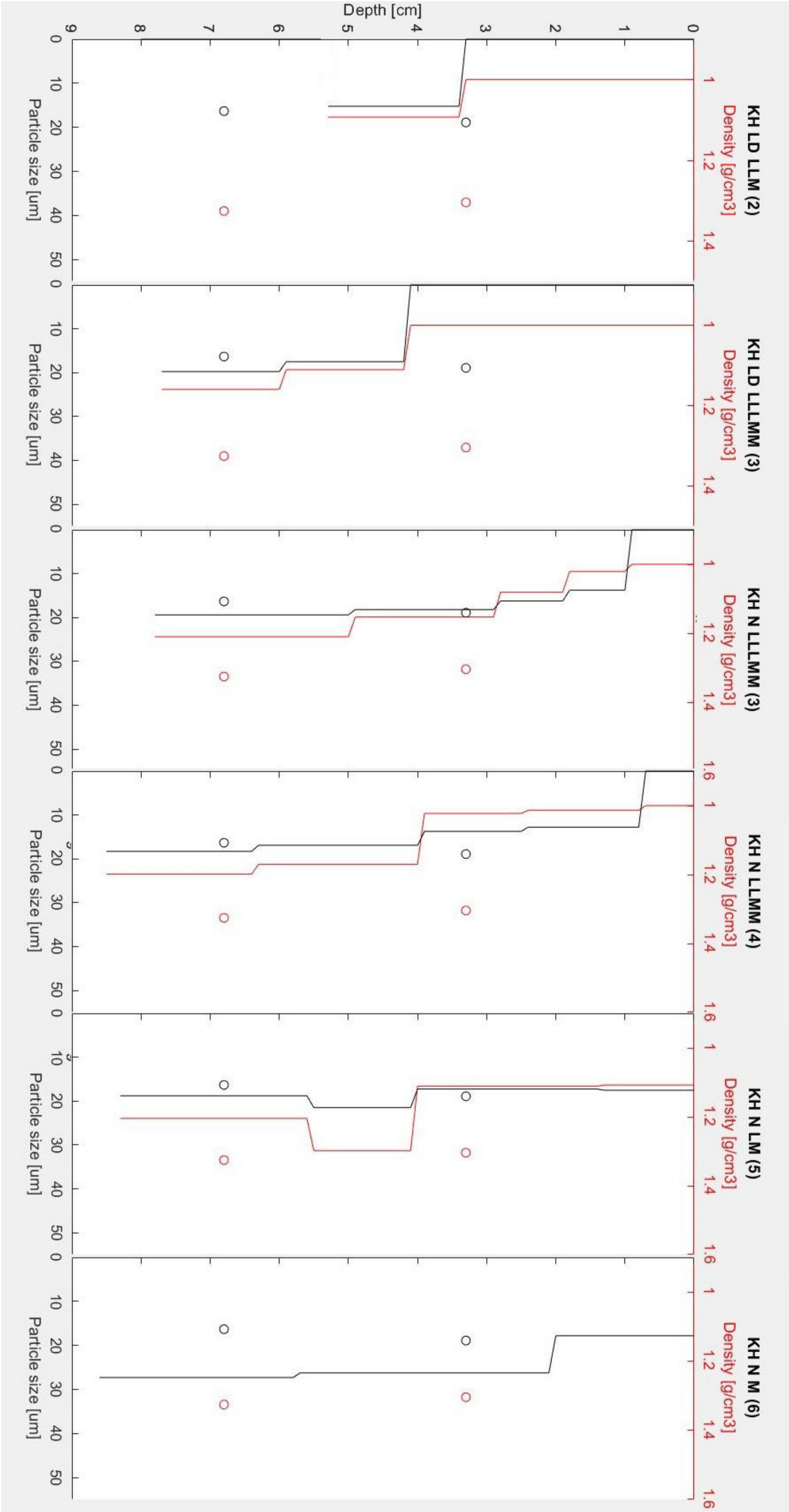

Figure 7.1: Density and particle size plot of the samples from site KH. These plots show the density and mean particle size of the sample over its depth. The small circles show the mean particle size and density of the control sample.

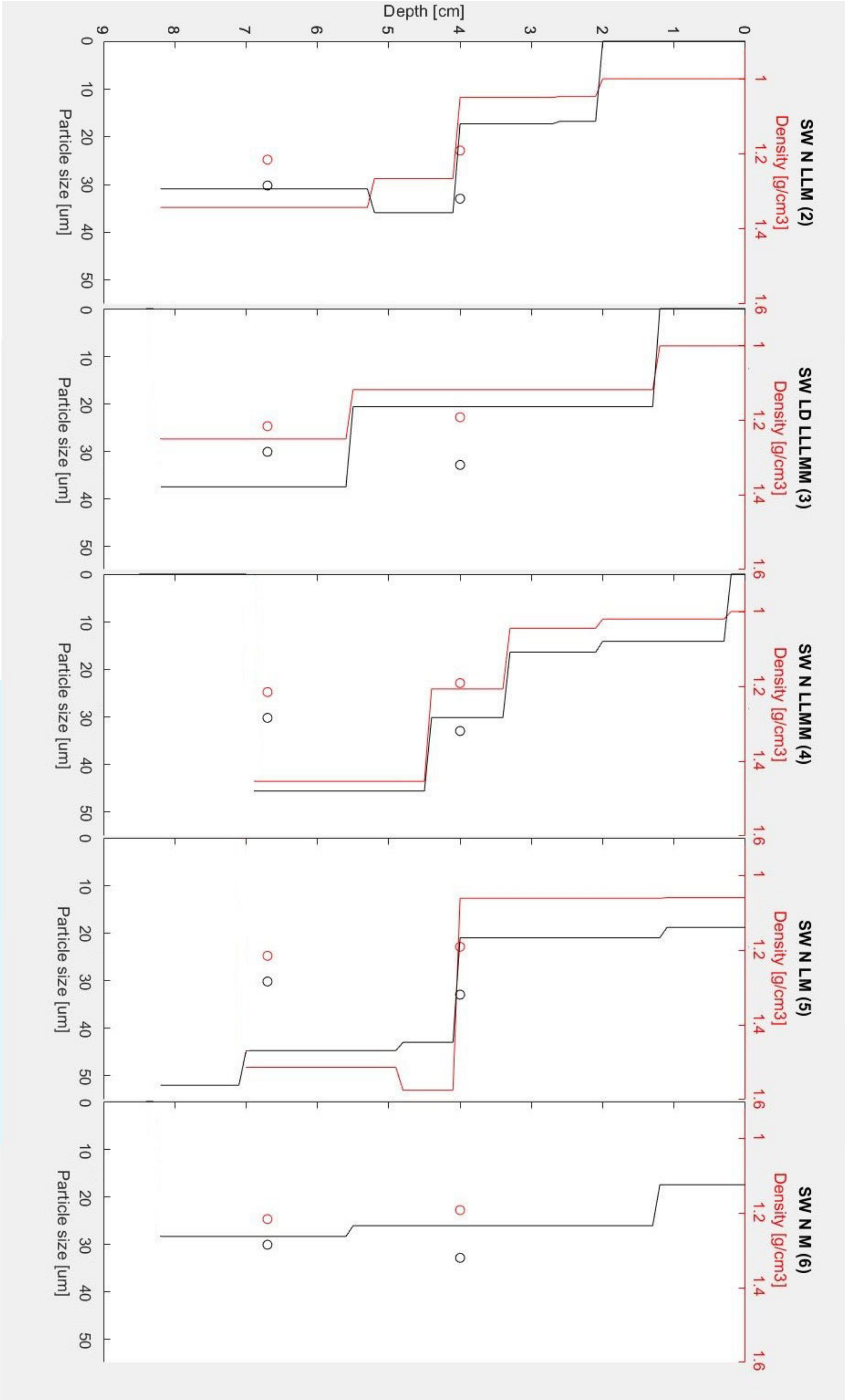

Figure 7.2: Density and particle size plot of the samples from site SW. These plots show the density and mean particle size of the sample over its depth. The small circles show the mean particle size and density of the control sample.

7.0.1. SW Settled

This part shows the data of sample SW where the fluid mud had settled. PS stands for ”Particle Size” which is the mean particle size.

Table 7.1: Data from sample SW N L (1) (figure 7.3) from site SW that experienced energy level 1 for 24.5 hours

Time [h]	24.5			
Energy level [#]	1			
SW N L	**Depth [cm]**	**Thickness [cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	5	-	-	-
L1	6.9	1.9	x	x
L2	7.4	0.5	x	x
L3	8.7	1.3	x	x
L4	10.5	1.8	x	x
L5	13.0	2.5	x	x

Table 7.2: Data from sample SW N LLM (1) (figure 7.4) from site SW that experienced energy level 2 for 70.5 hours

Time [h]	70.5			
Energy level [#]	2			
SW N LLM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.8	-	-	-
L1	6.8	2.0	x	x
L2	7.4	0.6	1.0466	16.755
L3	8.8	1.4	1.0498	17.276
L4	10.1	1.3	1.2659	35.87
L5	13	2.9	1.34269	30.897

Table 7.3: Data from sample SW N LLMM (1) (figure 7.5) from site SW that experienced energy level 4 for 25 hours

Time [h]	25			
Energy level [#]	4			
SW N LLMM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.5	-	-	-
L1	4.8	0.3	x	x
L2	6.6	1.8	1.02	14.108
L3	7.9	1.3	1.0448	16.385
L4	9.0	1.1	1.2069	30.137
L5	11.5	2.5	1.4539	45.569
L6	13.0	1.5	x	x

Table 7.4: Data from the control sample (figure 7.6) from site SW that experienced no kinetic energy for 220 hours

Time [h]	220	
Energy level [#]	0	
Control SW	**density**$[g/cm^3]$	**Mean particle size [um]**
Top	1.30429	32.278
Bottom	1.32559	29.7

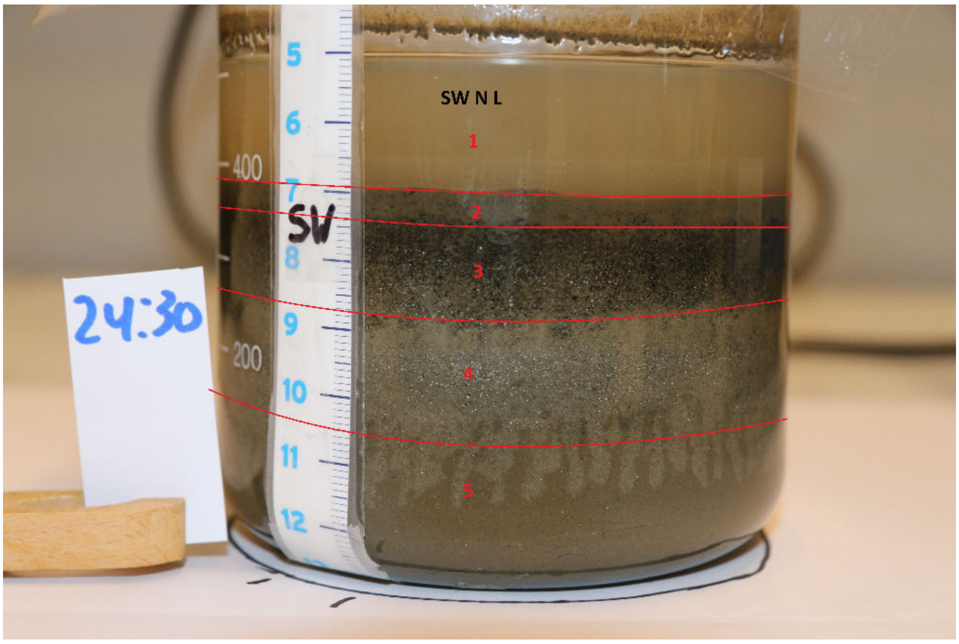

Figure 7.3: Sample SW N L(1) Layers

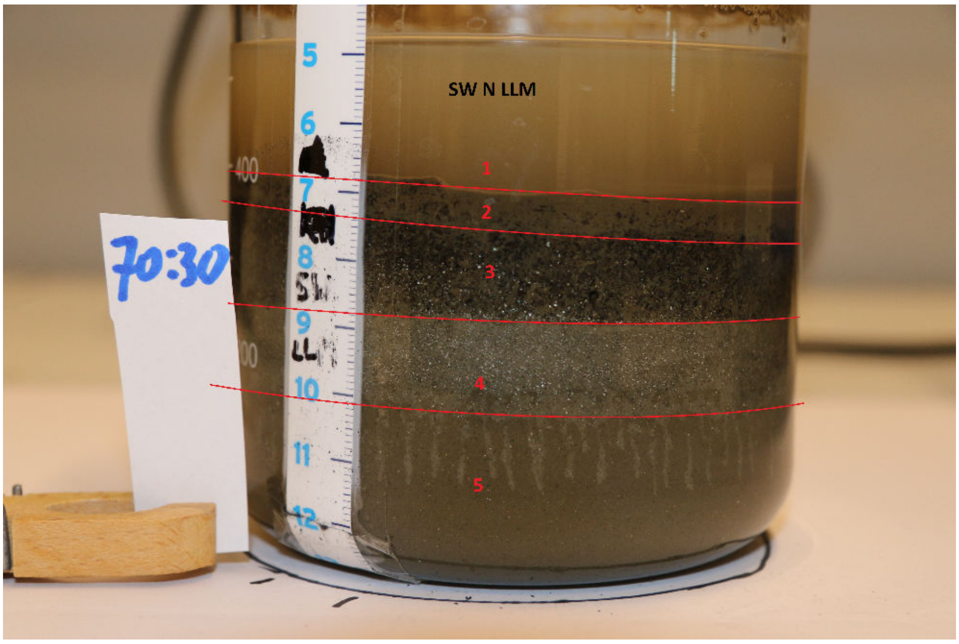

Figure 7.4: SW N LLM(2) Layers

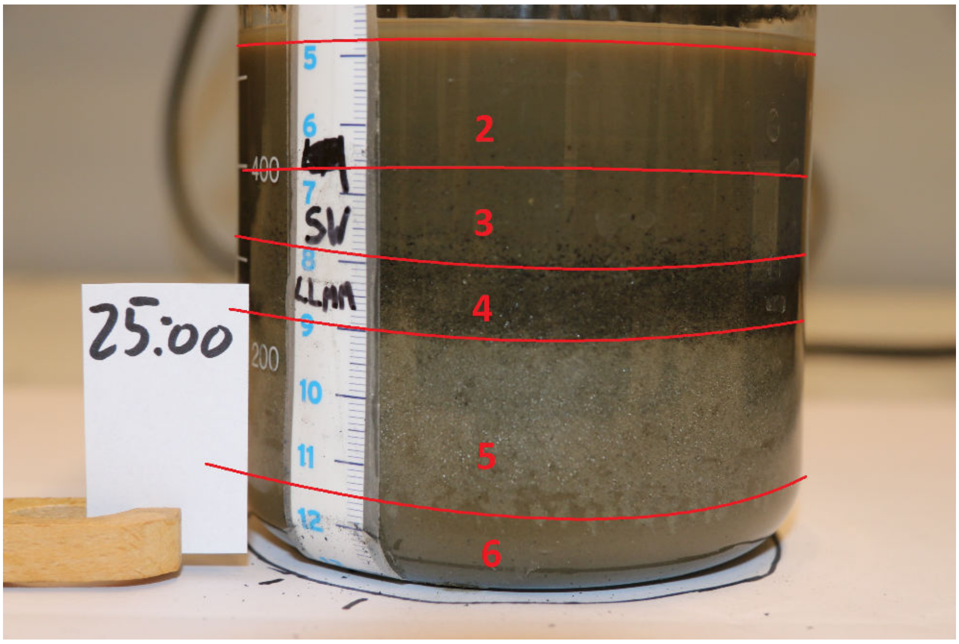

Figure 7.5: SW N LLMM(4) Layers

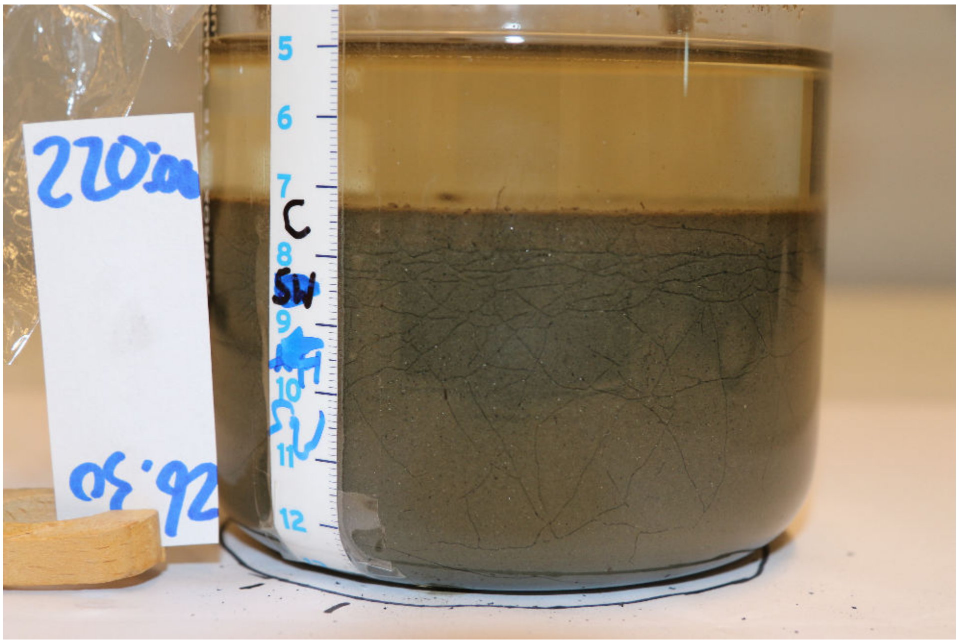

Figure 7.6: SW control

7.0.2. SW unsettled

This part shows the data of sample SW where the fluid mud stayed suspended.

Table 7.5: Data from sample SW N M (6) (figure 7.7) from site SW that experienced energy level 6 for 23 hours

Time [h]	23			
Energy level [#]	6			
SW N M	**Depth[cm]**	**Thickness[cm]**	Density[g/cm^3]	Mean particle size [um]
Top	4.8	-	-	-
L1	6.1	1.3	x	17.539
L2	10.4	4.3	x	26.189
L3	13.0	2.6	x	28.435

Table 7.6: Data from sample SW N LM (5) (figure 7.8) from site SW that experienced energy level 5 for 24 hours

Time [h]	24			
Energy level [#]	5			
SW N LM	**Depth[cm]**	**Thickness[cm]**	Density[g/cm^3]	Mean particle size [um]
Top	4.8	-	-	-
L1	6.0	1.2	1.0601	18.833
L2	8.9	2.9	1.0617	20.997
L3	9.8	0.9	1.57484	42.948
L4	11.9	2.1	1.51356	44.69
L5	13.0	1.1	x	51.979

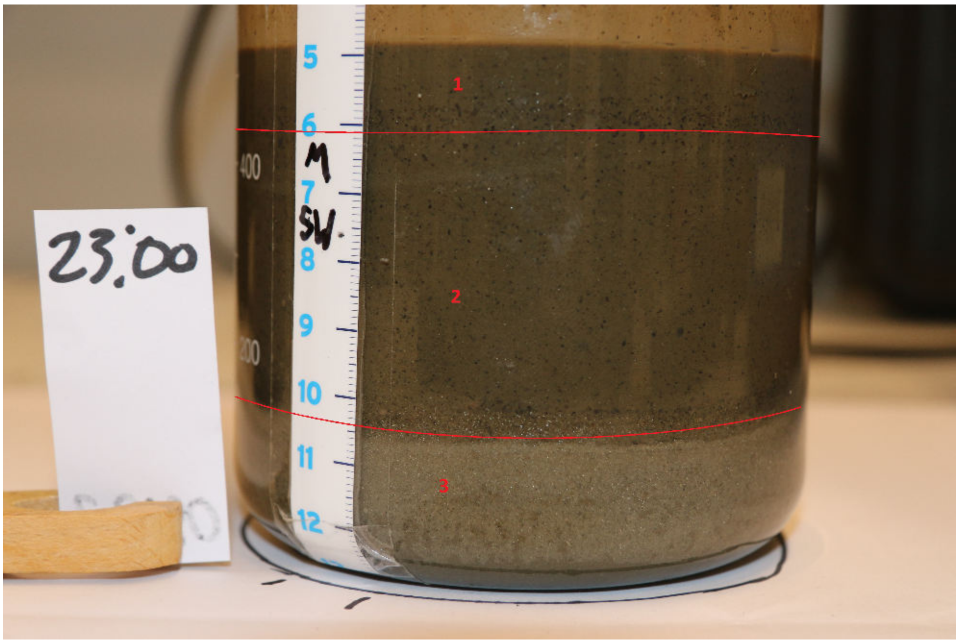

Figure 7.7: SW N M (6) Layers

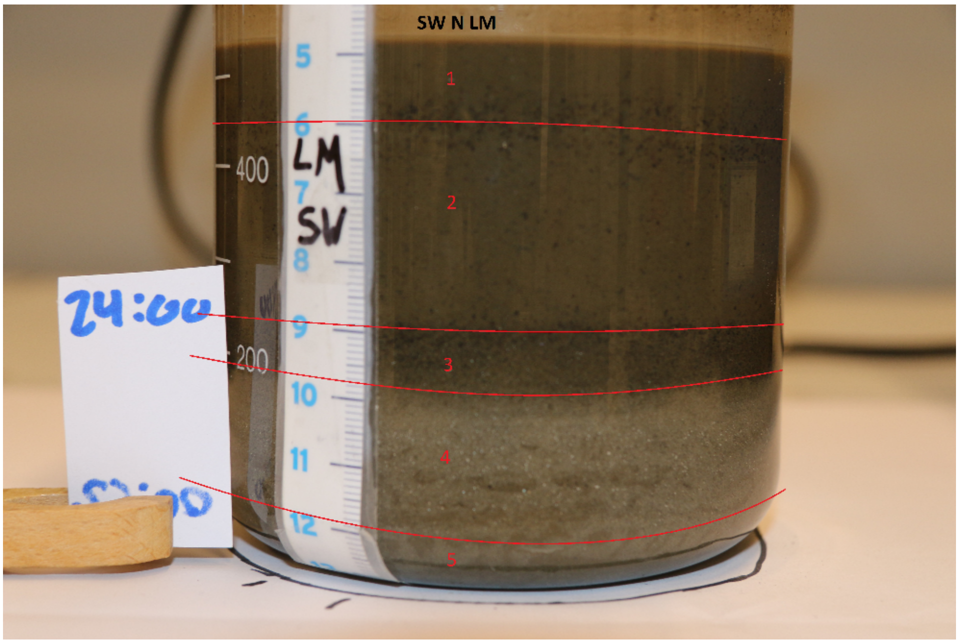

Figure 7.8: SW N LM (5) Layers

7.0.3. SW diluted

This part shows the data of sample SW where the fluid mud was diluted

Table 7.7: Data from a diluted sample SW LD LLLMM (3) (figure 7.9) from site SW that experienced energy level 3 for 22 hours

Time [h]	22			
Energy level [#]	3			
SW LD LLLMM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.8	-	-	-
L1	8.5	3.7	x	x
L2	10.2	1.7	1.1175	20.673
L3	13.0	2.8	1.2497	37.582

Table 7.8: Data from a diluted control sample SW LD control (figure 7.9) from site SW that experienced no kinetic energy for 22 hours

Time [h]	22	
Energy level [#]	0	
SW LD Control	**density**$[g/cm^3]$	**Mean particle size [um]**
Top	1.2312	32.851
Bottom	1.2565	29.289

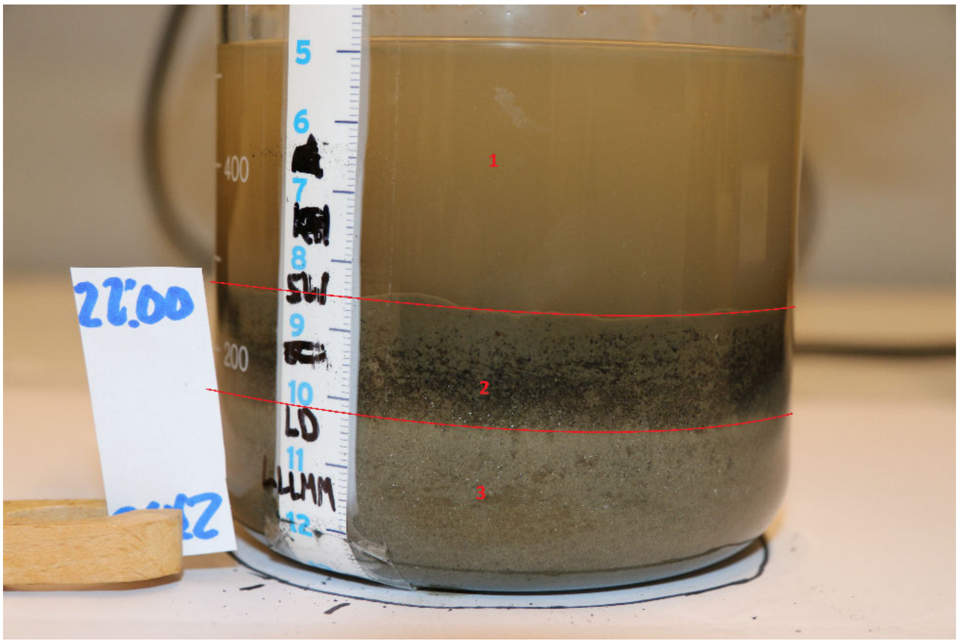

Figure 7.9: SW LD LLLMM(3) Layers

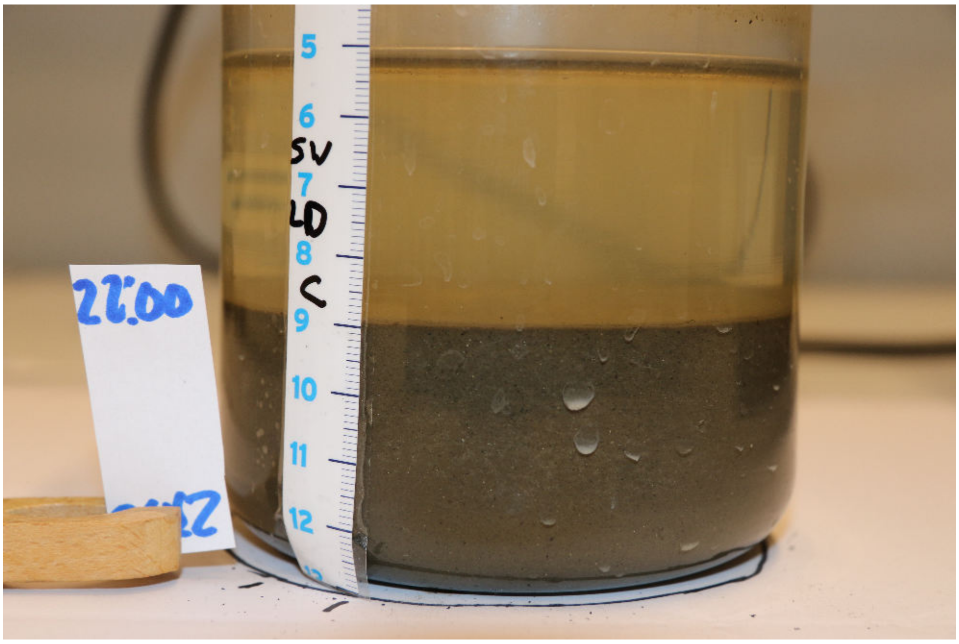

Figure 7.10: SW LD Control

7.0.4. KH Settled

This part shows the data of sample KH where the fluid mud was settled.

Table 7.9: Data from sample KH N LLLMM (3) (figure 7.11) from site KH that experienced energy level 3 for 47 hours

Time [h]	47			
Energy level [#]	3			
KH N LLLMM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	5.2	-	-	-
L1	5.3	0.1	1.0	0
L2	7.1	1.8	1.0209	13.75
L3	8.1	1.0	1.081	16.227
L4	10.1	2.0	1.153	18.171
L5	13.0	2.9	1.21029	19.388

Table 7.10: Data from sample KH N L (1) (figure 7.11) from site KH that experienced energy level 1 for 24.5 hours

Time [h]	24.5			
Energy level [#]	1			
KH N L	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	5.1	-	-	-
L1	5.8	0.7	x	x
L2	6.5	0.7	1.0551	14.386
L3	8.0	1.5	x	x
L4	10.1	2.1	x	x
L5	13.0	2.9	x	x

Table 7.11: Data from the control sample (figure 7.13) from site KH that experienced no kinetic energy 220 hours

Time [h]	220	
Energy level [#]	0	
KH Control	**density**$[g/cm^3]$	**Mean particle size [um]**
Top	1.19132	18.9
Bottom	1.2154	16.317

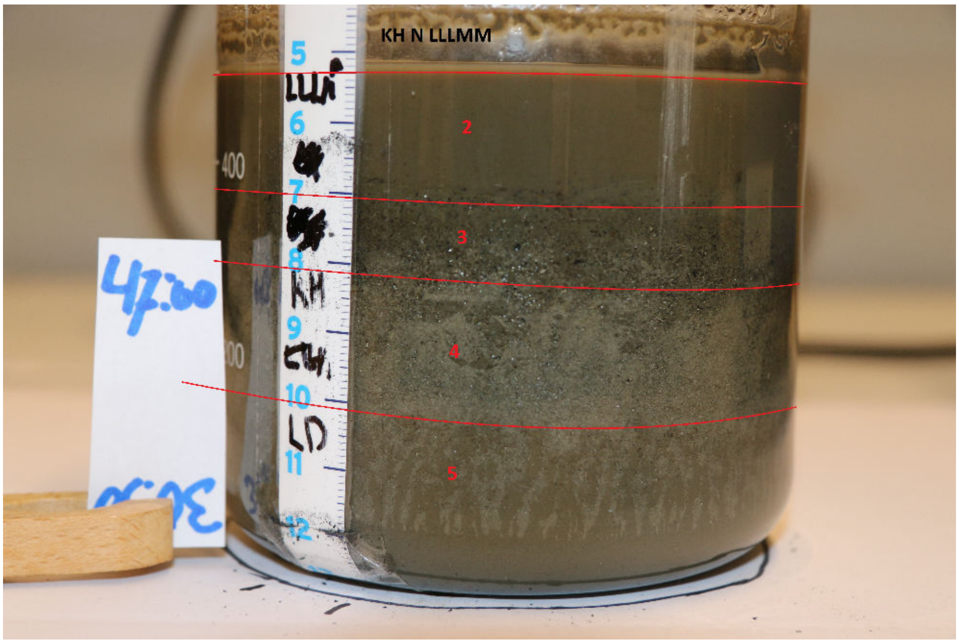

Figure 7.11: KH N LLLMM (3) Layers

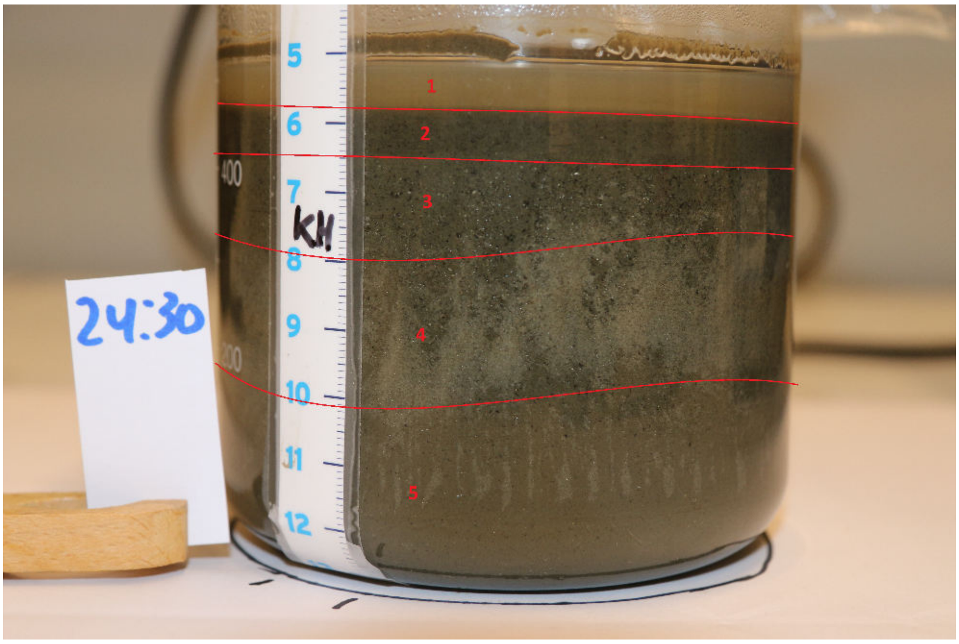

Figure 7.12: KH N L (1) Layers

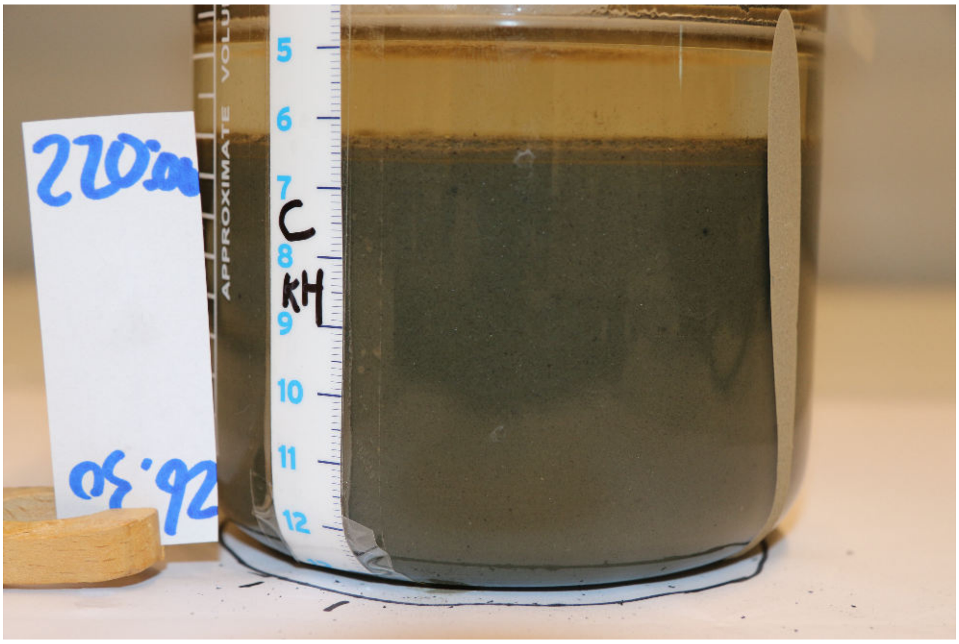

Figure 7.13: KH Control

7.0.5. KH unsettled

This part shows the data of sample KH where the fluid mud stayed suspended.

Table 7.12: Data from sample KH N LLMM (4) (figure 7.14) from site KH that experienced energy level 4 for 50.5 hours

Time [h]	50.5			
Energy level [#]	4			
KH N LLMM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.5	-	-	-
L1	5.3	0.8	1.0	0
L2	7.0	1.7	1.0134	12.763
L3	8.5	1.5	1.0228	13.727
L4	10.9	2.4	1.1701	16.906
L5	13.0	2.1	1.1992	18.289

Table 7.13: Data from sample KH N LM (5) (figure 7.15) from site KH that experienced energy level 5 for 24 hours

Time [h]	24			
Energy level [#]	5			
KH N LM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.7	-	-	-
L1	6.1	1.4	1.10805	17.5395
L2	8.8	2.7	1.11115	17.2425
L3	10.3	1.5	1.298205	21.48
L4	13.0	2.7	1.2048	18.798

Table 7.14: Data from sample KH N LM (6) (figure 7.16) from site KH that experienced energy level 6 for 23 hours

Time [h]	23			
Energy level [#]	6			
KH N M	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	4.4	-	-	-
L1	6.5	2.1	-	17.82
L2	10.2	3.7	-	26.251
L3	13.0	2.8	-	27.295

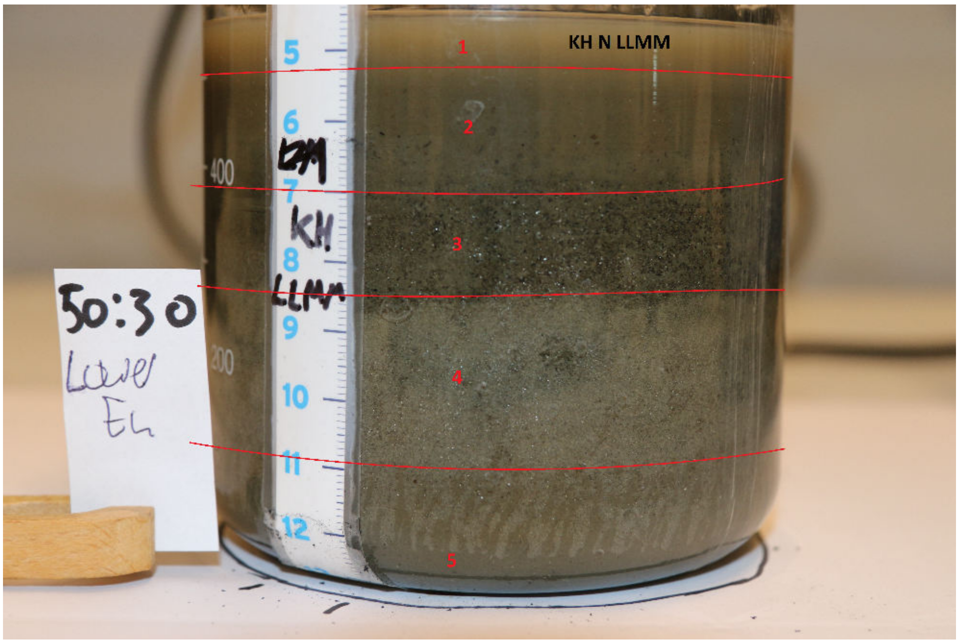

Figure 7.14: KH N LLMM (4) Layers

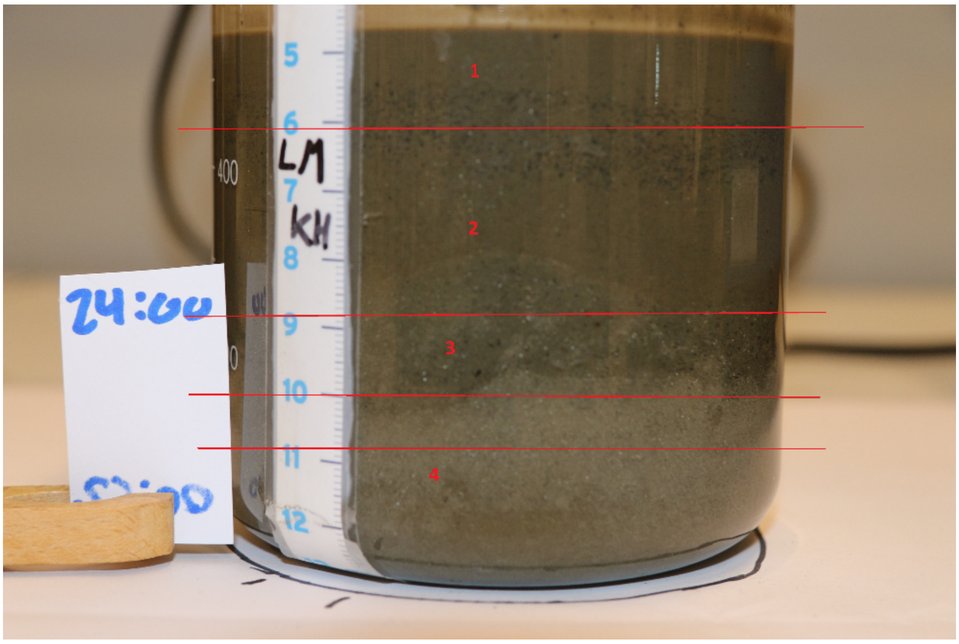

Figure 7.15: KH N LM (5) Layers

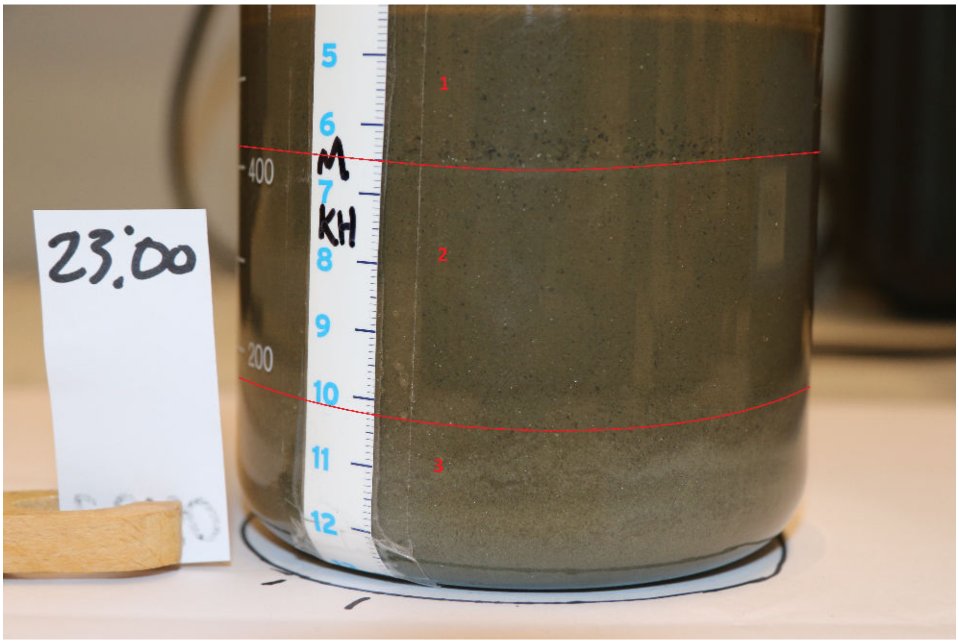

Figure 7.16: KH N M (6) Layers

7.0.6. KH diluted

This part shows the data of sample SW where the fluid mud was diluted.

Table 7.15: Data from a diluted sample KH LD LLLMM (3) (figure 7.17) from site KH that experienced energy level 3 for 26.5 hours

Time [h]	26.5			
Energy level [#]	3			
KH LD LLLMM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	5.3	-	-	-
L1	9.5	4.2	1.0	0
L2	11.3	1.8	1.1108	17.496
L3	13.0	1.7	1.1596	19.753

Table 7.16: Data from a diluted sample KH LD LLM (2) (figure 7.18) from site KH that experienced energy level 2 for 70.5 hours

Time [h]	70.5			
Energy level [#]	2			
KH LD LLM	**Depth[cm]**	**Thickness[cm]**	**Density**$[g/cm^3]$	**Mean particle size [um]**
Top	5.0	-	-	-
L1	8.4	3.4	1.0	0
L2	10.4	2.0	1.092915	15.231
L3	13.0	2.6	0	0

Table 7.17: Data from a diluted control sample (figure 7.19) from site KH that experienced no kinetic energy for 70.5 hours

Time [h]	26.5	
Energy level [#]	0	
KH LD Control	Density$[g/cm^3]$	Mean particle size [um]
Top	1.1347	18.843
Bottom	1.1488	

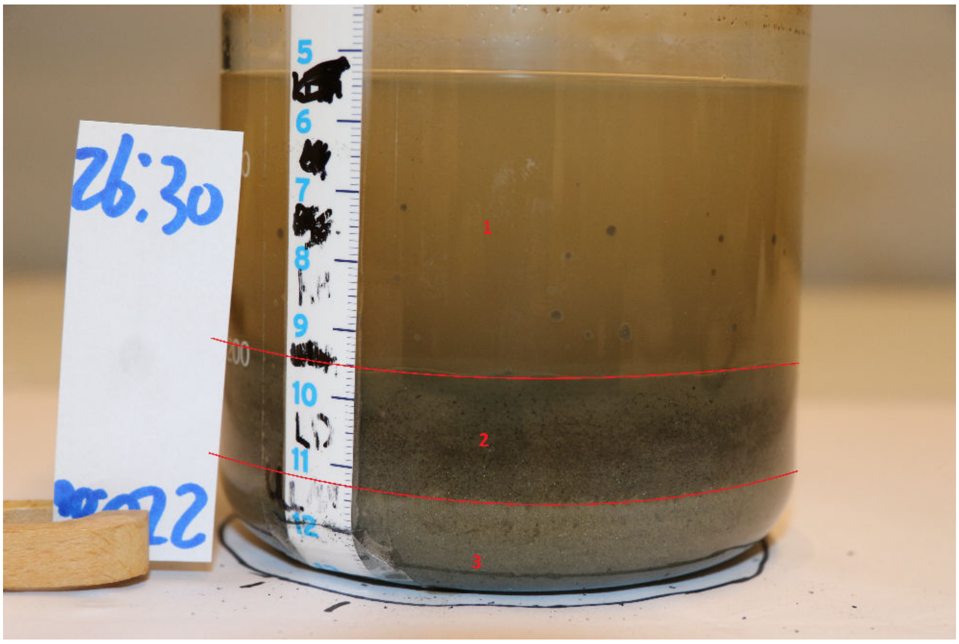

Figure 7.17: KH LD LLLMM (3) Layers

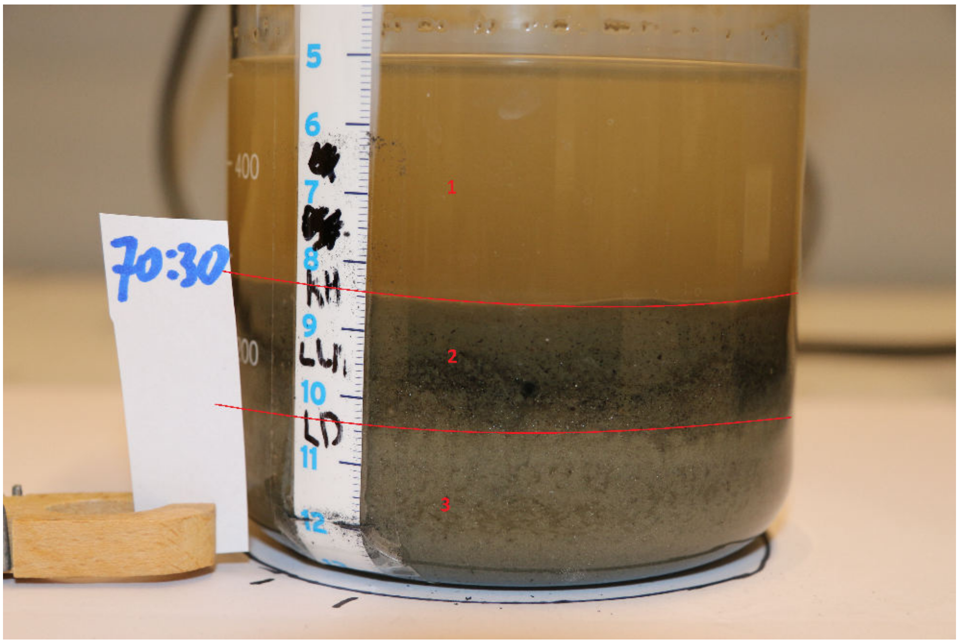

Figure 7.18: KH LD LLM (2) Layers

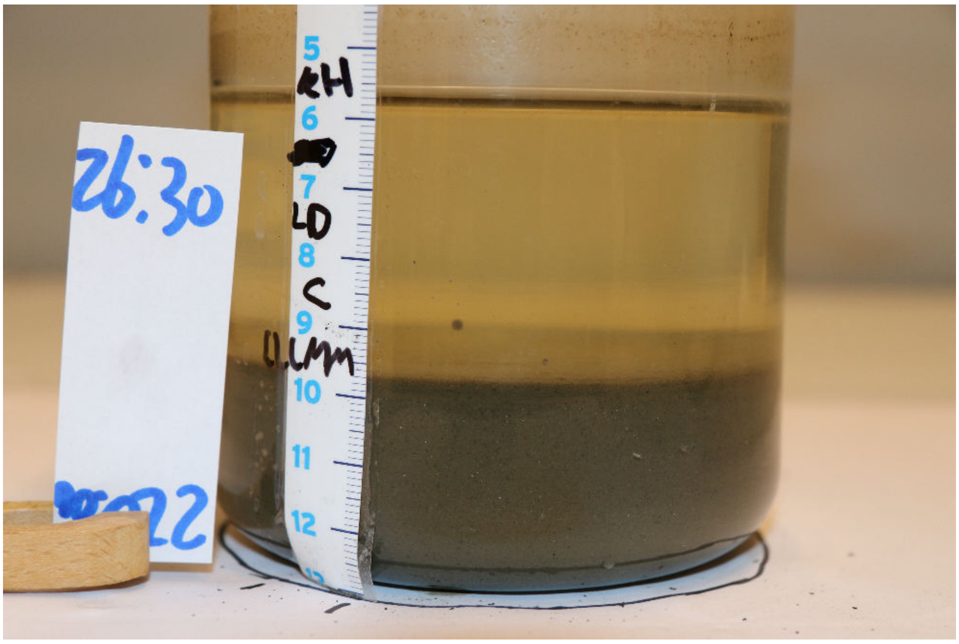

Figure 7.19: KH LD Control

7.0.7. Rate of settlement

Each code represents an experiment. The first part is the sample material, the second part is the dilution type and the third part is the kinetic energy level. For example KH N L(1) is the sample material from site KH. It was undiluted so the density was normal (N) and the kinetic energy was low, which I abbreviated with an L. I added a number for every kinetic energy level to make that part more clear. Level 0 had no kinetic energy and level 6 had the highest kinetic energy.

Table 7.18: This table shows what the abbreviations for every experiment means

First part	Abbreviation for:	Second part	Abbreviation for:	Third part	Abbreviation for:
SW	Sample material from location SW	N	Normal density	C (0)	This was the control sample, it experienced no kinetic energy
KH	Sample material from location KH	LD	Lower density	L (1)	Lowest kinetic energy
				LLM (2)	Higher kinetic energy than L (1), but lower than LLM (2)
				LLLMM (3)	Higher kinetic energy than LLM (2), but lower than LLMM (4)
				LLMM (4)	Higher kinetic energy than LLLMM (3), but lower than LM (5)
				LM (5)	Higher kinetic energy than LLMM (4), but lower than M (6)
				M (6)	Highest kinetic energy

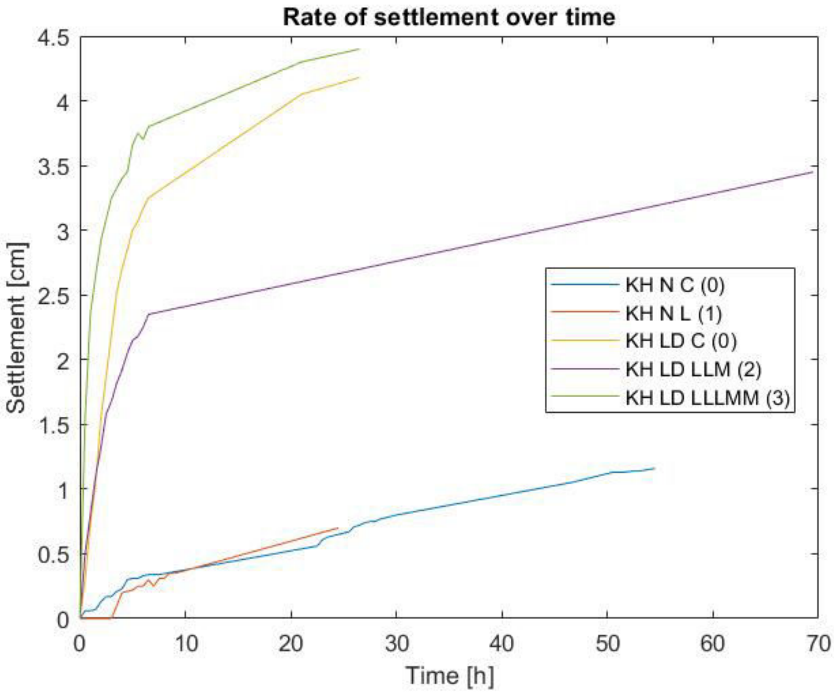

Figure 7.20: Amount of settlement over time of the samples from site KH

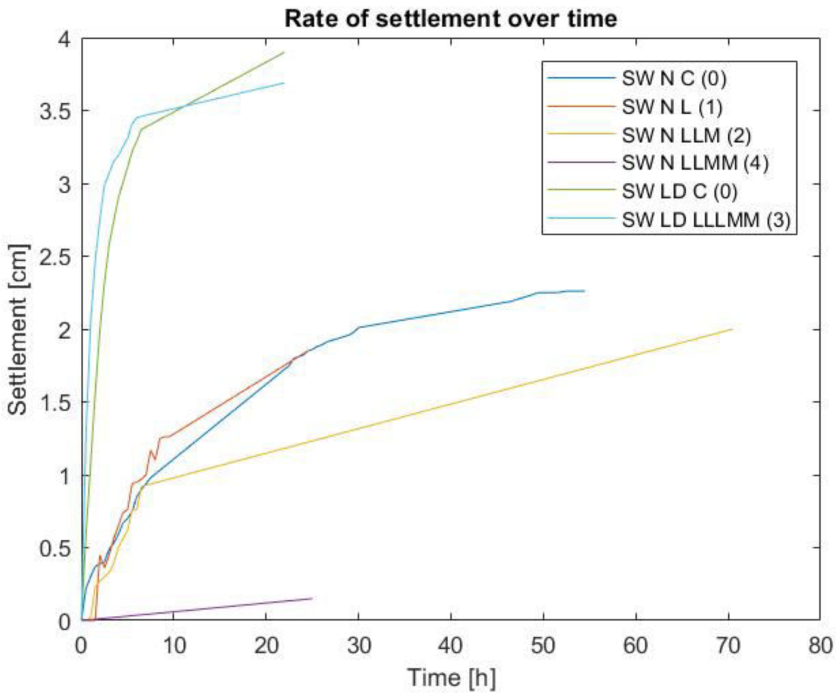

Figure 7.21: Amount of settlement over time of the samples from site SW

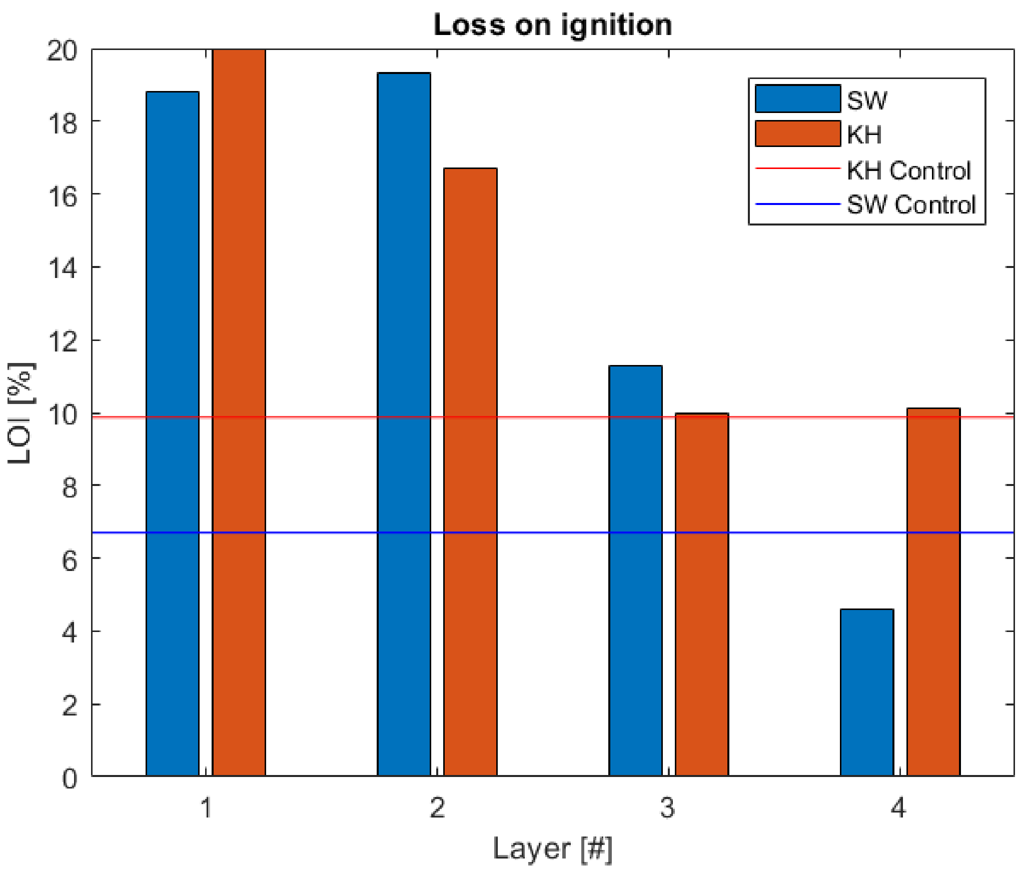

Figure 7.22: Loss on ignition of layer 1 to 4 of the samples that experienced kinetic energy compared with a homogenised control sample that experienced no kinetic energy

7.1. Pre-research

7.1.1. Beginning of research

Before the main experiment could begin, a few smaller experiments had to be done. There where a lot of things that to be considered. The smaller experiments had to planned carefully since there was a limited amount of sample material. In the rest of this next chapter is described how the final method was developed by conducting 2 smaller experiments. This information could be used when someone wants to repeat or improve this research.

7.1.2. Developing the method

Considering the materials available, the plan is to put the fluid mud in a container and to put that container on the shaker for some time. Before doing this, some criteria have to be considered:

1. The shape of the containers (see pre-research 1)

2. The type of movement (see pre-research 2)

3. The way of documenting

The following experiments have been conducted to investigate these criteria. Older samples have been used for these experiments. These samples are not the same as the samples that have been used for the final experiment.

7.2. Pre-research 1

Purpose of the experiment

The shape of the container could influence the sedimentation process. A cylindrical container will be used for the experiment. That is because cylindrical containers are more abundant in the lab than other containers. The height and diameter are the variables of the container. The following questions have been asked:

7.2.1. Research questions

- How is the sedimentation process of fluid mud in rest, influenced by the diameter of the container?

- How is the sedimentation process of fluid mud in rest, influenced by the height of the container?

7.2.2. Equipment

Container	Diameter	Height
Cylindrical container (2x)	X	Y
Cylindrical container	2X	2Y
Bottle	A	B

- Camera

- Measuring tape

- Tape

7.2.3. Method

Two cylindrical containers have to be of the same size. These have to be filled up to different heights so that the influence of the height can be tested. The next cylindrical container has to be about twice as wide as the other two so that the influence of the diameter can be tested.

The last container has to have a different diameter and height than the other containers. With this the influence of a different height and diameter on the settlement will be tested. The measuring tape has to be stuck on the sides of the containers so that the settlement can be measured. The camera can be set to take a photo every half an hour. These photo's can be turned into a time-lapse video to give a nice overview of the settlement process.

The sample is homogenised in the morning and separated over the containers. The containers are then sealed with plastic wrap to prevent dehydration. During the day the settlement is monitored. The time during that day is also used to download some software for the camera. The software will be needed to operate the camera from the computer and to let it take pictures automatically. Around 19:00 the software and camera where set up to begin the recording process. The containers where homogenized by flopping them upside down 3 times. During the night a picture was taken every 10 minutes. As a result this delivered 840 photo's.

7.2.4. Results

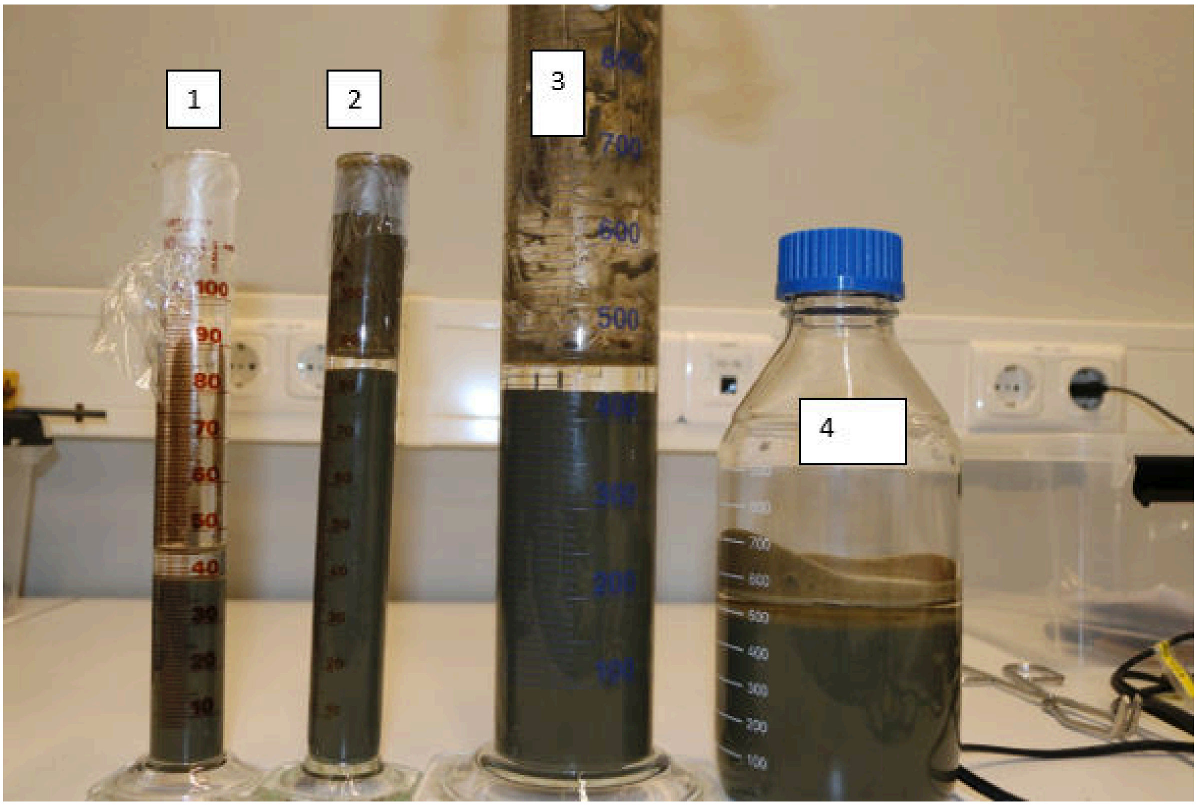

Figure 7.23: Set up of pre-experiment 1

Density of the sample: 1,1153 $\left(\frac{g}{cm^3}\right)$

Table 7.20: The settlement of every sample after 19.5 hours

Settlement of the sample after 19.5 hours			
Container	Settlement [cm]	Diameter [cm]	Height [cm]
3	1,7	6,0	16,3
1	1,5	2,5	8,5
4	1,0	10	8,7
2	0,9	2,5	16,3

Table 7.19: The settlement of every sample after 16 and 19.5 hours

Results				
Container (#)	1	2	3	4
Diameter	2.5	2.5	6.0	10.0
Height [cm]	8.5	16.3	16.3	8.8
Settlement after 16 hours [cm]	1.3	0.8	1.5	0.8
Settlement after 19.5 hours [cm]	1.5	0.9	1.7	1.0

It was clearly visible that there was still settlement in the afternoon. Also, the pictures don't show a lot of detail about the mud.

7.2.5. Discussion

Table 7.21: Comparison of samples

Comparision	Container	Discussion	Conclusion
1	1 & 2	In container 1 is more settlement than container 2. The diameter of container 1 and 2 are the same. The height of container 2 is almost twice as high as the height of container 1.	The higher the container is filled with fluid mud, the slower the settlement is.
2	1 & 3	Settlement is about the same. The diameter and height of sample 3 are around 2 times as large.	If the diameter and the height and diameter of the container become larger, the settlement will become faster, but not significantly on short run.
3	1 & 4	The settlement of container 4 is 5 cm less than container 1. That is 33% of the total settlement of container 1. There is only a significant difference in the diameter. The diameter of container 4 is 4 times as large.	The smaller the diameter of the container, the faster the settlement.

Comparision	Container	Discussion	Conclusion
4	2 & 3	Both container are filled to the same height. The diameter of container 3 is more than 2 times as large. The settlement of container 2 is nearly 2 times as small as the settlement of container 3.	The larger the diameter of the container, the faster the settlement.
5	2 & 4	The settlement of both samples is nearly the same. Container 2 is filled two times as high as container 4. The diameter of container 4 is 4 times as large as container 2.	When the diameter and the height of the container become larger, then there is no influence on the speed of settlement.
6	3 & 4	The settlement of container 3 is 7 cm larger than container 4. The diameter of container 4 is 4 cm larger than the diameter of container 3. The height of container 3 is nearly 2 times as large as the height of container 4.	When the diameter of the container becomes smaller, but the height of the container becomes larger, the settlement will become faster.

Table 7.22: Of each comparison of table 7.21 is shown how the variation of the diameter and height of the container influenced the settlement velocity. And arrow up means increase and an arrow down indicates a decrease

comparison	1	2	3	4	5	6
Diameter	-	↑	↓	↑	↑	↓
Height	↑	↑	-	-	↑	↑
Settlement velocity	↓	↑	↑	↑	-	↑

Statement 3 and 4 are in mutual contradiction. Statement 2 and 5 are also in mutual contradiction. For the rest of the statements it can be argued that the difference in diameter and height is not the same. For example, the diameter of container 4 is 4 times as large as the diameter of container 2. While the height of container 4 is only 2 times as large as the height of container 2. This could have a significant influence on the results. It could also be argued that the sample was not well homogenized before the experiment was set up. The experiment is not conducted sufficiently to exclude faults in the set up. The largest chance is that the inconsistence of the results is caused by the homogenization of the sample. Nevertheless it could be presumed that there is an indication that the diameter and height have an influence on the speed of settlement. It is just not clear yet how the diameter and height have an influence on the speed of settlement.

7.2.6. Conclusion

The results are not consistent enough to draw a reliable conclusion. It may be suggested that the height and diameter have an influence on the speed of settlement.
It is not clear how the speed of settlement of fluid mud is influenced by the height and diameter of the container.
During further research attention is required so that the height of the sample must be large enough so that a clear result of the settled material can me shown. Also the container should have the same shape for every experiment so that the influence of its geometry can be excluded. Of different dimensions.

7.2.7. In addition

Because this was just a small research about the final set up of the experiment, there has not been a lot of depth into the theory why the settlement was faster or slower.

7.3. Pre-research 2

7.3.1. Purpose

The movement of the fluid mud in the container has to resemble the movement of the mud in the canal as much as possible. Also it can be monitored how the mud behaves in containers of different shapes.

7.3.2. Research question

- Which shaker imitates the natural movement of the mud in the harbour?
- How does the shape of the container influence the movement of the fluid mud?

7.3.3. Equipment

- Different types of shakers (4 are available)
- Measuring cylinder with a diameter of 2,5 cm
- Measuring beaker with a larger diameter than the measuring cylinder
- Camera
- Measuring tape
- tape

7.3.4. Method

The following set up is made to conduct the experiment.
The samples have been homogenised and poured in the containers. Next to the shakers there are two control samples in rest.
In the middle of the picture is the shaker. This shaker moved 1 dimensional. The camera has been set on a tripod in front of the samples. It made a picture every 10 minutes during the night.
Also some containers have been filled with the sample and they have been placed on the other shakers. With these experiments the movement of the mud has been monitored and not the long term settlement.

7.3.5. Result

Layering has been formed.
The measuring cylinder was filled too high. This caused a more unclear layering of the sample.
The pictures are not detailed enough. No layering is visible on the pictures but it is clearly visible to a person watching.
The measuring cylinder had much smaller waves than the measuring beaker. The kinetic energy of the mud grows larger when the diameter of the container grows larger.
One of the shakers was a roller. It made the container roll around its axis. This caused the mud to stick to every side of the container. Therefore the sample was not visible. No

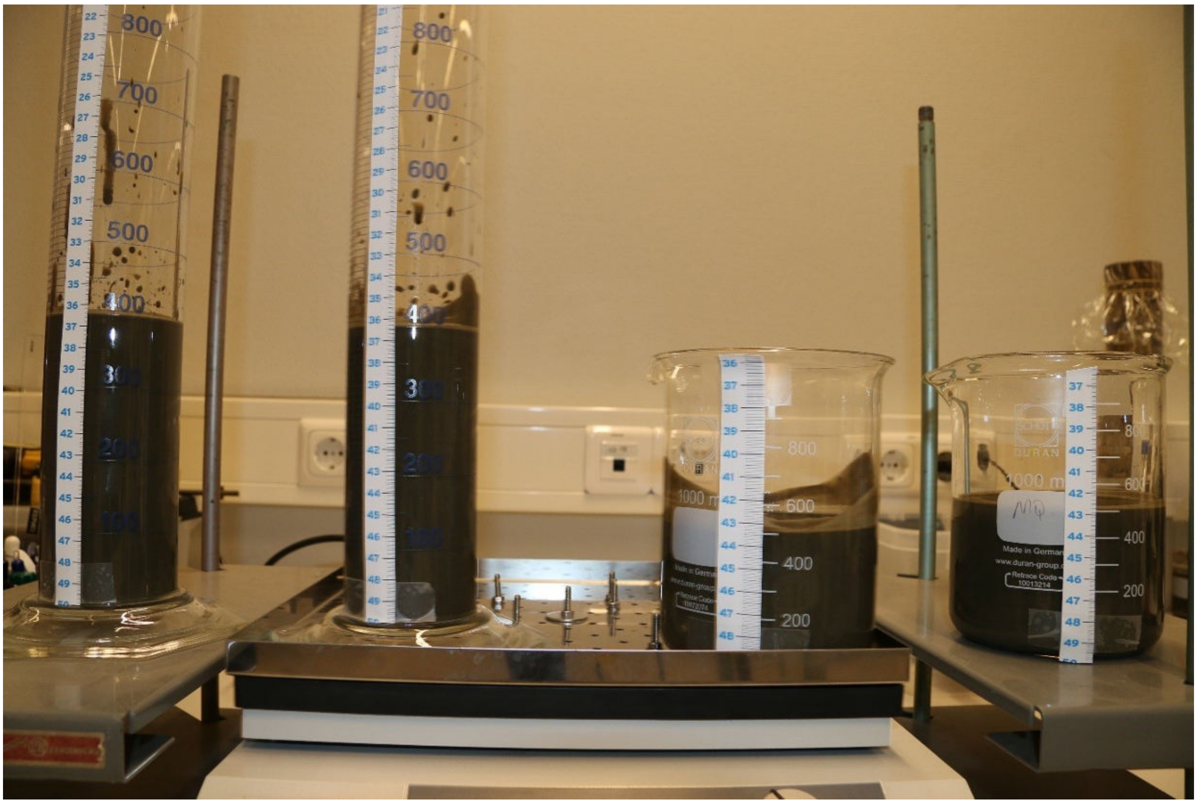

Figure 7.24: Set up of pre-experiment 2

documentation could be made.
The 2 2D shakers imitated the natural movement the best.
The 1 D shaker gave the fluid mud inconsistent movement over its surface. In the middle there was hardly any movement and on the sides there was the most movement. This caused the settlement to be unevenly distributed over the sample. Also the layers where mixed up a little on some places.

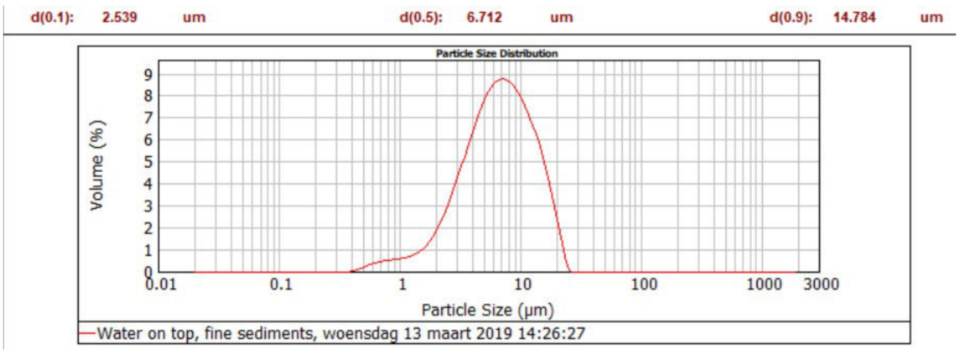

Figure 7.25: Particle size distribution of layer 1 from a year old test sample

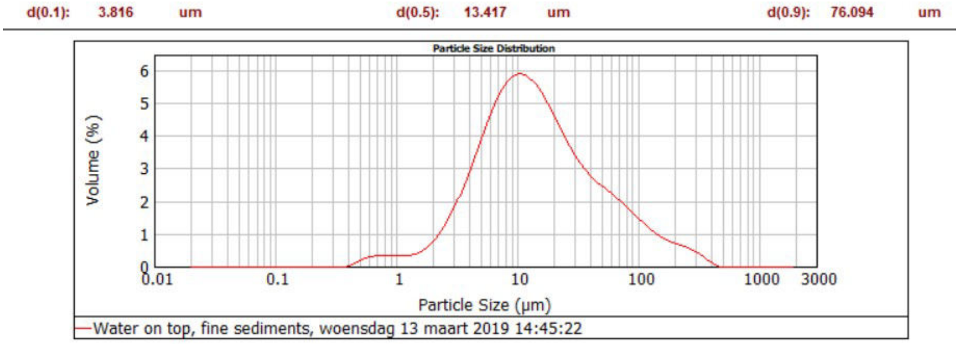

Figure 7.26: Particle size distribution of layer 2 from a year old test sample

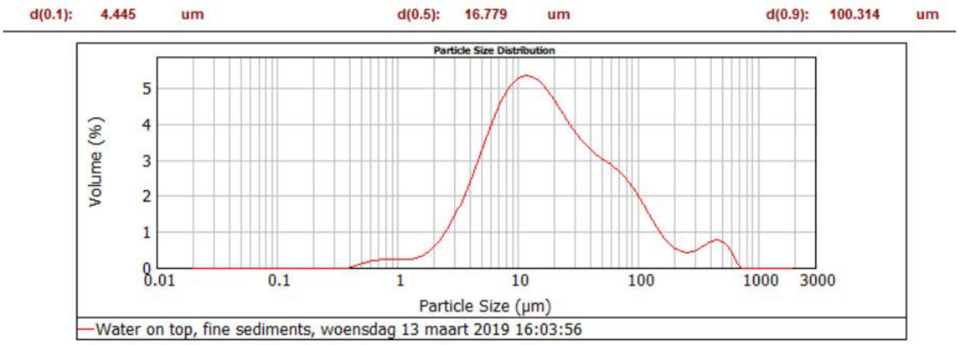

Figure 7.27: Particle size distribution of layer 3 from a year old test sample

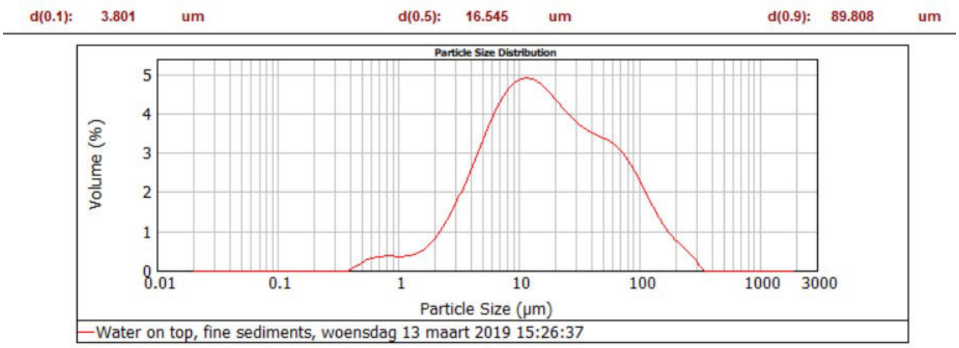

Figure 7.28: Particle size distribution of layer 4 from a year old test sample

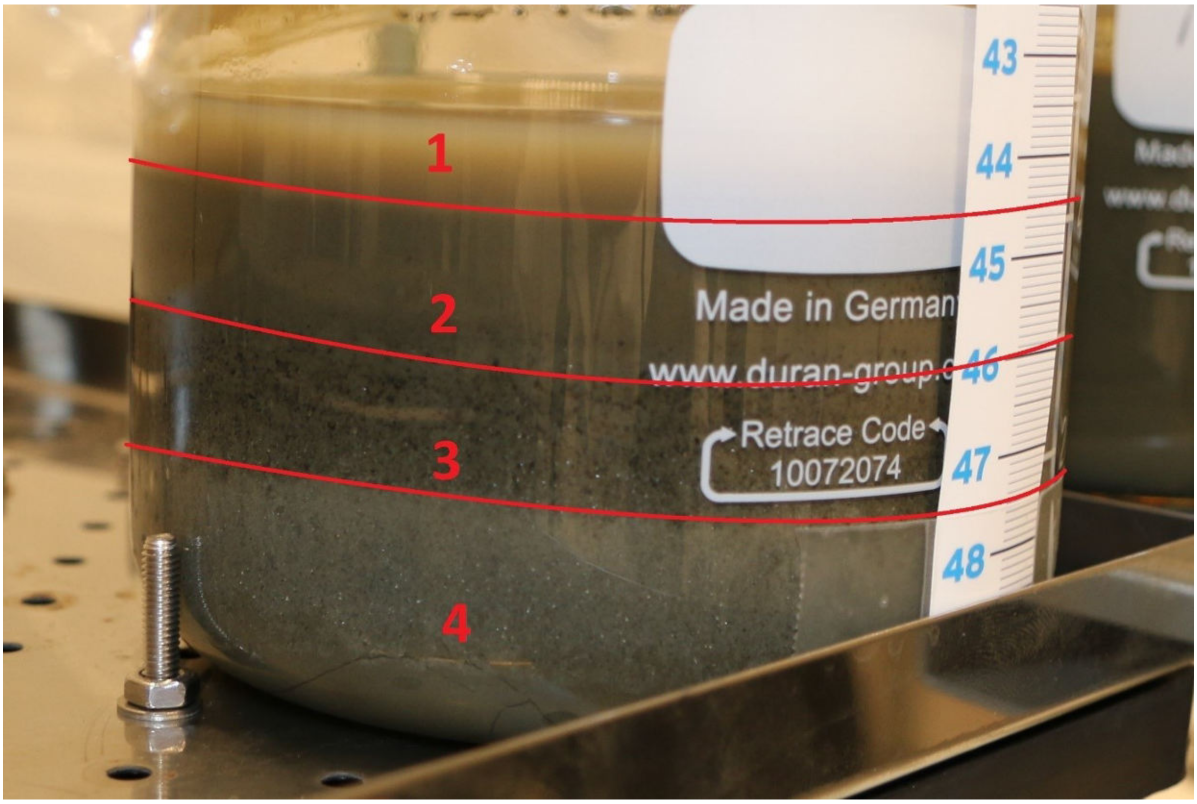

Figure 7.29: The layers that have been formed by pre-experiment 2

7.3.6. Conclusion

To obtain a good quality picture of the sample, the picture must be taken from close by. The 2D shakers are best suited for the experiment. The method of shaking given by these shakers will probably create a uniform layering in the sample.

7.3.7. Manner of documenting

It is important to document the development of the layers. The best way to do this is by making pictures. The pictures must be made manually every time to ensure the correct focus. Also the sample must be taken out of the shaker every time a picture is made. The sample must be placed at the same distance from the camera every time.
Based on the pictures, settlement can be monitored. Afterwards the layers can be extracted separately for analyzation.

Bibliography

[1] Zhen-Gang Ji. *Hydrodynamics and water quality: modeling rivers, lakes, and estuaries*. John Wiley & Sons, 2017.

[2] Jannes Kamphuis, Jeroen Verwilligen, and Reinder Meinsma. Fluid mud and determining nautical depth. *Hydro International*, 2013.

[3] R Kirby, WR Parker, and WHA Van Oostrum. Definition of the seabed in navigation routes through mud areas. *The International Hydrographic Review*, 57(1), 1980.

[4] William H McAnally, R Kirby, Sharon H Hodge, Timothy L Welp, N Greiser, P Shrestha, D McGowan, and P Turnipseed. Nautical depth for us navigable waterways: A review. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 142(2):04015014, 2015.

[5] S Te Slaa, DS van Maren, Q He, and JC Winterwerp. Hindered settling of silt. *Journal of Hydraulic Engineering*, 141(9):04015020, 2015.

[6] Rewert Wurpts. 15 years experience with fluid mud: Definition of the nautical bottom with rheological parameters. *Terra et Aqua: International Journal on Public Works, Ports and Waterways Developments*, (99), 2005.