Suspended sediment distributions under regular breaking waves

Bachelor thesis

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Preface

This document contains the final report of my Bachelor thesis. In a period of 12 weeks I have been collecting data, analyzing the data and drawing conclusions what resulted in this report. With doing this research and writing this report I am able to show my learning progression that I have made in the Bachelor of Civil Engineering at the University of Twente. My main interests lie with sediment transport and the forming of waves and that is why doing this research was a great opportunity for me. Because of the inspiring researchers that I have worked with, I feel even more attracted to learn more about the processes in the near shore environment. With this thesis I learned to be very critical towards the results and the previously executed experiments. Also, I experienced reading and evaluating scientific papers to my own results, which I have not done before. By joining this research team, I have come to meet some experienced engineers and researchers.

I would like to thank Joep van der Zanden for explaining every process that I did not understand and Dominic van der A for his help during the experiments. This research was supported by Sinbad and Hydralab projects and by the University of Twente, University of Aberdeen and the University of Liverpool. The results of my research are useful for the data that was obtained by other instruments. Further I would like to thank Jan Ribberink, David Hurther, Peter Thorne, Tom O'Donoghue and Iván Cáceres for their help, inspiration and their assistance during the project. I hope that those who are not working in this field of expertise are able to learn something about processes that occur in the near shore region.

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Summary

In November and December 2013 experiments were conducted to find out what the effect of breaking waves is on the sediment transport processes. The research was conducted in the CIEM wave flume in Barcelona, where a beach with a slope of 1:10 was created. The beach consisted of medium sized sand (D_{50}= 0.246 mm) and the slope was established to create breaking waves. The waves with a height of 0.85 m and a period of 4 s broke at the top of the slope and 13 measurements of 10 minutes were taken. A suction sampling system was used to measure the concentrations. The suction sampling system consists of suction nozzles that are attached to a pump. With this pumps water and sediment are extracted at different elevations in the water column. The used instruments in this report were attached to the mobile frame that could move in the cross-shore and in the vertical direction. This way the position of the instruments could be changed per measurement. The measuring procedure and the changing conditions during the experiments resulted in a random error of 11.3%. The errors are mainly based on findings of Bosman *et al*. (1987). Because this experiment has different conditions than the experiments where Bosman *et al.* found the errors, the total error is assumed to be higher.

The measured and calculated sediment concentrations show that the highest concentrations are found near the bottom. Sediment concentrations and its distributions were different depending on the measuring position in the wave. Three zones were distinguished: the shoaling zone (zone before breaking), the breaker zone (zone where the waves break) and the surf zone (zone between breaking zone and the shore). In the breaker zone the highest concentrations were found and the turbulence of the breaking wave kept the sediments in suspension. The sediment concentrations in the surf zone were ±2 times lower than in the breaker zone and the concentrations decreased further shoreward. In the shoaling zone the concentrations were comparable to the surf zone, but the concentrations at higher elevations were lower.

On the top of the 1:10 slope a sand bulge was formed by wave-induced currents. This bulge is called a breaker bar and as the time passed it increased in size. As it became higher, the waves plunged stronger and the sediment concentrations increased. The breaker bar did not find an equilibrium height like was expected, so the plunging strength increased every measurement.

When the data was approached with a trend line, the concave Rouse trend line fitted best for almost all the measurements. This was different from the findings of Aagaard *et al.* (2013) who found an exponential profile in the breaker zone. For this report a literature study performed with which the results were compared. It was found that the shapes of the concentration profiles are generally in line with other researches. Because not many measurements were taken for this report, the results give only a good estimation of the processes that occur under, and around breaking waves.

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1. Introduction

1.1 Background and motivations

In the past, models have been made that examined the effects of breaking waves on the sediment transport in the surf zone. Because the sediment transport processes in the surf zone are not fully understood, due to missing detailed measurements, experiments were conducted in the CIEM wave flume. A wave flume is a stretched container of 100 m long, 7 m deep and 3 m wide in which a beach is created (Figure 2-a). When the flume is filled with water, a wave generator (Figure 2-b) can create near-full scale waves that break on the beach. In November and December 2013 experiments took place in the CIEM wave flume of the Universidad Politècnica de Cataluña (UPC) in Barcelona. With this research we try to improve the existing models by performing series of experiments. In comparison to previous experiments, more detailed data is obtained about the sediment transportations and especially the transport under breaking waves. This is therefore an important research that may help to understand better how the erosion of, and deposition onto beaches occurs. In previous years, many experiments were conducted in the field and in the laboratory environment. These previous experiments and its results will be used to compare the data that was retrieved from the experiments. The aim of the experiments is to identify main processes and examine the driving sand transport under large-scale regular breaking waves.

The reason why this wave flume was chosen, was because here it was possible to create conditions that are required for the experiments. It provided a closed environment what eases the control of conditions and that makes it possible to obtain a large amount of data under preferred circumstances. The conditions that can be reached in this wave flume are representative for the reality and cannot be realized in the more commonly used small-scale wave flumes. Ripples were formed at the bottom what causes a different effect on the fluxes in the water column. Measurements took place from the 8th of November until the 20th of December.

1.2 Research plan

The research consisted of experiments with regular breaking waves and the data was collected by using different types of instruments. The data that will be analyzed in this report consists of sediment concentrations and the distribution of the sediment over the height of the water column. To do that, relationships with the measurement positions and the changing of the sand bed profile are analyzed. As can be seen in figure 1, the bed profile changed during the measurements and a bulge of sand was formed where the breaking waves collapsed. The breaking process took place on

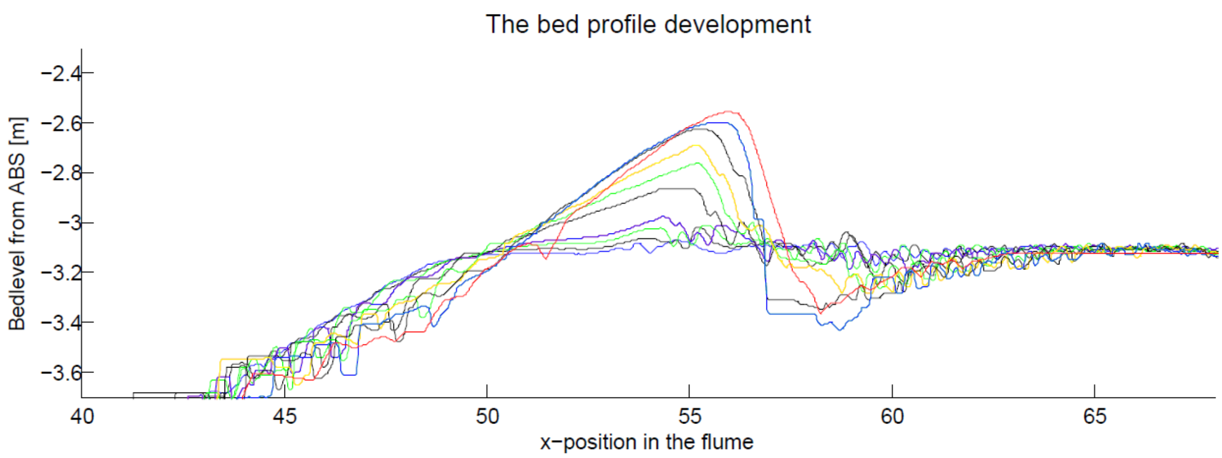

Figure 1: The changing bed profile over the time

top of the created sand slope and it has an effect on the breaking waves. What this effect is and what processes occur will be described later on in the report. Other processes occurred as well in the experiments and therefore four research questions were drafted. The aim of the report is to find answers to these particular questions:

1. How is the sediment distributed over the height of the water column and the cross-shore direction?
2. What is the effect of the plunging strength on the sediment concentration?
3. What trend line fits the best through the data?
4. Are the results comparable to previous conducted experiments?

The results in this report consist of analyzing the measurements with monochromatic breaking waves. To collect data under these circumstances a suction system was used that pumped up water and sediments at different elevations in the water column. This instrument generates data that show the sediment concentrations and the sediment distribution over the height of the water column. Measurements for sediment transport processes will take place in the shoaling, breaker and surf zone and focus on the sediment movements caused by a breaking wave.

This report is composed of several topics that are described in different chapters. In the second and third chapter background information is given about the breaking process, the measuring equipment and the way the results are analyzed. Then in chapter 4 the results of the data analysis are given. This consists of discussing the effects of breaking waves per zone, over the time and the comparison to previous conducted researches. In paragraph 4.4 trend lines are plotted through the data to attribute a certain profile to the retrieved data. In paragraph 4.6 the errors that occurred during the measurements are described in an error analysis. The report will be completed with a discussion and a conclusion of the results.

Figure 2: Three pictures of the CIEM wave flume in Barcelona: a) the empty flume with the counterfeit beach b) the wave paddle that generates waves and c) the measuring of plunging waves

2. Theory

With the suction measurements, it is intended to understand the effect of breaking waves on the distribution of the sediments over the height of the water column. To understand these correlations some background information is required. Kana *et al.* (1979) were the first to rank the principal factors that are controlling the suspended sediment concentration. The most important factors are the elevation above the bed, the breaker type, the distance relative to the breaker point, the beach slope and the wave height. All these processes that occur in the beach zone are described in Appendix I. There is explained why waves break, how they break, the different types of breaking waves and the course of wave energy in the breaking process. In this chapter the breaking of waves and the different types of breaking waves will be discussed first. The process of how sediments are moved by the water will be described after that. Then the breaker bar development and the classification of the zones in the measurements will be described in paragraph 1.3 and 1.4. Finally, in paragraph 1.5 and 1.6 the optimal intake velocity of the suction system and the equations for the fitting of the data will be described.

2.1 The breaking of waves

Many experiments have been done before with the conditions of breaking waves (*e.g.* Kana *et al*., 1979). Waves are of influence on the deposition and erosion of sand in the beach zone. Different types of breaking waves have been described in Appendix I. The experiments in this report are conducted with one type of breaking wave; the plunging wave. Plunging waves are characterized by an arched shape with a convex back and a concave front. When it breaks like in figure 3, it dissipates its energy over a short distance, what causes turbulence in the breaker zone. Also a surf bore is created as the top of the wave forms an air bubble between the crest of the wave and the plunging top. The waves start to break due to an increasing bed level (a shoaling bed) that causes a deceleration of the wave and an increasing wave height. This causes the wave to become unstable and it breaks (see also Appendix I). Another important factor in the breaking process is the wave height and the water level that determine the position of breaking. When the water level is too high, the shoaling process does not affect the waves enough to break. In the experiments, the slope and the wave height were calculated and adjusted until the right place of plunging was found.

Figure 3: A plunging breaker

2.2 Sediment movements

The goal of the experiments is to understand more about the sediment movements under breaking waves. The main process that influences the movements are the underwater fluxes. These fluxes can be influenced by different factors, but the propagation of waves has the most influence. When a wave crest is approaching the breaking point, the underwater flux is seawards (towards the wave). In the trough or right after breaking, the cross-shore flow along the bed reverses and a shoreward flow is created. This cycle is repeated for every wave and the velocities near the bottom increase or decrease depending on the wave height, the water level and the type of breaker.

Depending on the velocities of the currents and the grain size, the friction of the water flow with the sediment particles can bring sediments in suspension or transports them in the cross-shore direction. When the sediment is moved by the underwater currents, they can be transported higher into the water column. The breaking of the wave causes turbulence and because of this turbulence sediment is brought in or remains in suspension. The shoreward flow induced by the plunging wave transports the sediment in the upper part of the water column. Because the water balance need to be restored after the shoreward flow, there is also an undertow directed seaward. The undertow is the flow that restores the water balance and transports sediments. Sediment is also present in the top of the plunging breaker. So when it breaks, it is deposited in the shoreward direction. These processes are shown in figure 4, where the flows are represented by vectors.

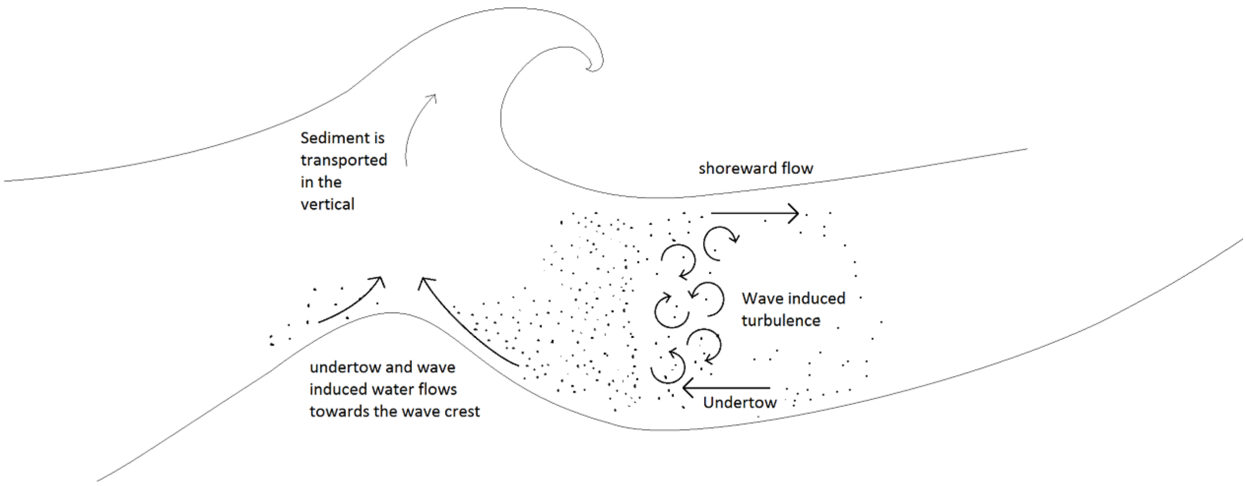

Figure 4: The fluxes that are of influence on sediment transportations

The back- and forward water movement moves sediments near the bottom what creates ripples. When the near bottom velocities increase, larger ripples will be formed and eventually the large ripples transform into a sheet flow layer. Sheet flow is a layer of water near the bottom in which high concentrations of sediments are in suspension. The shapes of the ripples contribute to the prevailing flow structure in the bottom boundary layer. The bottom boundary layer is a region of flow that is influenced by the friction with the bed and in this research it was present until 15 cm above the bed. In this layer the friction causes the flow to be more turbulent than in other layers. The currents in this boundary layer can move sediment into the higher flow layers of the water column.

2.3 The breaker bar

When the bed profile is not horizontal, but has a slope, the vortices toward the wave become stronger because the water level in front of the wave decreases. The shoreward directed water flow into shallower water is compensated by the undertow. Because less water in front of the wave is available, the wave becomes instable and it breaks. The turbulence induced by the breaking wave prevents the sediment to settle and it is free to be transported by the currents. On the edge of a slope waves break due to the shoaling process and a breaker bar is formed. A breaker bar is a buildup of sand that is created by the deposition of sediments by the flow and the sediment suspension by the turbulence (see figure 1). The height of the bar influences the strength of the breaking wave and thus the amount of turbulence in front of the wave (Yoon, Cox and Kim, 2013). Over time, erosion off, and deposition onto the breaker bar should create an equilibrium height (see *e.g.* Komar, 1998).

When the sediment is moved from the bottom, the sediments are also exposed to be transported by different currents at different elevations (Ogston and Sternberg, 2002). The different fluxes at different elevations affect the distribution of sediment over the height of the water column and the other way around the suspended sediment particles influence the flow velocities. When waves break, a turbulent kinetic energy is produced at the surface and near the bottom in the boundary layer (Deigaard *et al.*, 1986 and Smith *et al.,* 2002). This causes a mixing of the flows at different elevations, so more sediment can be brought, or remains, in suspension. The importance of turbulence created by breaking waves in relation with the sediment suspension is supported by the findings of Puleo *et al*. (2000). They found that 80-90% of the variance in the suspended sediment transport can be explained by a relationship with an estimate for the plunging generated turbulent dissipation.

2.4 The classification in zones

To say something about the influence of the breaking wave on the sediment suspension, the measurements are divided into three zones. Also the influence of the measuring position on the results can be described with these zones. The first zone that is distinguished is the shoaling zone. The processes in the shoaling zone are in chapter 4.5 compared to the results that were found in the non-breaking zone (*e.g.* Ahmari *et al.* (2010), Deigaard *et al.* (1986) or Ogston *et al.* (2002)). This is done, because in the shoaling zone the waves do not break and the main process of sediment movement are related to the wave-induced currents.

The second zone that is distinguished is zone in which the waves will break: the breaker zone. This zone begins at the point where waves become instable and start to break and ends where the crest of the wave collapses on the water. The surf zone is defined as a narrow strip of water between the breaker zone and the shore. As described by Yoon *et al*. (2013) 50-65% of the sediment suspension events in the surf zone are associated with turbulent events. In figure 5 the zones are shown and the width is determined on the basis of all the measurements.

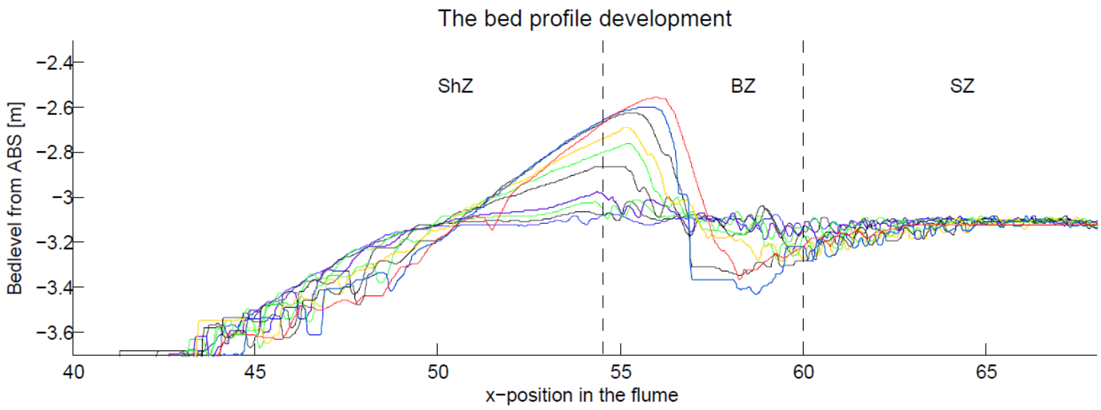

Figure 5: The three distinguished zones, the shoaling zone (ShZ), the breaking zone (BZ) and the surf zone (SZ)

Besides the three zones that are distinguished, also three timeframes are distinguished in paragraph 4.2. The timeframes are chosen because of the forming of the breaker bar over time. The comparison with the use of timeframes can show relationships and differences between sediment distributions at different positions in the wave.

2.5 The optimal intake velocity

In paragraph 4.1 the procedure of data cleaning will be explained. The main criterium that was used to ignore data was the intake velocity. Bosman *et al.* (1987) stated that the optimum intake velocity can be calculated by means of the maximum orbital velocity. The orbital velocity is the time it takes for a particle to complete an orbit; *i.e.* for the particle to move from crest to trough and back to the crest of the next wave as the wave-form passes (The Open University, 1989). The maximum orbital velocity is 1.5 m/s and following Bosman *et al.* (1987) the optimum intake velocity is therefore assumed to be 2,36 m/s (≡ 1 L/min).

2.6 Allocating the data to a profile

The obtained data will be allocated to two types of profiles. In previous researches the data was also allocated to one of these profiles and so it is a good method to verify if the retrieved data was reliable. The two types of profiles are a concave Rouse profile and an exponential profile. The Rouse-shaped curve describes best the vertical mixing that occurs mainly through diffusion. This means that small turbulent vortices produced by bed friction expand as they propagate vertically. It becomes upward concave on a plot of log(C) against sand it can be described by a power-function (1).

$$C(z) = C_a \left(\frac{z_a}{z}\right)^n \tag{1}$$

where n is the Rouse suspension number and C_a is the reference concentration and is determined some small distance above the bed, usually at $z_a = 0.01\ \mathrm{m}$ (Kobayashi, Zhao and Tega, 2005).The mixing occurs mainly through convection and the mean (wave-averaged) sediment concentration profile and can be described by the relationship (Nielsen, 1992):

$$C(z) = C_0 e^{-\frac{z}{l_s}} \tag{2}$$

where C_0 is the reference concentration at the bed ($z = z_0$), l_s is the length scale for the exponential decay of sediment concentration and the length scale is described by Nielsen (1986) as:

$$l_s = \frac{dz}{d} \ln C \tag{3}$$

Nielsen (1992) described that the exponential profiles emerge when coherent vortices are ejected from a rippled bed or when coherent turbulent vortices produced by wave breaking lift sediment upward from the bed.

The given descriptions of the processes and the explained formulas will be used in the evaluation of the results. In Appendix I information about the other types of breaking waves, other processes in the beach zone and more information about the forming of the bed.

3. Instrumentation and experimental conditions

In order to measure the distribution of suspended sediments, a beach was created in the CIEM wave flume. The experimental conditions are different from field experiments, so the experimental conditions and boundaries are described in paragraph 3.1. Further the transverse suction system (TSS) and the volume meter are used to measure the concentrations at different elevations in the water column. These two instruments and other relevant instruments that were used in the experiments are described in paragraph 3.3.

3.1 The experimental conditions

As described in the introduction, the wave flume is a stretched container in which a beach profile was prepared. The CIEM wave flume is 3m wide, 7m deep and 100m long and in shown in figure 6. When the flume was filled with water, a wave generator created near full scale waves breaking on the beach. The wave generator is positioned at one side of the flume and is driven by a large hydraulic pump. By moving back- and forward in a monotonic motion, the wave paddle produced precalculated monochromatic waves. The water that is used in the experiments is clear water, so the suction samples only contain particles that suspended from the bottom (see *e.g.* CIEMlab (2014) and Hydralab (2014)).

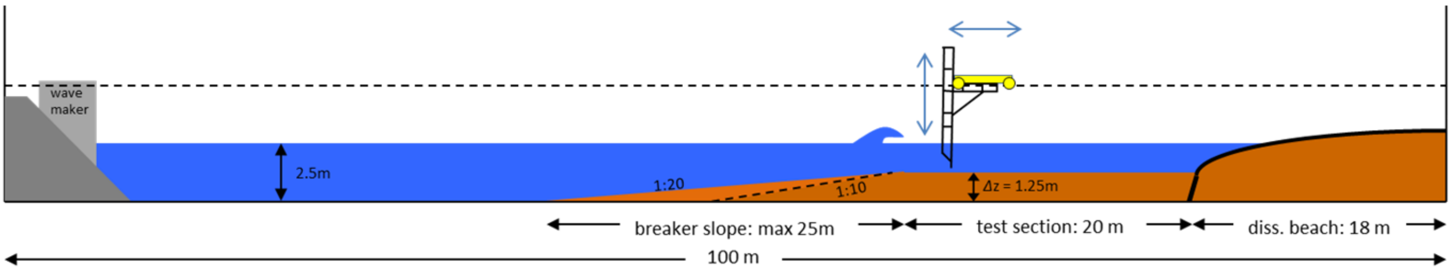

Figure 6: The measurement setup in the wave flume.

There are wave flumes of different sorts and sizes. They are all designed to simulate real conditions so more knowledge about the processes that occur in water-rich environments can be obtained. The CIEM wave flume in Barcelona is one of the largest flumes in Europe. Because of its size it can simulate near full size waves (CIEMlab, 2014). Using a flume for the experiments will exclude some factors that occur in nature. These factors are described in Appendix VI. The sand bed that was created in the flume consisted of a long horizontal plane with an offshore 1:10 slope (see Figure 6). The sand that is used to create the bed has an average grain size diameter of D_{50} = 0.246 mm and shoreward of the horizontal plane a fixed parabolic shaped beach is created that has an energy absorbing structure. The structure and the parabolic shape of the beach will decrease wave reflections towards the test section.

3.2 Wave conditions

Monochromatic waves with a period of 4 s and a wave height of 0.85 m were created in 15 minute during acquisitions. The maximum water level near the wave generator was 2.55 meter and with the increasing bed slope this level decreased to ±1 meter. All the waves plunged as was planned and during the measurements, the height of the breaker bar increased. In time this caused the waves to plunge at the same position in the flume. In total 22 measurements were conducted of which 13 were performed with the transverse suction system. Measurements took place at 9 different positions in the wave flume and thus in different sections of the wave, which is shown in figure 7.

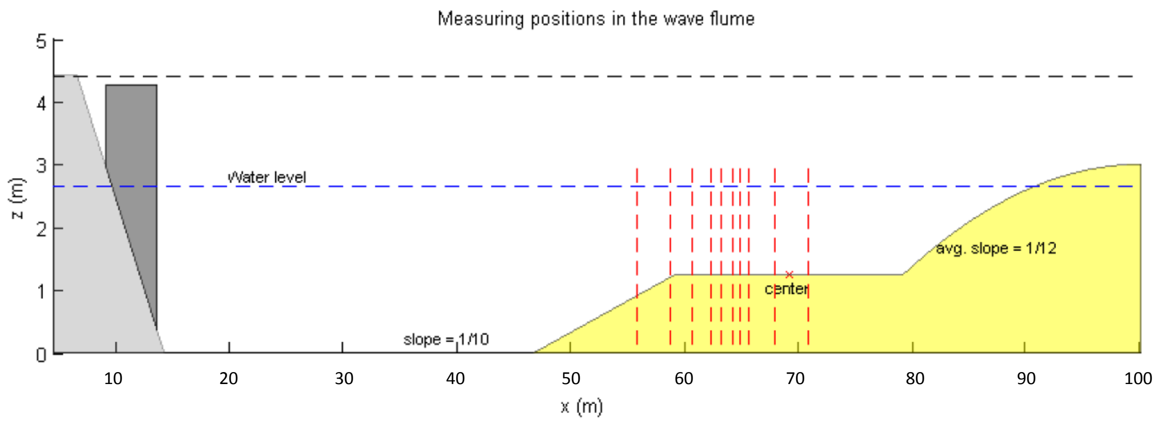

Figure 7: The measuring positions in the flume are shown with the red lines. The figure is not to scale.

3.3 The experiments and the instruments

To measure the concentrations at different elevations in the water column, several instruments were used. The samples were collected with the Transverse Suction System and they were transformed to concentrations with the volume meter. To evaluate the data, the bottom profile measurements and data from Acoustic Backscatter Sensors are used in the results. In this paragraph each of these instruments will be described in successive order.

The concerned instruments were attached to a mobile frame (see *e.g.* figure 2.c). The frame was attached to a moving trolley and could move in the horizontal (x) and the vertical (z) direction. This made it possible to measure at different positions in the breaking wave. The vertical movement was necessary to maintain the same distance between the nozzle and the bed, when the bed started to deform. In figure 8 the mobile frame with the attached instruments is shown.

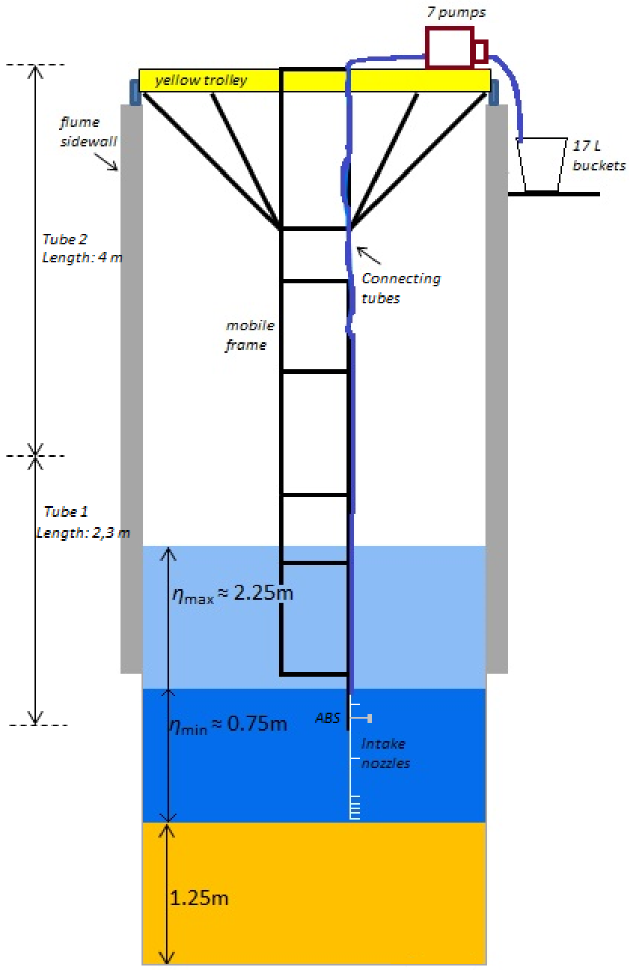

Figure 8: The positioning of the instruments in the wave flume.

3.3.1 Transverse Suction System (TSS)

A way to measure the average sediment concentrations at different elevations in the water column a transverse suction system (TSS) can be used (Bosman, J.J., 1987). The TSS is a system that extracts water and suspended sediment from different elevations in the water column. Because the flow directions and magnitudes under waves change continuously, the suction nozzles are positioned perpendicular to the breaking waves. The most constant delivery of sand in the area near the nozzles will then be reached. By measuring at different elevations, concentration profiles can be found that can provide information about the sediment movement. Seven suction nozzles with a diameter of 3 mm were distributed over the water column and every nozzle was attached to a pump. In figure 11 a close-up of the suction nozzles is given and the distances between the nozzles are shown. In Appendix IX-A the absolute height above the bed per nozzle is given. The deployment above the bed was determined after every run by using a scanning device that determined the deformation of the bed. For every measurement it was tried to position the lowest nozzle close to the bed without that it would be buried. After the measurements was calculated that the average absolute height above the bed was 4.3 cm. In the error analysis (paragraph 4.6) the deviation of the bed level is further explained.

The used pumps with the suction measurements were peristaltic pumps. A peristaltic pump creates a vacuum in the tube that links the suction nozzles to the 17 L collection buckets. The vacuum is reached by a rotating head that squeezes a flexible tube (see figure 9) and with the vacuum water with suspended sediments can be pumped up. In Appendix IV the different brands and the specifications of each pump is given. From the beginning of the wave generation, five breaking waves passed before the suction sampling begun. After five plunges, sediment had started suspend what was necessary when the average concentrations are measured. After water and sediment were collected in the buckets, the sand was given the time to settle. Then the abundant water will be drained from the buckets and the remaining sediment in the buckets is analyzed with a volume meter. Because many steps were performed in the measurement, they are described more extensively in Appendix V.

Figure 9: A peristaltic pump

3.3.2 From sediment samples to suspended sediment concentrations

The conversion of sediment samples to suspended sediment concentrations was done by using a volume meter. The principle of a volume meter is that the volume of the saturated is measured and that with this value the dry volume can be determined. So to be able to use the volume meter, the water was drained from the 17 L collection bucket and the remaining sediment was put in the cylinders of the volume meter. To prevent sediment to stay behind in the bucket, the bucket was rinsed with water and this water was added in the cylinders. By using a sieve the non-sand particles were removed from the sample. A volume meter consists of ten cylinders with different diameters (figure 10). The cylinder diameters range from 0.32 to 2.58 cm and smaller they are, the more accurate the amount of sediment can be determined. After the sand settled, the height of the sediment in the tube could be read from the ruler that was placed next to the tube. With the given diameters of the cylinder and the calibration factor β (Bosman *et al.*, 1987) the weight of the sediment could be determined. The calibration factor β is added to correct the systematic error that occurred in the measuring of the

Figure 10: The volume meter

sediment. To verify the outcomes of the volume meter, the sand samples were also dried and compared to the volume meter. In Appendix VIII is described what the differences between these two ways of collecting are. The measured concentrations and the results in this report are all derived from the measurements with the volume meter.

3.3.3 Profile measuring equipment

Two echo sounders were used to measure the bed elevations in the test section. This instrument emits a sound wave and its echo is measured. The bed profile was measured when no waves were present. The echo sounders are attached to a smaller trolley that was moved over the test section to take measurements. To find relationships between the height of the wave, the height of the breaker bar and the concentration distributions, the development of the bed profile is used. When all the profile measurements are showed in one figure, the development of the bed profile can be seen (see figure 5).

3.3.4 Acoustic Backscatter Sensors

An Acoustic Backscatter Sensor (ABS) emits an acoustic pulse of a high frequency towards the bottom and measures the acoustics returned. Thorne *et al.* (2002) explained that the magnitude of the backscattered signal can then be related to the concentration of the suspended sediment over the water column. Because the ABS can also measure the time delay between transmissions, it can also give the range to the sediment. The sand bed is shown by the ABS at a certain range where the concentrations are high. Before and after the measurement the bed level was determined. The absolute height of the suction nozzles above the bed is calculated by averaging the bedlevel of the first and the last 30 seconds of a run. This absolute height can then be used in the comparison of the sediment distributions in the vertical of the water column. The height differences between the nozzles and the ABS is shown in figure 11.

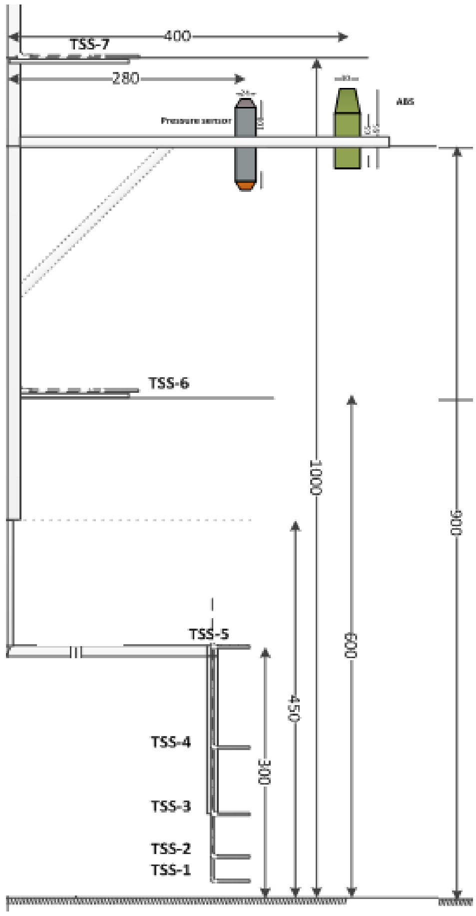

Figure 11: The height differences between the suction nozzles and the ABS

4. Results

In this chapter the raw data will be evaluated and compared to previous researches. The results will be discussed by showing figures with the bed development and the concentration profiles. The breaker bar, as described in paragraph 2.3, is formed by the sediment movements in the breaker zone. In figure 12 can be seen that the breaker bar increased every measurement. To evaluate the sediment distributions over the height of the water column at different positions in the wave, it is necessary to include the effect of the changing breaker bar. Therefore the three timeframes are distinguished. The measurements were also taken at different positions in the wave, so by distinguishing three different zones the effect of the measuring position to the sediment concentrations can be explained.

In paragraph 4.2 the results per timeframe will be described and in paragraph 4.3 the results per zone are shown. For analysis in the future the results are fitted to a concave Rouse, or to an exponential function in paragraph 4.4. In the final paragraph the results of the measurements are evaluated with literature. To draw conclusions, only the good measurements are analyzed and therefore the first paragraph will describe how insufficient and extreme values are removed from the data set.

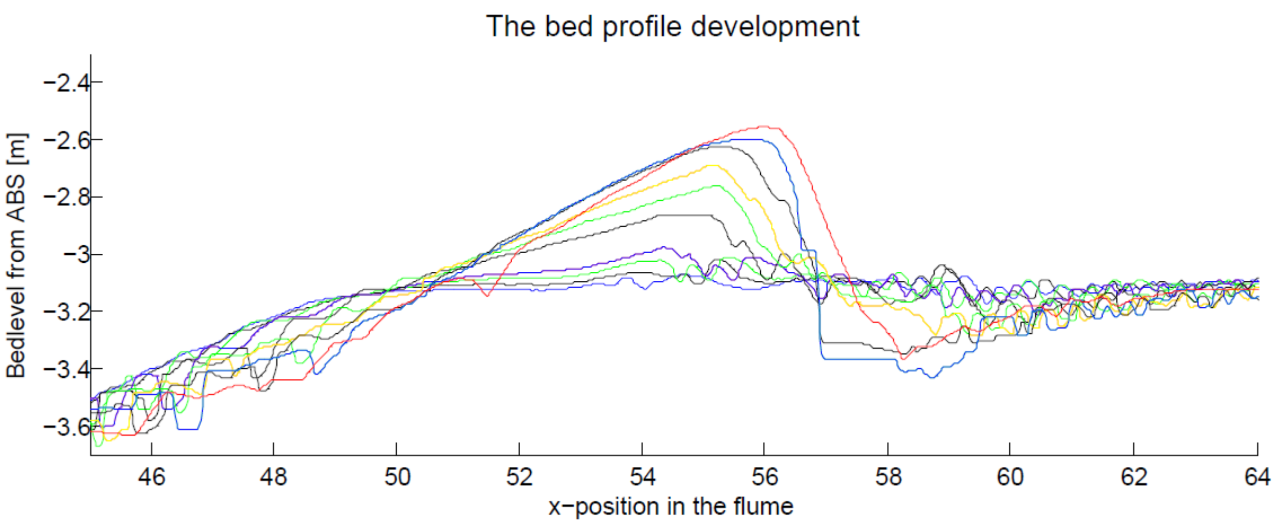

Figure 12: The development of the breaker bar and the bed profile

4.1 Data cleaning

Because only the good measurements can be analyzed the process of data cleaning is described in this paragraph. In every measurement seven data points were collected that correspond to the seven suction nozzles. The suction nozzles are all attached to peristaltic pumps and because the pumps have different intake velocities, the main criterion for selecting valid data was the intake velocity. As was described in chapter 2, the optimal intake velocity was 2.36 m/s (≡ 1 L/min). Because the weaker pumps were not able to pump up 1 L/min at its maximum intake capacity, values higher than 1.6 m/s are pronounced to be valid. At this velocity the pumps were able to up water and sediment at a constant flow.

As can be seen in figure 13, most of the data is declared valid to continue for the analysis. That pumps 1, 2 and 3 were stronger than pumps 4 to 7 and that can be seen in the intake velocity. Also the plunging of the waves that caused air bubbles in the water column influenced the intake velocity. Because the measuring position and the height above the bed changed, the waterlevel in the wave trough sometimes became lower than the elevation of the highest nozzle (nozzle 7). That is why most of the values of nozzle 7 are this low and are ignored. In contrast to nozzle 7, the first and the second nozzle contained extremly high values that were left away in the figure. These high values were obtained when the nozzle got buried in a ripple during the experiment. In Appendix IX-A all the discrepancies, the removed extreme values and the time adjustments are described for every measurement.

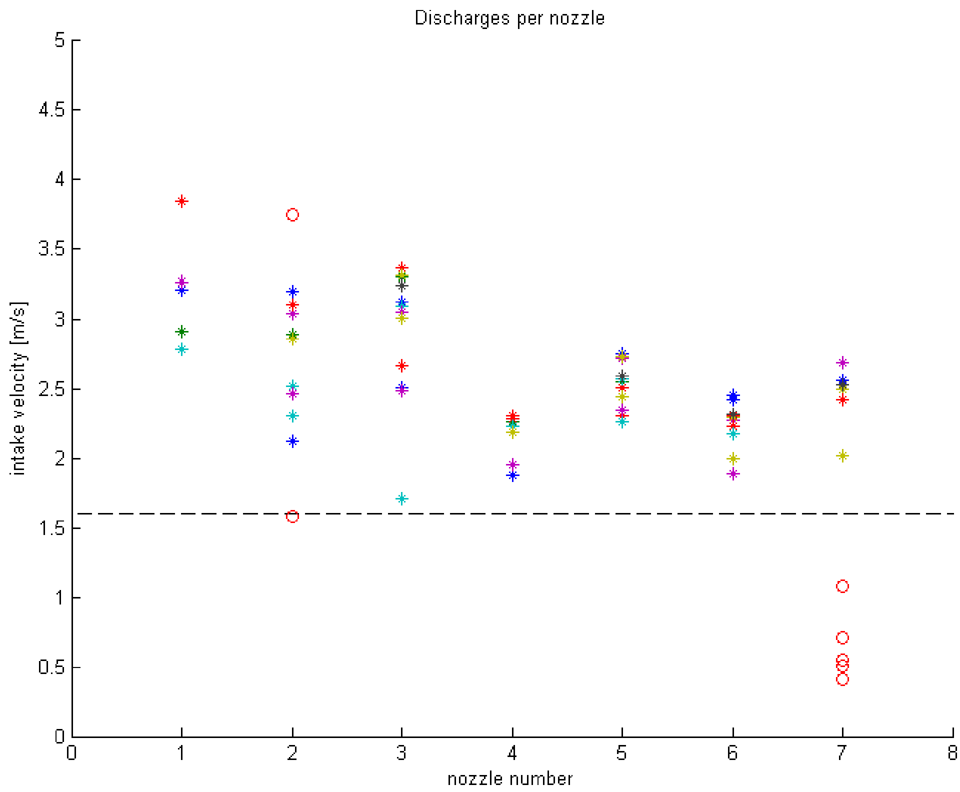

Figure 13: The discharges per nozzle. The outliers are shown with red circles.

4.2 Comparison of the results per timeframe

The three timeframes that are discussed are 0-60 minutes, 60-180 minutes and 180-365 minutes and are chosen this way because of the forming of the breaker bar. The comparison with the use of timeframes can show relationships and differences between sediment distributions at different positions in the wave. The effect of the breaker bar on the measurements is discussed in paragraph 4.3. In the first timeframe the bar does not have its final shape yet. In the second timeframe it is formed towards a representative height and in the last timeframe it has become towards its intended equilibrium height. They will be discussed separately in the following sub-paragraphs.

4.2.1 Measurements in the first 60 minutes

As can be seen in figure 14, the moving sediment near the bottom started to deform the bed under the measuring point. The sediment concentrations seem to increase over time, what can be attributed to the deformation of the bed. Because this increase is small, this is only an assumption. When looking at the figure, it can be noticed that the concentrations higher in the watercolumn are the same. On average the nozzles of runs 2 and 3 are positioned higher above the bed than in runs 1 and 4, what can have a small influence on the concentrations near the bed.

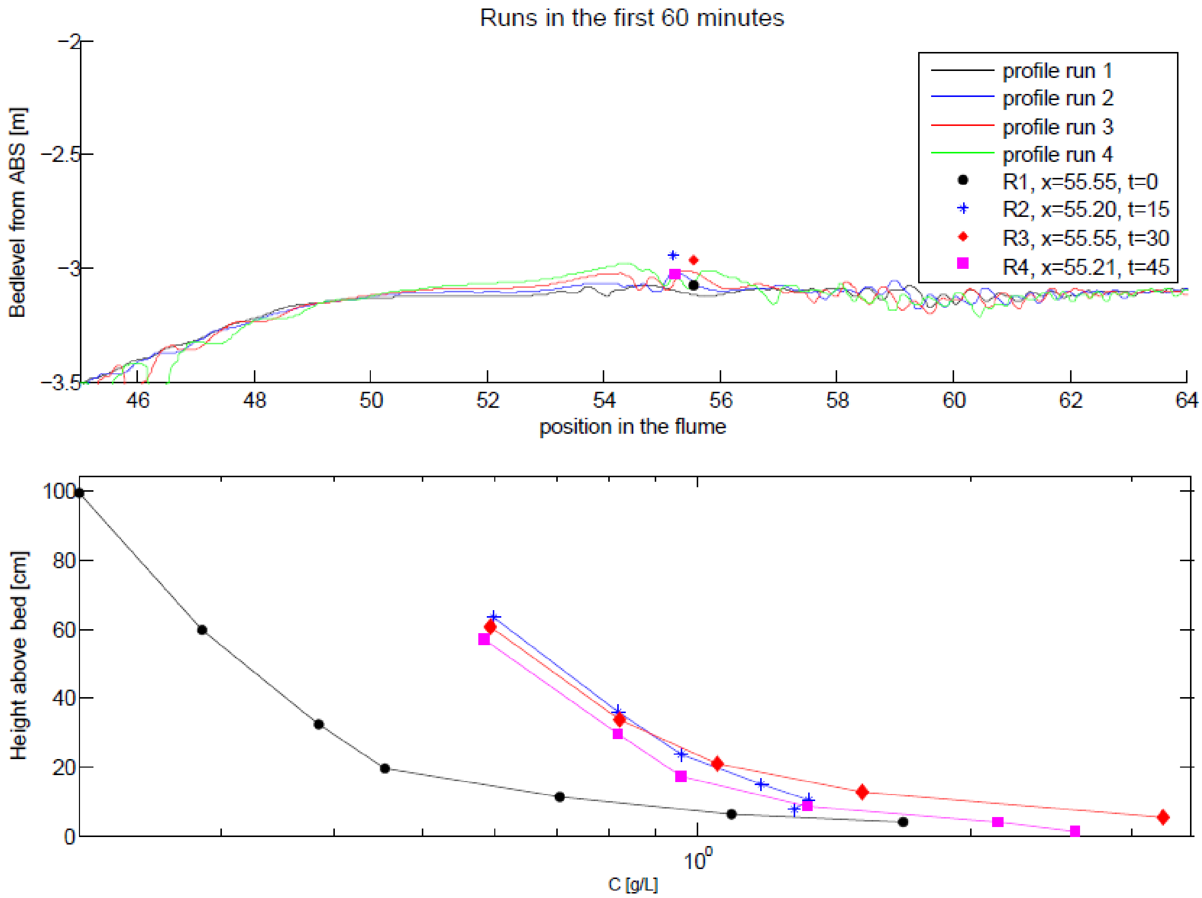

Figure 14: The measurements in the first 60 minutes with their positions in the flume and the bed profile given

4.2.2 Measurements in 60-180 minutes

In runs 5 to 12 the bed was developing more than in the first timeframe and the measurements were taken in different cross-shore positions. That is why the differences between the concentration plots are larger. The measurements of runs 5 and 12 are taken in the breaker zone and as can be seen, the concentrations are higher here than in the surf zone. Also remarkable is that the sediment suspension in the surf zone decreases further away from the plunging point, what can be related to the decreasing (breaking) wave energy. The breaker zone has also become smaller in comparison to the first 60 minutes because the waves are breaking more at the same position.

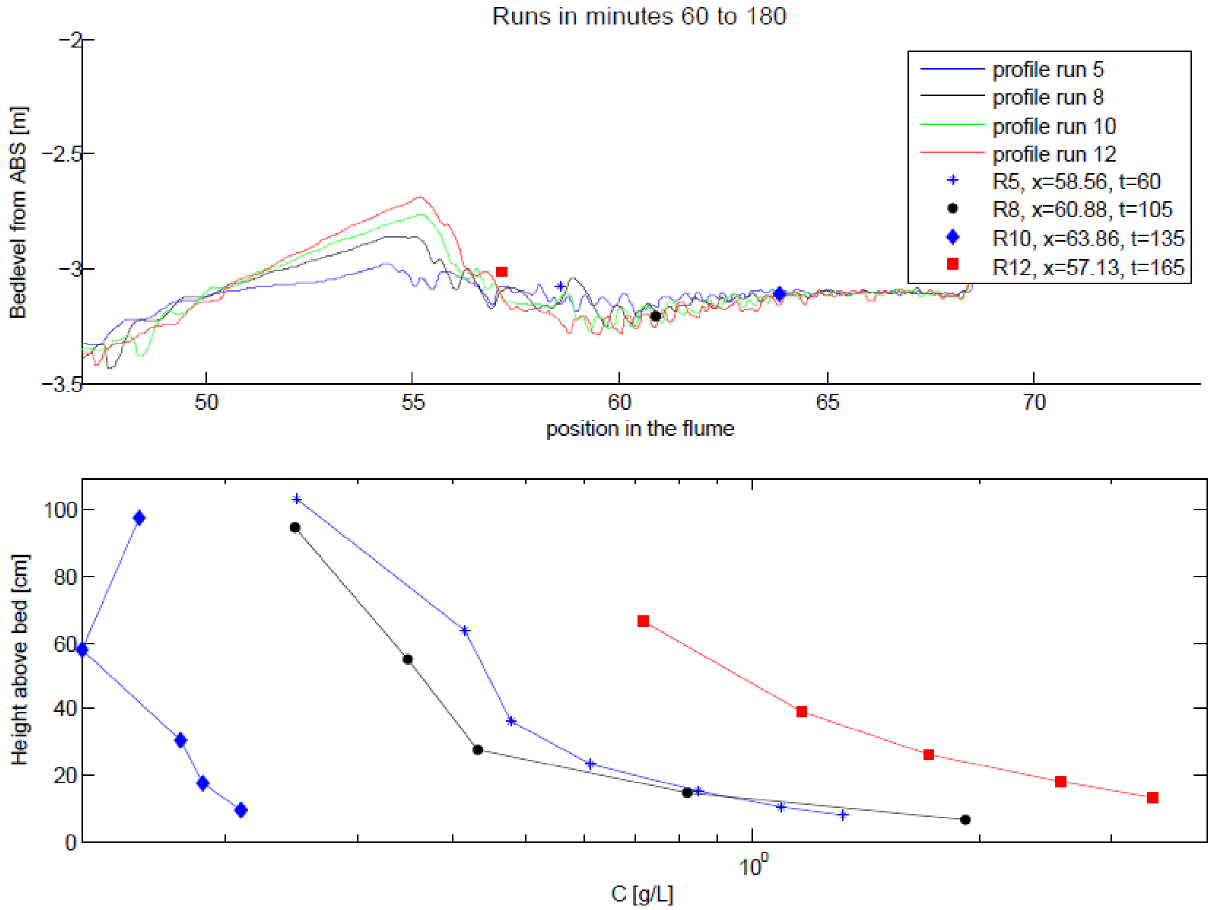

Figure 15: The measurements in 60-180 minutes with their positions in the flume and the bed profile given

4.2.3 Measurements in 180-365 minutes

In this timeframe, measurements in all zones were conducted. During all the acquisitions the breaker bar increased and did not find an equilibrium. If more measurements were conducted it probably would have found an equilibrium. The equilibrium height of the bar was higher than was presumed, so it did not stop growing during the experiments. The bar development caused the plunging point to move shoreward by a meter. Figure 16 shows that sediment in the breaker zone is transported higher in the water column than for the other zones. A significant difference in concentrations can be found between runs 14 & 18 and runs 20 & 22. The concentrations in the breaker zone are ±2 times as high as the concentrations in the shoaling zone. By looking at the concentrations of the measurement in the surf zone (run 16) it can be concluded that the plunging breaker dissipates a lot of its energy around the plunging point. This indicates that the plunging right after the breaker bar has a vertical orientation and that this decreases the shoreward flow. So less sediment is transported towards the surf zone.

From this timezone and figure 15 can be concluded that the position in the wave is of influence on the sediment concentrations. The concentrations in the breaker zone are the highest and there the sediment is suspended higher in the water column than in the other two zones.

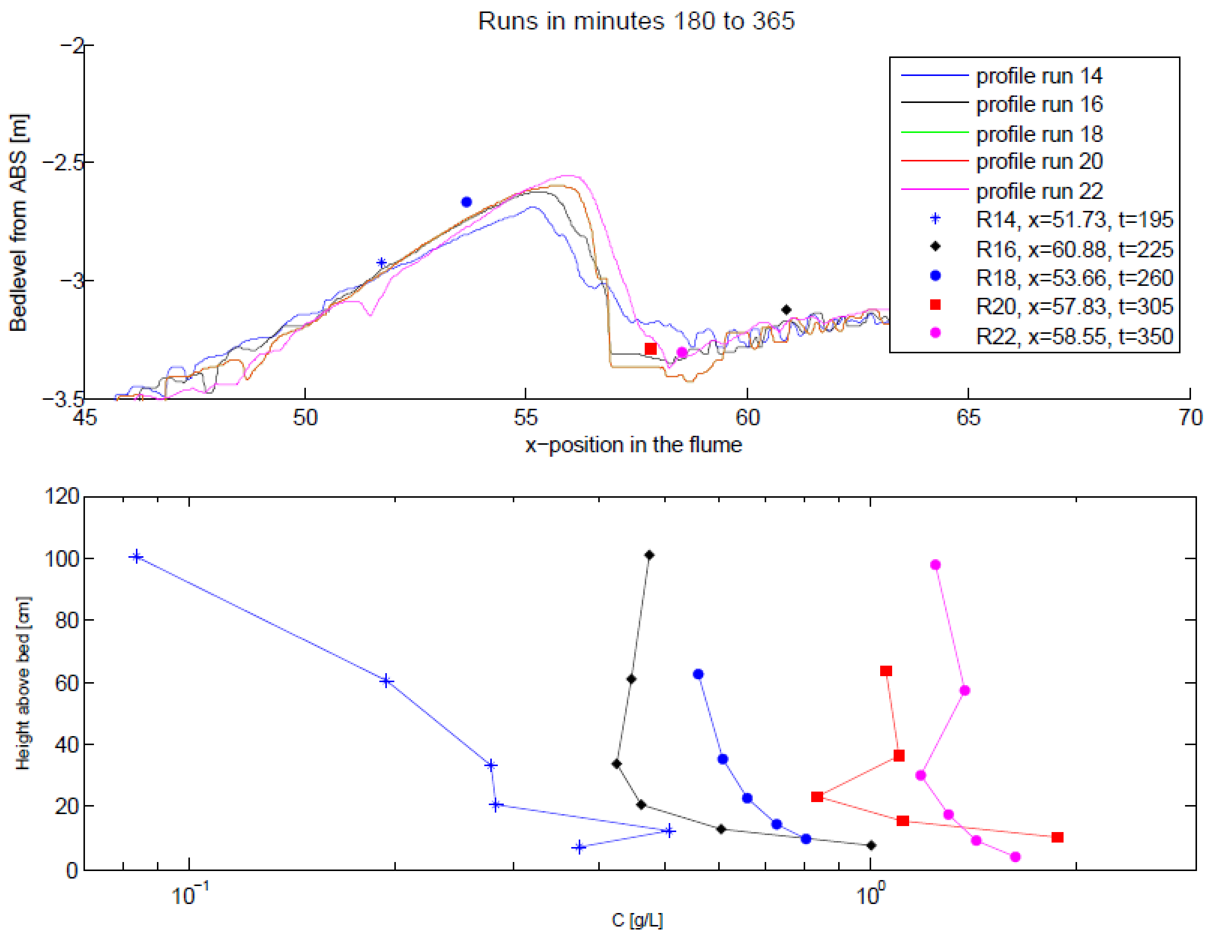

Figure 16: The measurements in 180-365 minutes with their positions in the flume and the bed profile given.

4.3 Comparison of the results per zone

In the previous paragraph the effect on the sediment distribution related to the cross-shore position was shown. In this paragraph the effect on the sediment distribution related to the (bed) developments in the time are discussed. The concentration gradient can be appointed to many factors. Three zones are defined to clarify what the effect of the changing profile over the time is. The three zones are shown in figure 5 (paragraph 2.5) and consist of the shoaling zone, the breaker zone and the surf zone. The breaker bar was formed around x = 55 m, measured from the wave paddle and the surrounding area is shown to see the development of the bar.

4.3.1 Measurements in the shoaling zone

As can be seen in figure 17, both measurements in the shoaling zone are taken when the breaker bar was already formed. Closer to the top of the breaker bar the concentrations increase. The differences in concentrations can be attributed to several things. The measuring position is important, because the currents in the water are different in the breaking zone (see chapter 2). Also the height of the breaker bar can be of influence to the concentrations. An increasing height of the bar causes an increase in wave height. Thereby the downward force increases when it plunges. The stronger plunge causes a stronger undertow towards the face of the wave what can increase the sediment movement on top of the bar.

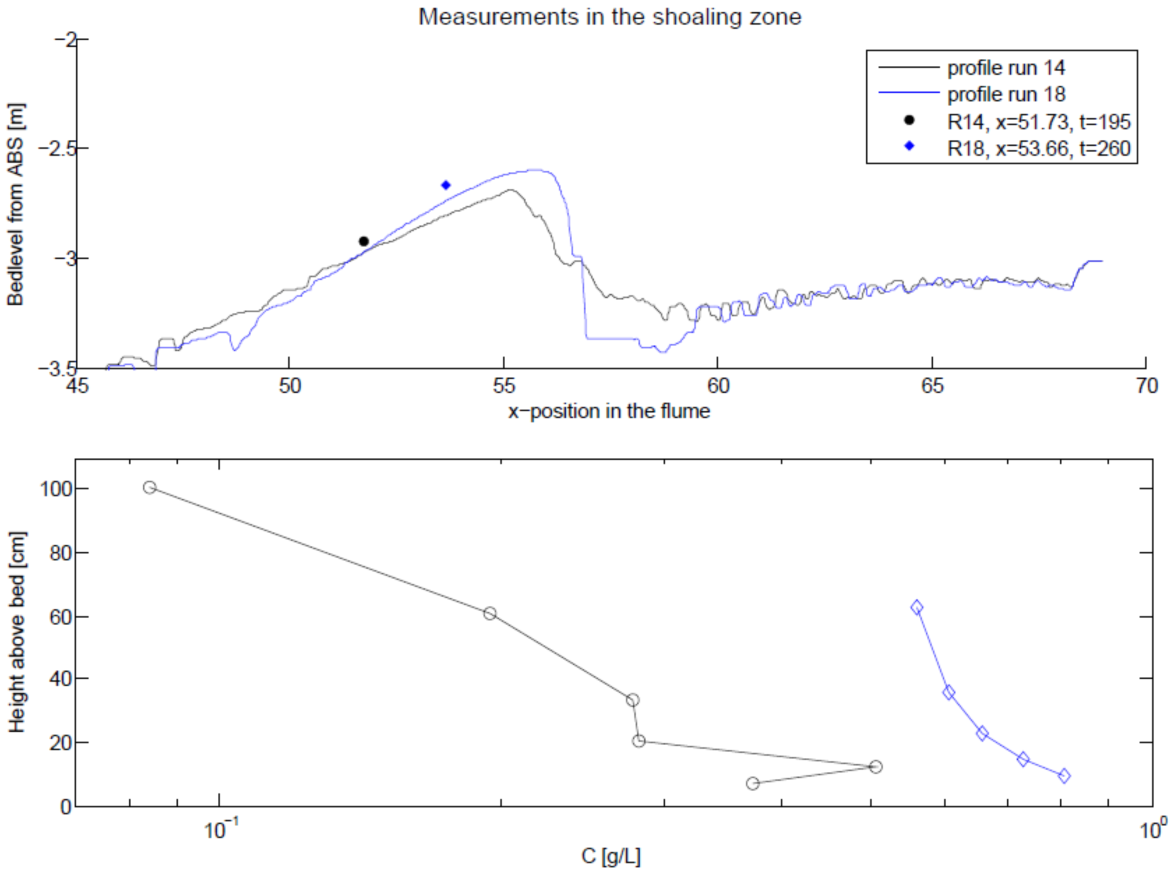

Figure 17: The measurements in the shoaling zone

4.3.2 Measurements in the breaker zone

Most measurements were conducted in the breaker zone and their results are shown in figure 18. In Appendix IX-B, this figure is divided in three figures to show the relations more precise. As the breaker bar grows, the concentration profiles change. Therefore it can be concluded that the height of the breaker bar is of influence on the sediment mixing in the water column. With the increasing bar the concentrations at higher elevations increase as well. This increase in concentrations is shown best by the differences between runs 5 and 22 and can be explained by the seaward flowing undertow that becomes stronger with higher waves. The undertow moves sediment because of friction and it follows the elevations in the bed when it is flowing seawards (see also chapter 2). In conclusion, the increasing height of the breaker bar causes the sediment to be transported to higher elevations in the water column. Then turbulence, induced by the breaking wave, causes the sediment to stay in suspension longer what is illustrated by the concentration profiles of runs 20 and 22.

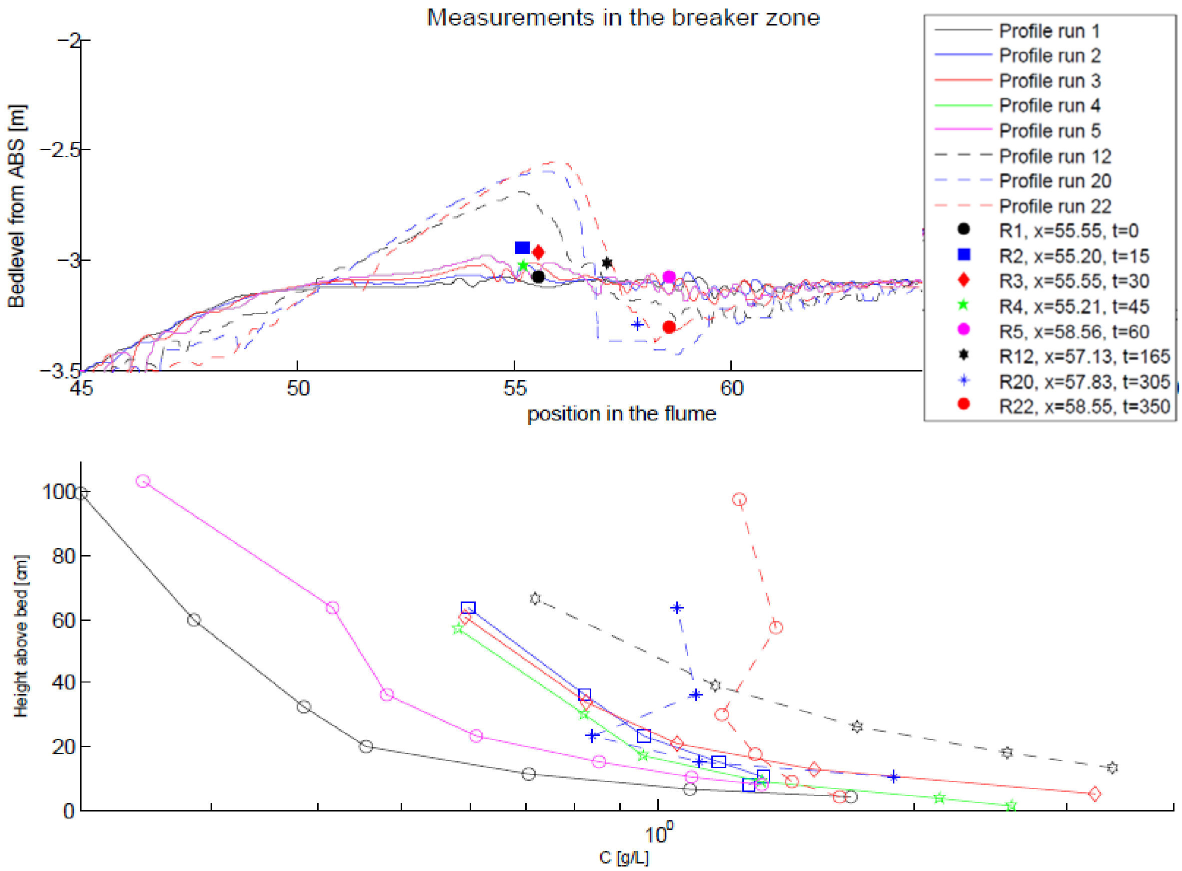

Figure 18: Measurements in the Breaker zone

4.3.3 Measurements in the surf zone

The surf zone is the area after the breaker zone and in the surf zone the wave has a shoreward flow induced by the breaking wave higher in the water column. Near the bottom an undertow is present that restores the water balance in the zone. The wave loses its remaining power after plunging by rolling towards the fixed beach. The decreasing of wave power in the surf zone is caused by friction with the bed and the currents. The decreasing of the wave power (see chapter 2) can be found in the concentrations that decrease when the measurement was performed further away from the plunging point. In run 8 the higher concentrations near the bottom can be explained by the strength of the plunge. The stronger plunge also has a more vertical orientation, what caused more sediment mixing near the breaking point. In run 8 the breaker bar was lower than in run 16, where the sediment mixing is more because of the stronger plunge. The decreasing concentrations can be explained by the influence of turbulence and the currents that maintain the water balance.

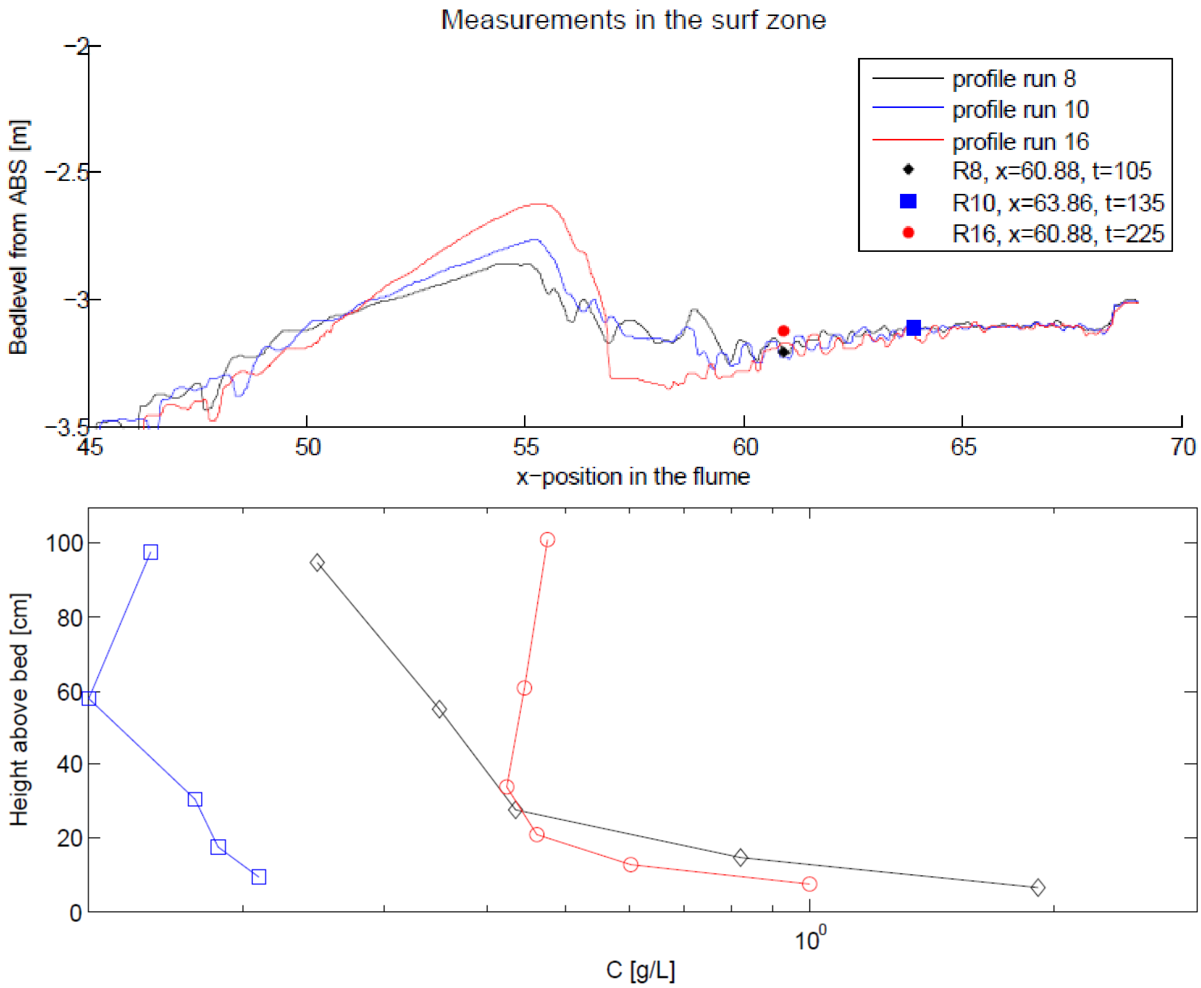

Figure 19: Measurements in the surf zone compared.

4.4 Allocating the data to a concave or an exponential fit

For further research and implementing the results into models it is necessary to determine the shape of the profiles that were found. Aagaard and Jensen (2013) fitted their results with either a Rouse (concave) profile or an exponential profile. The formulas for the exponential and the concave Rouse profile were described in chapter 2 and will be applied in this paragraph for the collected data.

Aagaard *et al.* (2013) showed that the measured profiles from the surf zone were the most similar with the Rouse shaped profile. The measurements in the breaker zone corresponded better with an exponential curve. Their research did not feature measurements in the shoaling zone. Table 1 shows the correlation coefficient with both profiles. As can be seen, the Rouse profile fits the best for most of the runs. In the first runs, the correlation coefficients do not differ much, but in later measurements a clear rouse profile is found. This differs from the experiments of Aagaard *et al*. (2013) what can be explained by the different measurement conditions. The results of this report were retrieved from a flume experiment and the results from Aagaard *et al*. (2013) were retrieved in the field at three locations on the North Sea coast. For the lowest 4 nozzles the fitting of the results have also been calculated. That was to see if different results are found if only the data close to the bottom were observed. Because these results were almost the same as in Table 1, they are shown in Appendix IX-C.

Table 1: The results of the allocation of the profile to the raw data

Run:	Best fit with a profile of:	Position in the wave:	Size of breaker bar:	Rouse; C_a	Rouse suspension number:	Rouse correlation coefficient:	Exponential; C_0	Exponential; l_s	Exp. correlation coefficient:
1	Rouse	BZ	Small	4,596	0,746	**0,995**	2,036	0,131	**0,958**
2	Exponential	BZ	Small	2,769	0,341	**0,967**	1,467	0,652	**0,986**
3	Rouse	BZ	Small	11,346	0,769	**0,997**	4,198	0,160	**0,955**
4	Rouse	BZ	Small	3,007	0,373	**0,981**	2,514	0,215	**0,944**
5	Rouse	BZ	Medium	4,744	0,630	**0,996**	1,421	0,380	**0,944**
8	Rouse	SZ	Full size	10,454	0,921	**0,995**	3,058	0,129	**0,978**
10	Rouse	SZ	Full size	0,308	0,175	**0,891**	0,203	2,318	**0,779**
12	Rouse	BZ	Full size	15,000	0,631	**0,997**	5,396	0,256	**0,983**
14	Rouse	BBZ	Full size	1,869	0,378	**0,861**	0,772	1,170	**0,608**
16	Rouse	SZ	Full size	1,850	0,376	**0,831**	0,750	1,252	**0,574**
18	Rouse	BBZ	Full size	1,246	0,199	**0,995**	0,813	1,461	**0,929**
20	Rouse	BZ	Full size	3,701	0,363	**0,696**	1,549	1,095	**0,497**
22	Rouse	BZ	Full size	1,734	0,080	**0,793**	1,453	5,262	**0,556**

The reference concentrations (C_a and C_0), the suspension number n and the exponential length scale l_s are optimized for every run to fit a profile through the data. To see if the optimized values are reliable they are plotted over the time in figure 20.The reference concentration was expected to increase over time, because increasing concentrations near the bed were found. This is also the reason why a decrease in the suspension number n was expected. Only the parameters from the breaker zone are shown, because in this zone the most measurements were taken. The other zones consisted over too little measurements to make an estimation of the trend.

The reference concentrations in the Rouse and in the exponential profile seem to increase over time, looking at the first 6 measurements. The last two measurements (runs 20 and 22) are discussable, because in the first two plots of figure 20 show a lower concentration. This lower value can be caused by the lowest nozzle that was buried and ingored in the data. The reference concentration was then calculated from a higher altitude above the bed, where the concentrations are expected to be lower. In addition, the breaker bar was not formed in the first five measurement, what causes the values to be less reliable. The Rouse suspension number *n* shows a decreasing trend, like was expected when the concentrations increase. The length scale seems to increase, what was also expected. Because of the little amount of measurements and the different elevations above the bed it is difficult to draw solid conclusions. To be able to do that, more measurements are required.

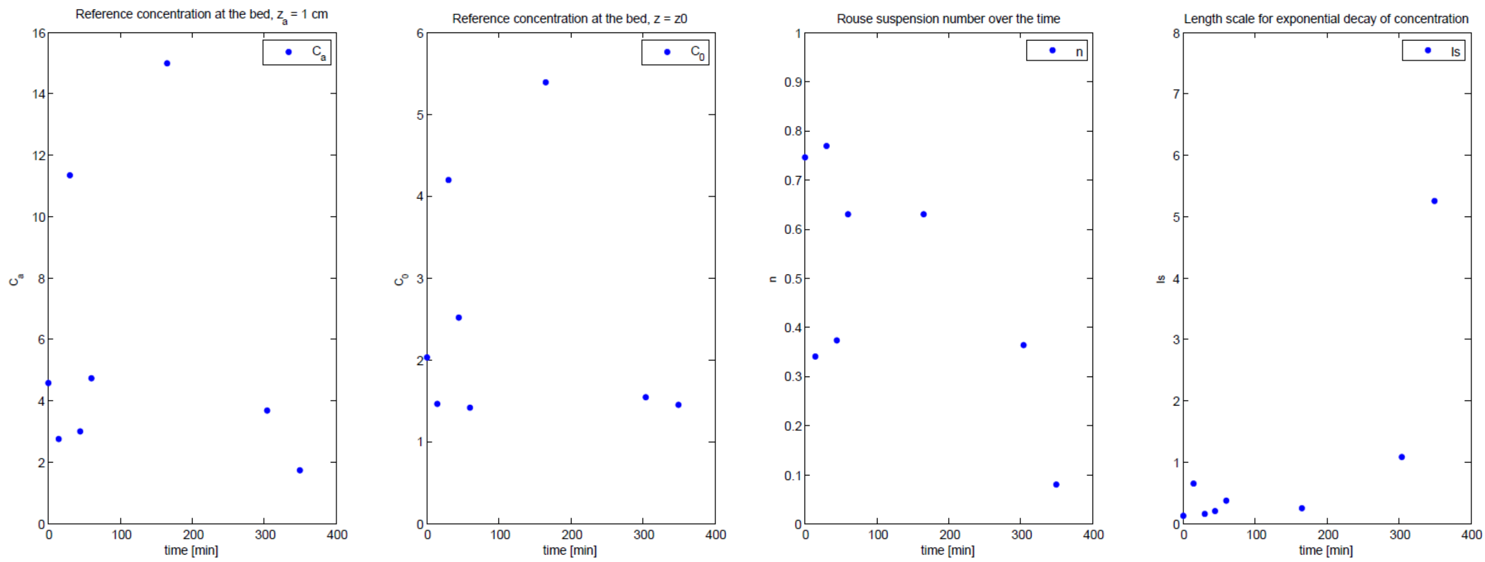

Figure 20: The progressment of four parameters in the breaker zone that are used for the Rouse or Exponential profile.

Beneath, the fitting of the results of three representative runs with the Rouse profile are presented (figure 21). In Appendix IX-C the fitting results of all the experiments are shown. The concentration profiles per zone show that in the breaker zone the most sediment mixing takes place. The differences between the surf and the shoaling zone are small, but in general the sediments are transported higher in the water column in the surf zone. Also can be seen that in the shoaling zone the concentrations near the bed are very high what may indicate that a sheet flow occurred.

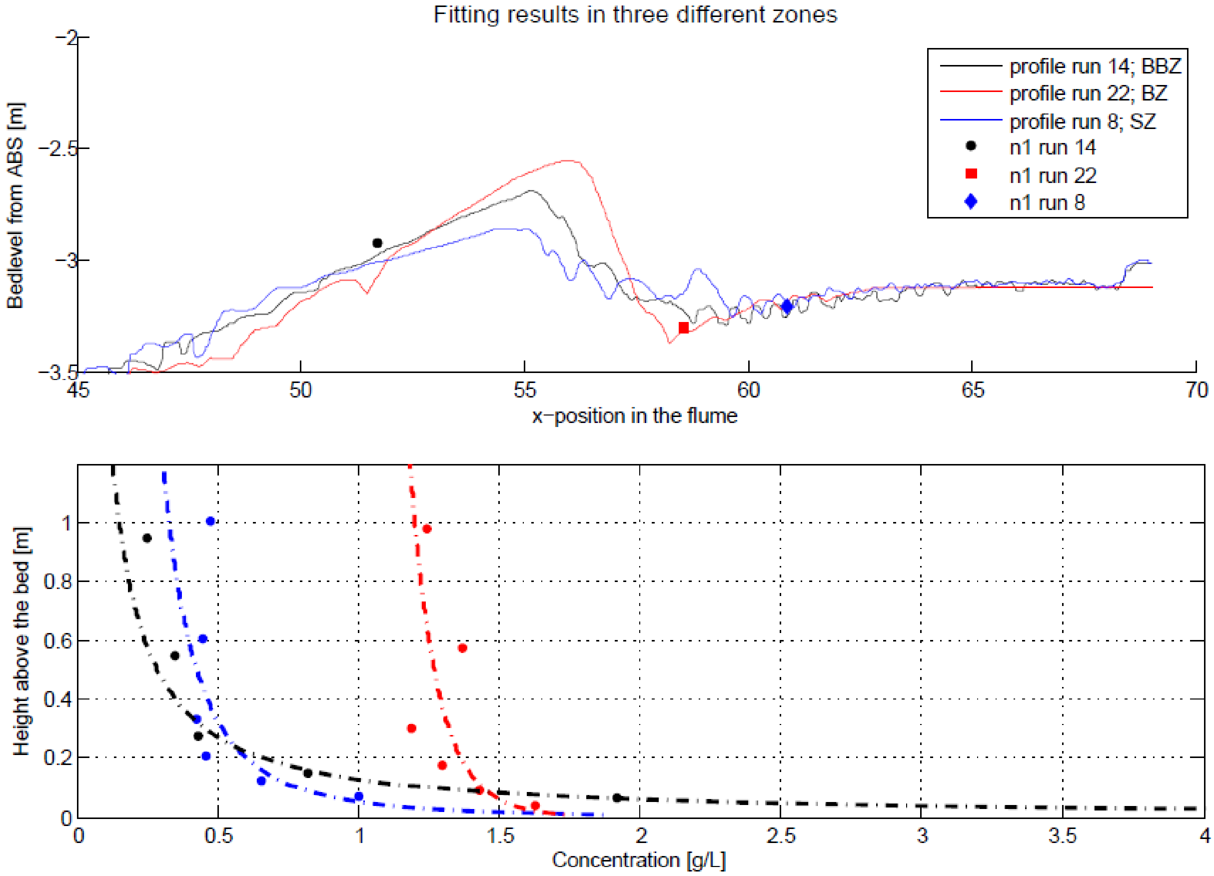

Figure 21: Three fitted results in three different zones compared

4.5 The results evaluated with literature

Previous studies consisted of experiments in a field or laboratory environment. Field research differs a lot from laboratory research, because of the larger water depths, tidal influences, weather circumstances, types of waves and the occurrence of longshore currents. Also because waves approach the shore from different angles and the breaking position changes, it is more difficult to know exactly the measuring position in the wave. These factors can be controlled or are excluded in laboratory experiments and that is why only a rough comparison with the flume measurements can be made.

Many articles covered the suspended sediment concentrations, but most of them are performed with different instruments what makes it hard to compare them with our results. Therefore, a selection is made that will be used to describe and compare the similarities and differences of the results. The literature that is not described in this paragraph but is concluded in the literature study can be found in the literature matrix in Appendix VII. In the sub-paragraphs that follow, the main objective is to compare the shape of the concentrationprofiles to the profiles found in the literature.

Because the articles speak of the breaker and the surf zone but not of the shoaling zone, the results from the shoaling zone are compared to experiments in the non-breaking zone. The relevant researches that are conducted in the field are discussed first, followed by the researches in a laboratory environment. For each zone a comparison and an explanation for the differences is given. This paragraph will end with a short conclusion in which will be summarized in what degree the results are comparable to the literature and if the obtained data may be considered valid.

4.5.1 Field experiments

Bolaños, Thorne and Wolf (2012) conducted experiments under non-breaking waves in the near shore site. The sediment concentrations that were obtained in the near bed region vary between 0.005 and 0.03 g/L and they are best fitted with an exponential function. These results are different to our research, where the concentrations varied between 0.01 and 1.5 g/L in the shoaling zone. This can be explained by the larger waterdepth (4.5 m) which makes that the influences of the waves on the near bottom velocities are smaller. Still the shape of the concentration profiles are comparable to the results in our experiment. Beach *et al*. (1996) did as a part of another research measurements in the shoaling zone what gave low concentrations (<0.7 g/L), but the shape of the concentration profile is comparable.

In the breaker zone Beach *et al*. (1996) found concentrations in the bottom boundary layer between 0.4 and 1.7 g/L, which is in line with our measured concentrations in the breaker zone. Different to our research was the less steep (1:60) beach slope, what has an influence on the breaking process (see paragraph 4.3.2). Together with the comparable average wave height of 0.9 m, it can be concluded that the waves plunged with lower strength. Still the sediment concentrations and the shape of the profile are comparable, which can be explained by the smaller sand particles (D_{50} = 0.17 mm) that are taken in suspension faster.

Another experiment in the breaker zone was conducted by Ogston and Sternberg (2002), who did both laboratory and field experiments. The suspended sediment concentrations under breaking waves (here: spilling breakers, see Appendix I) in the field experiments show comparable results. The highest concentrations are found in the near-bed region and higher in the water column sediment concentrations were more uniform. A remarkable result in the measurements of Ogston *et al*. (2002) was a small increase in the concentrations in the upper part of the water column what was also found in the results in paragraph 4.3.2.

Many researches have been done to describe the processes in the surf zone, but not many contained comparable sediment concentration measurements. The research of Deigaard, Fredsøe and Hedegaard (1986) was comparable to our research. They conducted experiments with an average wave height of 0.7 m and the mean grain size diameter was 0.12 mm. Under spilling breakers and this small grain size the concentrations that were found were very low (0.0001 to 0.0004 g/L) compared to our results (0.4 to 1.5 g/L). Even with these small concentrations the results show an increasing sediment concentration towards the bottom, which is comparable to our results. As already described in paragraph 4.4 Aagaard and Jensen (2013) allocated their measuring results to an exponential or to a concave Rouse profile. They measured at three different sites on the North Sea shore and each site had different conditions (see Appendix VII). In the breaker zone they found that the results were approached the best with an exponential profile and in the surf zone with a

Rouse profile. In our experiments the Rouse profile fitted best for all the three zones, but because of the reasons that were given in paragraph 4.4 this is discussable.

Beach *et al*. (1996) show that with plunging waves it is possible that concentrations in the surf zone are low on top of the bottom boundary layer and then increase with the height in the water column. As can be seen in measurement 16, 20 and 21, this phenomenon was found in this research as well.

4.5.2 Laboratory experiments

Prior to the research, some expectations for the concentration profiles were raised. According to Schretlen *et al.* (2010) the profiles in the shoaling zone should give decreasing concentrations in the upper section of the water column. Towards the bottom, the concentrations increase. This also comes forward laboratory experiments with non-breaking waves of Ahmari and Oumeraci (2011). In this research these profiles were found as well, but also a more vertical oriented concentration course was found in the breaker and surf zone. Thorne, Williams and Davies did large flume experiments in 2002 with regular and irregular non-breaking waves. The results of the regular non-breaking waves show a concentration profile with an increasing concentration closer to the bed. Suction measurement concentrations lied between 0.3 and 3.5 g/L, which is very close to the concentrations in the shoaling zone in this research. This is because the wave heights are more or less the same (0.6-1.3 m) and the mean grain size (D_{50} = 0.330 mm).

For a better comparison with literature more data is needed. Not many researches used a transverse suction system or showed average sediment concentrations in the results. When it is assumed that the shapes of the obtained concentration profiles give a good indication, most of the shapes in previous conducted experiments are comparable. In conclusion, it is not possible to compare the results quantitatively. Nevertheless, the concentration profiles indicate that the conducted experiments in general give results that are usable for further research.

4.6 Error analysis

An error analysis was done because the data collection procedure consisted of many steps where errors could occur. It is tried to correct the systematic errors where possible and by performing the measurements in a systematic way, the errors also have been reduced. The actions that were undertaken each measurement are also described in Appendix VIII. For these reasons the systematic errors are not discussed here. Irregularities that occurred during an acquisition were notated in a logbook and have been taken into account in the results and in the error analysis.

Bosman *et al*. (1987) were the first to do measurements with the transverse suction system. They stated that the relative concentration error $\Delta C_s/C_s$ is found to be rather constant near 10%. The 10% error in the height due to 1 mm height difference is increased by a 5% random error due to the accuracy of the wet volume measurement (see Appendix VIII). Some extra calculations were performed to find errors in the measuring procedure that are different from the error description of Bosman *et al.* (1987). One of these calculations was performed to see if there is a large difference between the analysis with the volume meter and dry weighing. In Table 2 can be seen that the use of the volume meter is not very different from the dry weighing of the samples.

Table 2: The calculation of the error between dry weighing and the volume meter (pump 1 was defect in this measurement)

Nozzle #:	Measured true dry weight [g]:	Weighed dry weight [g]:	Difference	Factor:	Deviation [%]:
1	-	-	-	-	-
2	20,85	21,36	0,51	1,024	+2,43
3	12,45	11,82	-0,63	0,949	-5,09
4	7,33	6,93	-0,40	0,946	-5,44
5	11,66	12,35	0,69	1,059	+5,94
6	8,94	9,42	0,48	1,054	+5,36
7	2,85	2,99	0,14	1,049	+4,88

The calculation result in an average error of 4.86%, what is in accordance with the 5% random error described by Bosman *et al*. (1987). Further the error that occurred during the flushing of the water from the 17 L buckets was estimated to be 1%. This error is taken into account, because the finest sand particles are hard to see and they could have been flushed away during this process (see Appendix VIII). In our experiments the height above the bed is taken as an average value of the height in the beginning and in the end. In Table 3 the height deviation above the bed for the lowest nozzle is given. The values are obtained by calculating the difference between the bed level before and after the measurement. As can be seen, the value deviates more than 1 mm for every measurement. The random error is probably higher than the 10% that is determined by Bosman *et al.* (1987).

Table 3: the height difference between before- and after the measurement given in centimeters

Run:	2mhz	3mhz	4mhz	Average deviation:
1	1,50	1,50	1,45	1,48
2	2,50	2,00	2,00	2,17
3	-4,57	-3,00	-3,00	-3,52
4	-3,81	-4,45	-4,50	-4,25
5	-1,12	0,50	1,50	0,29
8	3,65	-0,28	-3,43	-0,02
10	-5,50	-4,00	-2,00	-3,83
12	3,00	4,13	3,50	3,54
14	0,57	0,50	-0,50	0,19
16	-5,41	-5,14	-3,50	-4,68
18	-1,15	-1,00	-1,08	-1,08
20	-0,48	-0,59	0,00	-0,36
22	5,95	7,00	7,50	6,82

The total error consists of a random error of 11.3%. Because of the changing bed level the height differences were much higher. That is why the determined 10% error by Bosman *et al.* is probably higher. To get more trustworthy values for this and other errors, more measurements should be taken. This error analysis only shows a broad approximation for the values of the errors.

5 Discussion

By using a wave flume, many factors are excluded that normally occur in the near-shore region. These factors are of importance when the obtained data is evaluated. In this chapter the focus will mainly lie on the discussion of the measuring conditions, deviations in the data and the measuring procedures.

When the experiments started, there was no breaker bar and thereby the waves plunged at different positions in the flume. In the first 5 measurements the bar started to form. After that it had the shape of a bar and the waves started to plunge at the same position. Even though the measuring position in the first runs was almost the same, the data is less reliable because of the changing plunging point. In the following runs the breaker bar increased in height and did not find an equilibrium height as was expected. That is why the plunging strength and the turbulence increased every run. The breaking wave formed a surf bore when it collapsed. The walls of the wave flume obstructed the trapped air to be released from the sides. This process caused air bubbles to be trapped in the area of measuring, what influenced the sediment distribution over the height of the water column. Effects of the trapped air can be seen in the concentration profiles, where the sediment concentration at 50 cm above the bed was lower than other measurements. Sometimes also an increase in concentrations was found for the two nozzles that were positioned high in the water column.

The TS-system measures an average sediment concentration at different elevations in the water column. The average concentrations are insecure because of the changing bed profile, the changing measuring position and the changing conditions in the flume. Moving ripples caused the nozzle elevation above the bed to change during the run and this resulted in the lowest suction nozzles to be buried. That and malfunctioning of the pumps is why some data had to be ignored. This way less information about the sediment concentrations was obtained. Also, unwanted particles were collected during the measurements. Although the samples were sieved before evaluating them with the volume meter, some non-sand particles arrived in the volume meter- and the dry weighing measurements.

To estimate the sediment distribution profile, two different trend lines were fitted through the data. In contrast to the research of Aagaard *et al.* (2013) this resulted in a concave Rouse profile instead of an exponential profile in the breaker zone. Even though this is an interesting difference, the fitting of the data is very inaccurate. Per run, for (a maximum of) seven measurements a profile was fitted through the data that has an error of more than 10%. With more data, a more accurate profile could be fitted through the data and then it is possible that another optimal profile is found. It is difficult to compare the results of this research with other researches, because in this research measurements were done with conditions that were not specifically used before. Still, it was possible to determine whether a plausible result was generated.

The error analysis is mainly based on the findings of Bosman *et al.* (1987). If a more thorough error analysis would be performed it is expected that a higher total error would be found. In the process of obtaining data, collected sediment can be lost at several moments. Bosman *et al.* (1987) did not describe all the steps that were conducted in this research and he calculated the total error on the basis of 1 mm height deviation. Our measurements were taken above a changing bed profile, what caused height deviation to be in the order of centimeters. Therefore the error is assumed to be higher than the 11.3% that it is now.

Because not many measurements are conducted, it is difficult to draw conclusions to the results. The many points of discussion can be reduced by performing more measurements and by proceed with the analysis of the data that was obtained by the instruments that are not covered by this report. In the next chapter conclusions will be drawn on the basis of the available data.

6 Conclusions

The results are given and the possible explanations for the concentration profiles that were found are described. In this paragraph an overview is given of all the conclusions concerning the results in the previous chapters. In the introduction four research questions were drafted. The conclusions regarding these questions are described following the layout of the report.

1) How is the sediment distributed over the height of the water column and the cross-shore direction?
2) What is the effect of the plunging strength on the sediment concentrations?
3) What trend line fits the best through the data?
4) Are the results comparable to previous conducted experiments?

To begin with, the wave generator created plunging waves and the effect of the plunging was clearly visible as was expected. The medium sized sand (D_{50} = 0.246 mm) was transported into suspension and the measurements with the Transverse Suction System were performed. In the first five measurements, the breaker bar was still forming and the point of plunging was different in the runs. After the fifth measurement, the breaker bar started to form and the wave started to plunge at the same position. To see what the effects of the changing bed level and breaker bar are, three zones were distinguished: the shoaling zone, the breaker zone and the surf zone. In the shoaling zone the concentrations were higher closer to the breaking point. Based on literature and the chapter Theory, this happened because of the wave-induced velocities and the undertow that are merged at the top of the breaker bar. From the measurements in the breaker zone it was seen that the increasing bar influenced the vertical sediment mixing, because sediment concentrations increased in the height. The sand was taken into suspension mainly by the undertow (The Open University, 1989). The plunging wave created turbulence it is presumed that this turbulence kept the sediment in suspension. This is why the concentrations at higher elevations were higher than in the other two zones. Also, some concentration profiles were found that showed an increase in the upper part of the water column. This probably happened because of the turbulence and air bubbles that were created by the surf bore. With measurements in the surf zone it could be seen that closer to the shore the sediment concentrations became lower.

Besides the three zones, three timeframes were drafted in which the effect of the cross-shore position are related to the sediment distributions. The three timeframes that were discussed were 0-60 minutes, 60-180 minutes and 180-365 minutes and were chosen according to the forming of the breaker bar. The concentrations in the breaker zone were ±2 times higher than in the shoaling and surf zone. Also, the more shoreward of the plunging point the measurement was taken, the lower the concentrations were that were found. For the shoaling zone this was the other way around, so the concentrations decreased further away from the plunging point in the seaward direction.

Two trend lines were fitted though the data. The concave Rouse trend line showed best the course of the concentration profile for almost all the measurements. One measurement in the breaker zone was better allocated with an exponential profile. The correlation factor, that describes the percentage of data that was covered by the profile, shows that the difference between the two profiles is very small. With more data, the differences between the two tested profiles would be clearer and better conclusions could be drawn. In the measuring with the TSS and the volume meter many errors could occur. With a broad error determination an error of 11.3% was found. The errors are mainly based on findings of Bosman *et al*. (1987) and some are determined by calculating the concentrations in comparable ways. Because of the changing bed levels and the few measurements that were taken the error is presumably higher. More precise data was obtained by other instruments that use the TSS measurements as calibrations and for a comparison. Analysis with these other instruments is required to get a more precise image of the distribution of the sediment concentrations and to define the errors better.

In general, the concentration distribution was different in every zone and for every measurement. However, all the concentration profiles showed that the highest concentrations were found close to the bottom. The course of the obtained data is generally in line with previous conducted researches. More measurements are required to draw better conclusions. The generated results can be used for the analysis of other instruments and provide a good directive for the concentration distributions in the different zones.

7 References

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Appendices

I. Theory

With the suction measurements, it is intended to find correlations between the breaking of the waves and the distribution of the sediments over the height of the water column. These correlations, how sediments suspend and why waves actually break are important factors to understand. Kana *et al.* ranked in 1979 the principal factors that are controlling the sediment concentration. The most important factors are the elevation above the bed, the breaker type, the distance relative to the breaker point, the beach slope and the wave height. In this paragraph these factors and the corresponding processes will be explained. Firstly, the breaking of waves and the different types of breaking waves will be discussed. Hereafter the process of sediment movements will be described. In this report a comparison of the obtained results in different parts of the beach zone will be made. Finally, to understand better where the origin of these differences lie, an overview of the characteristics of these zones is given.

A. Processes in the beach zone

Waves are created by the surface friction of the wind, the tide and swell. The height and the speed of the wave used to calculate the wave energy. Because of the law of conservation of energy, the wave energy has to be maintained as it moves toward the shore. The energy balance can be described as follows (The Open University, 1989):

$$E = \frac{1}{8}(\rho g H^2) \qquad (4)$$

where ρ is the density of the water, g is the gravitational force and H is the wave height. When a wave approaches shallow water, the waveheight will increase due to the shoaling bottom. That is because the wave energy has to stay the same and while the depth decreases, the energy will push the wave from a horizontal to a more vertical direction. The wave power is a rate at which energy is supplied per unit length of wave crest:

$$P = E * c_g \text{ [J/s/m] or [W/m]} \qquad (5)$$

where E is the energy of the wave and c_g is the speed (celerity) of the wave. If the group speed reduces, the wave energy must increase to maintain the power (The Open Univesity, 1989). At some point the height of the wave will become inbalanced and the wave will. When it is breaking, the potential energy will be transformed into kinetic energy, what produces a downward force to the shoreward side of the wave. After breaking, the remaining wave engergy will be absorbed in the surf zone, where the wave gets a rolling form in which it moves towards the shore. One of the simplest theorems that describe the changing of energy is the roller theorem. The roller theorem shows the conversion of the wave energy into a wave breaking dissipation to heat D_h and conversion to turbulent energy of a roller D_w :

$$\frac{\partial E_w}{\partial t} + \frac{\partial E_w c_g}{\partial x} = -D_h - D_w \qquad (6)$$

In this equation the term $E_w c_g$ is referred to as the energy flux and E_w is the wave energy that consists of the sum of the potential (E_p) and the kinetic energy (E_k) (Svendsen I. , 2006).

To maintain the mass balance of water, an undertow transports the water seawards again is required. The balance can be described by the orbital movement of the water. Ardhuin, O'Reilly, Herbers and Jessen (2003) describe this balance as the overall momentum balance and visualized this in figure 22. In this figure it can be seen that the momentum fluxes are changing due to the shoaling bottom. Also, the wave height and wave length change with the shoaling bottom. Another evident observation is that due to the shoaling bottom the undertow seawards ("mean flow momentum flux") becomes stronger, what causes the water level to descend.

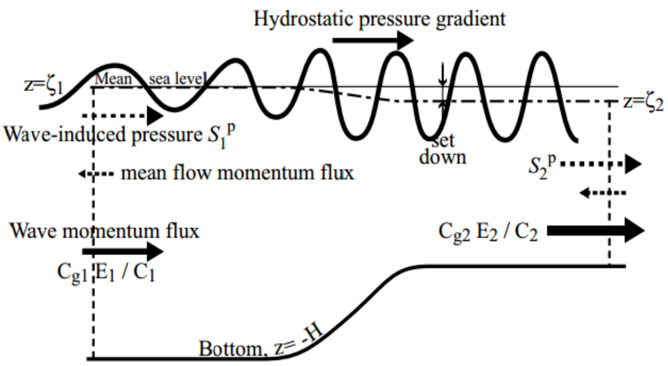


Figure 22: Balances of fluxes in the near shore region

B. Breaking waves

Waves are of influence on the deposition and erosion of sand in the beach zone. Four types of breaking waves can be distinguished and they are shown in figure 23: spilling breakers, plunging breakers, collapsing breakers and surging breakers. The two most researched types of breaking waves are spilling and plunging breakers. These types of breakers are most important for the sediment transport in the beach zone, because they cause the most turbulence in the water that affects the sediment stirring from the ground. Plunging waves are characterized by an arched shape with a convex back and a concave front. When it breaks, it dissipates its energy over a short distance. Spilling breakers are characterized by foam and turbulence at the wave crest. Collapsing waves are similar to plunging breakers, except that the waves may be less steep and instead of forming a tube, the front face collapses. Surging waves occur only on very steep beaches and are characterized by long, low waves and the waves remain unbroken when the wave slides up the beach (The Open University, 1989). One of the most important factors in the breaking process is the slope of the beach. In the experiments that were conducted in Barcelona, the slope and the wave height were calculated and adjusted until the right place of plunging was found. It can be seen in figure 22 that the different breakers are related to a different slope. Plunging waves are known for creating the most turbulence in the breaker zone and this type of wave is discussed in this report.

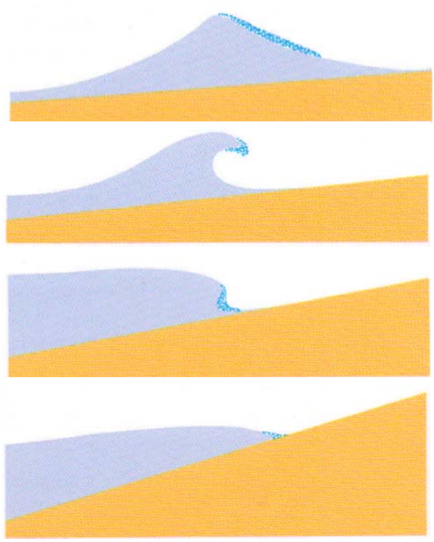


Figure 23: Four types of breaking waves; 1) Spilling, 2) Plunging, 3) Collapsing, 4) Surging

As described above, wave height increases due to the shoaling sea bottom. The type of breaking is commonly represented by the Iribarren number (Battjes, 1974):

$$\xi = \frac{(\tan\beta)}{\sqrt{\frac{H}{L_0}}} \tag{7}$$

where β is the local cross-shore bed slope, H is the wave height and L_0 is the deep water wave length. This number is a dimensionless parameter that is used to model several effects of (breaking) surface gravity waves on beaches and coastal structures. The threshold from spilling to plunging breakers is a ξ of 0.4-0.5 (Battjes, 1974). Aagaard and Jensen (2013) did field measurements of near-bed sediment concentration and sediment diffusivity in the breaker and inner surf zone from three different beaches. By using the Iribarren number they could determine the breaker type, and when they looked at the bed formation they could seek for similarities with the vertical sediment mixing in the water column.

C. The formation of the bed and the suspending of sediments

The propagating of waves create flows under water. Figure 23 shows the changing in the near bed flows when a wave passes (Ahmari and Oumeraci (2011)). It shows that when the wave crest is approaching, the underwater flux is towards the wave. In the trough, the cross-shore flows along the bed reverse and flow backwards is created. This cycle is repeated for every wave and depending of the wave height and the water level, the velocities near the bottom increase or decrease. Depending on the current speed and the grain size, the friction of the water flow with the sediment particles will move the sediment. When the current speeds are low, small ripples are formed and while the speeds increase larger ripples are formed. When the waves become higher or propagate above shallower water, velocities near the bottom will increase. This creates a thin layer of very large sand concentrations grows and decays during a wave cycle. This thin layer of sand is called sheet flow and occurs due to the increasing water velocity near the sea bed (*e.g.* Ribberink and Al-Salem, 1995).

When the bed profile is not horizontal, but has a slope, the vortices towards the wave become stronger and because of the decrease of water level with the increasing slope, the vortices backwards become less strong. This causes a lack of water in front of the wave what causes it to break. When the processes that are described above happen on a larger scale, a breaker bar can be formed on the edge of a steep slope. The first waves that are approaching the shore break as a cause of the breaker bar. The height of the bar influences the strength of the breaking wave and thus the amount of turbulence in front of the wave. This is a dominant mechanism for sediment suspension (Yoon *et al.*, 2013).

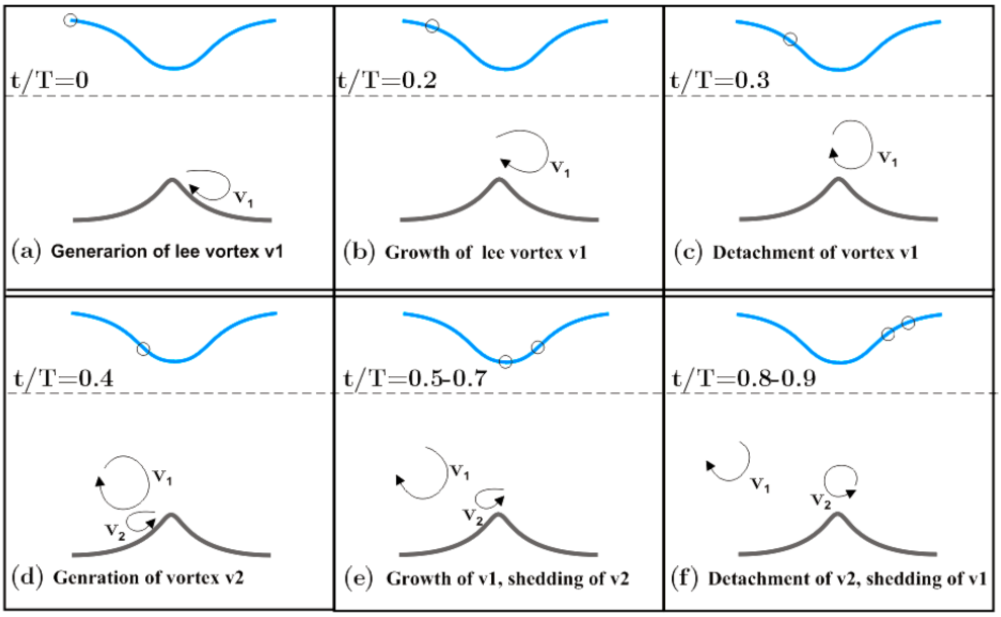


Figure 23: The under water flows due to propagating waves (Ahmari *et al.*, 2011)

When the sediment is moved from the bottom, it will also make movements in vertical directions. If this happens, the sediments are exposed to be transported by different currents at different elevations (Ogston *et al.*, 2002). The different fluxes at different elevations affect the distribution of sediment over the height of the water column and the other way around the suspended sediment particles influence the flow velocities. When waves break, a turbulent kinetic energy is produced in the roller at the surface as well as at the bottom in the wave boundary layer (Deigaard *et al*., 1986).The turbulence causes to mix the different flows at different elevations, so that more sediment can be brought in suspension away from the bed.

The importance of turbulence created by breaking waves in relation with the sediment suspension is supported by the findings of Puleo *et al*. (2000). They found that 80-90% of the variance in the suspended sediment transport can be explained by a relationship with an estimate for the bore-generated turbulent dissipation. The sediment transport on the low side of the surf bore is much higher than before the bore, which implies that bore-generated turbulence may alter local sediment transport processes. Although these measurements were conducted in the swash zone, the effect of a strong turbulent plunge can be the same. Smith *et al*. (2002) also agree that the turbulence that is induces by bores and breaking waves plays a significant role in sediment suspension. The experiments were conducted in a small wave flume. He looked at time series and found correlations between the occurrence of breaking waves and the increasing of the sediments. In paragraph 4.3 the results of the experiments of this research are discussed and here the influence of the turbulence, caused by breaking waves, is taken into consideration.

II. TSS measurement and the volume meter

The Transverse Suction System (TSS) generates data that shows the distribution of sediments over the water column. The information about the TSS is mainly derived from the article of Bosman *et al*. (1987). With the TSS method water samples will be collected over a longer period of time. The data that it provides will show an average concentration of sand in the water. With this average value the data generated by acoustic and optical instruments can be calibrated. Also comparisons can be made to find errors in concentration plots made by the other equipment. At seven different levels in the water column suction samples are taken.

In between the runs, the obtained samples were analyzed with a volume meter. To be able to use the volume meter, the water was drained from the collection bucket. The remaining sediment was put in the cylinders of the volume meter. After the sand settled in the cylinders, the height of the sediment in the cylinder could be read from the ruler that was positioned next to the tube. With the known diameters of the tube and the calibration factor β the weight of the sediment could be determined (Bosman *et al*., 1987). Then the measured concentration of sediments in the water (C [g/L]) could be calculated by dividing the dry weight (G [g]) by the water volume [L] in the bucket, see equation 8. The parameters that were used for calculations are shown in Table 4.

$$C = \frac{True\ mass}{Water\ volume} \tag{8}$$

Table 4: The used parameters that were used in the calculations with the volume meter

Description	Property	Value	Unit
Dry mass	G	Differs per measurement	Grams [g]
Density of sediment	ρ_s	1600	$[kg/m^3]$
Density of water	ρ_w	1000	$[kg/m^3]$
Average grain size diameter	D_{50}	0.246	[mm]
Relative grain size diameter	D_r	0.090	[mm]
Porosity	ε_0	0.36	Percentage
Calibration factor	β	1.407	[-]
Wet volume	$V_{sediment}$	Differs per measurement	dm^3 or Liter [L]

With the samples and the variables and parameters that are shown above, the dry mass (G) and the true mass could be calculated as follows:

$$G = 10^{-3} * \rho_s(1 - \varepsilon_0) * V_{sediment} \tag{9}$$

$$True\ mass = \beta * G\ [\text{g}] \tag{10}$$

where β is the calibration factor that Bosman *et al*. (1987) describe with the formula below:

$$\beta = 1 + \frac{1}{3} * \tan^{-1}\left(\frac{d_{50}}{d_r}\right) \tag{11}$$

III. The experimental set-up

A frame is attached to the yellow trolley that can be moved above the wave flume (see figure 25) In figure 24 the frame is shown including the instruments that are attached. The most important instruments for my research are the TSS and the ABS, which are positioned on the right side of the frame. The instruments that are shown in the figure can be adjusted in height according to the changing bed.

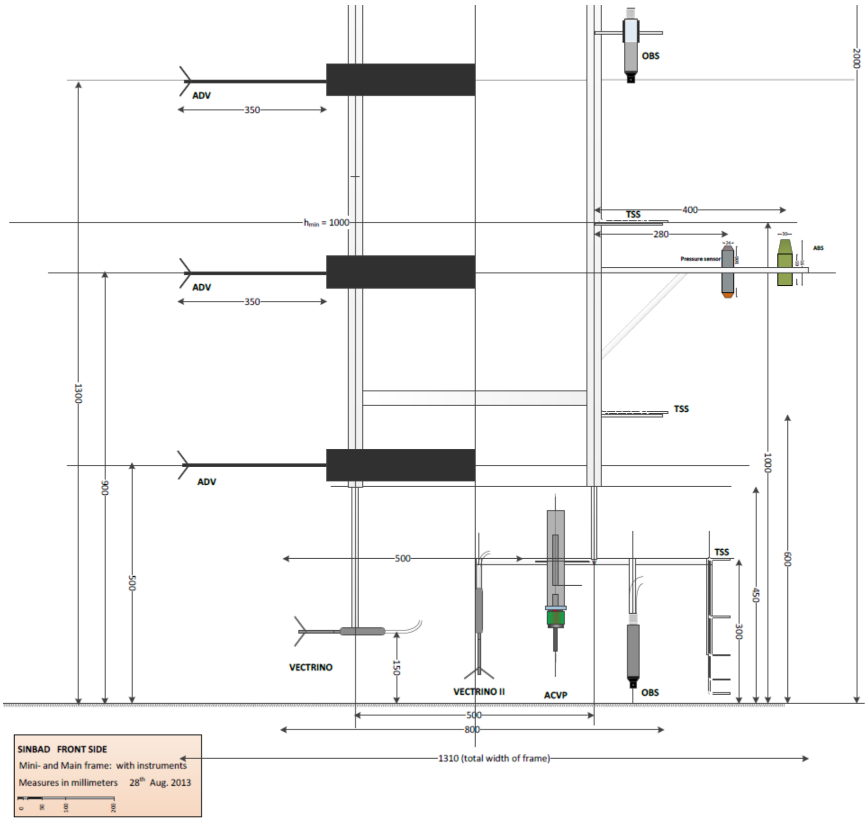


Figure 24: The experimental set-up with the position of all the instruments

Figure 25: The moving trolley and the in height adjustable measuring equipment

IV. Overview of pumping equipment

The pumps in Table 5 correspond to the nozzles in the wave flume. So pump 1 corresponds with nozzle 1 and is positioned the closest to the bed. Different types of pumps were used and that resulted in different pumping strength. The types and brands are described as well as the RPM (rounds per minute) that is used to fine-tune the intake velocity to the required speed. The last column 'On a block' shows if a (±15cm high) brick was positioned under the pumping device to improve the pumping ability.

Table 5: The properties of the pumps

Pump #:	Brand:	RPM:	On a block:
1	Watson-Marlow 603S	110	Yes
2	Watson-Marlow 603S	102	Yes
3	Watson-Marlow 603S	101	Yes
4	Watson-Marlow 505D*i*	260	No
5	Watson-Marlow 504S (IP55 Washdown)	Maximum	No
6	Watson-Marlow 503S	164 (=maximum)	No
7	Watson-Marlow 503S	164 (=maximum)	No

V. Measuring procedure

The measuring procedure is described in different steps. First the preparation that has to be done before every run is described. Then the executing of a run is described, followed by the analyzing steps that were performed with the volume meter.

Preparation for a run:

1. Make sure the aluminum cups are empty and cleaned. Dry the cups in the oven after cleaning.
2. Weigh the aluminum cups when they are dry and empty and notate the values on top of the data collection sheet in a three column table: “nozzle | cup | cup & sand”.
3. Flush the remaining water from the volume meter and rinse the tubes.
4. Fill the volume meter with water and make sure that no air bubbles are present in the cylinders. The air bubbles can be removed with the rod that is present at the volume meter.
5. Fill the spray bottles with water.
6. Fill the 1 L measuring cup, so you can refill the spray bottles during a measurement.
7. Bring the 17 L buckets to the yellow trolley and attach the tubes to the buckets in the right order. The numbers on the pumps correspond to the nozzles and thus to the numbers of the buckets.
8. Attach the plug and turn on the pumps.
9. Pump 4 needs to be checked before the run:
   - If it is turned on, press the button ‘step’ twice, so it selects ‘manual’
   - Press ‘enter’ and on the screen the RPM and the direction of pumping appears.
   - RPM should be around 260 and the direction should be CCW (counter clockwise).
10. Check if the scale is aligned.
11. Make sure a timer/stopwatch is ready to use. The best way to time is to measure with a timer on a phone and a backup timer on a watch.
12. Write down on the data collection sheet the date, the time and the number of the run.

Executing a run:

13. Start the pumps and check if no water gets spilled.
    - For Regular Breaking waves:
      i. Wait until 5 waves plunged, so the sediment has already started to move. The acquisition lasts 15 to 20 min.
    - For Irregular Non-Breaking waves:
      i. Start pumping after 10 min, because one wave cycle last for ±4 minutes. The acquisition will last 35 minutes.
14. Check continuously if water is pumped up. If air comes out of the tubes, you have to notate this so the time can be corrected afterwards.
15. It happens often, especially with the lowest nozzles, that the nozzles get stuck in moving ripples. You notice that by observing that air is coming out of the tubes. The only thing that can be done is to pump the water in the tubes back into the flume for about 5-7 s. Any barriers in the tubes or nozzles will be cleared in this way. Do not pump water towards the flume for more than 10 s, because then air bubbles are formed in the flume, what can influence the ABS data.

16. After 10 min of sample collecting the pumping devices are turned off.
17. Weigh the buckets + water with the scale and write down this value. Later on the concentrations and discharges will be calculated from this value.
18. Let the sand settle in the buckets.
19. Throw back abundant water into the wave flume by tilting the bucket. Start with draining the water fast and gradually slow down the draining. In this way, no (or very little) sediment will be lost. It is allowed to flush away leaves, paint or any other unwanted sediment during this process.
20. When the wave generator stops creating waves, clear the water from the tubes by pumping CW (clockwise). Look at the tubes on the mobile frame to see if all the water is cleared.
21. Unplug the plug and tie up the tubes, so the trolley can be moved for a profile measurement.
22. Take the 17 L buckets with the (remaining water and) sediment to the volume meter.

<u>Analyzing the samples with the volume meter*:</u>

23. Put the sieve (0,710 m/m) on top of the 2 L measuring cup.
24. Put the *unwanted* sediment from the 17 L bucket into the 2 L measuring cup, leaving behind the sand in the bucket. Spray some water over the sieve to make sure that no sand is left behind in the sieve.
25. Check for air bubbles in the volume meter
    - If you pour in the sediment when there are still some air bubbles left, it will be hard to remove the bubbles and it might even ruin the measurement. If it accidentally happens, the two tubes of the spray bottles can be attached together. Reach into the volume meter and fill the air bubbles with water, so the sediment can settle.
26. Pour the remaining sediment from the 17 L bucket into the volume meter with a funnel.
27. Clean the bucket during step 26 with a lot of water, so no sediment is left behind in the bucket. Enough water is used if you have to fill both spray bottles (±) twice per run.
28. Pour in the water + sediment from the 2 L measuring cup in the volume meter and repeat step 27.
    - Watch out that the volume meter does not flood due to the water you added.
29. Rinse the funnel and the sediment that remained on the sides of the tube.
30. Let the sediment settle.
31. Repeat step 23 to 30 for the next bucket and then continue with step 32. For example, put the retrieved sediment from nozzle 1 in the volume meter. Let it settle and continue with nozzle 2. When you finished with nozzle 2, continue with step 32 for the measurement of nozzle 1.
32. Tap (± 10 seconds, ±3 taps/sec) against the volume meter so the sediment will settle. It is possible that the sediment settles a little more after that.
33. Read off the height for all of the samples and note this on the paper and in Excel.
34. For the last nozzle the settling time equals the time that it takes to label the aluminum cups.
35. After the last measurement have been taken, flush the sediment from the volume meter into the aluminum cups. Be careful, because the water will flush in all directions. It helps to remove the water collector from the volume meter.
36. If the aluminum cups contain a lot of water after the transfer of sediment, you can try to drain the water. Otherwise, the cups need to be put into the oven (75 - 90 ℃).
37. Rinse the entire tube and clean the volume meter.

Sediment sampling for grain size distribution:

38. Take the cups with the dried sediment from the oven and weigh them. Write this down in the table on the data collection sheet (see step 2).
39. Write down the run and the nozzle on a bag and pour the sand in the bag. Roll the bag with sand and put it in another bag. In this second bag, put a paper with the run and the nozzle written on it. Tape the bag with sticky tape to close the bag and make sure that the samples do not get lost.

*Alternative way that is used for very small amounts of sediments:

a. Label the aluminum cups.
b. Put the sieve (0,710 m/m) on top of an aluminum cup.
c. Put all the sediment from the 17L bucket into the aluminum cup
d. Clean the bucket with a lot of water, so no sediment is left behind in the bucket. You use enough water if you have to fill both spray bottles (±) twice per run.
e. If the aluminum cups contain a lot of water after the transfer of sediment, you can try to drain the water. Then the cups need to be put into the oven (75 - 90 °C).
f. Rinse the entire tube and clean the volume meter.

VI. Disparities and advantages flume experiments

The experiments will be done in a wave flume, which results into a lot of assumptions. Factors that occur in real life are neglected in the wave flume. That does not matter, because the models that will be made are supposed to give better insights to existing models. Neglecting the different factors has advantages and drawbacks. They are summed up beneath:

Disparities:

- In the field a combination of different types of waves occur at the same time while in the wave flume only one condition was tested.
- The difference between the viscosity of sea water and the used water in the experiment is not taken into account. Although salt water will not cause large differences in the concentrations, the algae and the suspended debris can influence the amount of sediment concentration.
- Riptides are being ignored in the wave flume, as well as (oceanic) long shore currents and the tidal influences.
- The bed slope is established to let the waves break at a certain point. The slope of the bed is different for every beach and that has to be taken into account when the results of this experiment are used in different environments.
- The waves break normal to the shoreline. In reality, the angle of the waves to the shoreline differs.
- In the beginning of the experiments the water depth is uniform and the bottom has no bumps or hummocks. Eventually this will change, but it can be of influence in the first measurements.
- The effect of the wind is neglected in the flume experiments.

- Friction between the sides of the wave flume and the waves can influence the way of breaking.
- With a plunging breaker air can get trapped in the plunge, because it cannot be diverted to the sides of the wave.
- Friction between the waves and the instruments and friction with the mobile frame may deflect the wave.

Advantages:

- Because of ignoring some factors, it is easier to find relations between certain factors. It also makes it easier to model the processes that are being observed.
- In the wave flume the conditions are controlled, what results in less measuring errors. When errors do occur, it is easier to encounter and correct them.
- The wave flume creates waves that are near full-scale, what gives realistic results regarding the plunging effects
- The waves are regulated at a pre-calculated strength. This may be different from reality, but in this way it is possible to collect data in different parts of the wave and it makes it possible to repeat the experiments. More repetitions of a measurement gives more reliable data.

VII. Literature overview

In Table 6 an overview of the used literature is shown. The literature that is included in the table is used for the evaluation of the obtained results at the CIEM wave flume. With this data, the profiles, the concentrations and the differences in the conditions are compared. In paragraph 4.5 the evaluation with the literature is described.

Table 6: The overview of the studied literature

Author(s):	Laboratory or field measurements	D_{50} [mm]	Instruments used (only the ones with which comparisons can be made)	Location of measuring	Conditions / Remarks
UPC Barcelona, 2013-2014	Laboratory, CIEM flume	0.246	TSS, OBS, ADV	The surf zone, before and after breaking point	Regular Breaking, wave height: 0,85 m. Sediment movement research.
Aagaard and Jensen, 2013	Field experiments		ADV, FOBS	Different zones of the breaking waves Measure-ments are mainly representing spilling surf bore conditions	
	Vejers (VJ)	0.225			Significant wave height is about 6.5 m. Tides are semidiurnal with spring and neap tidal ranges of approx. 1.2 and 0.6 m. Steep slope of 0.057 Wave periods up to 6.5 s Maximum wave height at the instrument station was H_s = 0.7 m
	Skallingen (SK)	0.240			The local bed slope was 0.03 Wave periods between 4 and 8 seconds Inshore wave height was up to 0.6 meter. The breaker zone over the inner bar was located 50-80 m seaward of the instrument station which consequently experienced mainly spilling surf bores when submerged around high tide.
	Egmond aan Zee (EG)	0.275			The local bed slope was 0.04 Tidal range is 2.1 m Offshore wave heights were up to 3.75 m with zero-crossing wave periods of 6-9 s and maximum inshore wave heights of the beach face at the instrument station were H_s = 1.25 m. Storm conditions
Ahmari, Oumeraci and Gruene, 2010	Large Wave Flume (GWK, Hannover)	0.242	TSS, Optical Turbidity Meter, ABS	Non-breaking regular and irregular waves. Rippled bed regime	Regular waves (H=0.8 to 1.2m,T=5s) and irregular waves (H_s=0.8 to 1.2m) Plots are given where the ABS concentrations is plotted against TSS concentrations TSS-measurements were performed over a time period of about 20 minutes during each test TSS: 5 nozzles, nozzle speed=1.5m/s, 20min water extraction
Ahmari and Oumeraci, 2011	Large Wave Flume (GWK,	Medium sand	ABS, TSS	Regular and irregular	The bed was covered with 3-dimensional mega ripples superimposed with 2-dimensional steep ripples at the

	Hannover)	0.242		waves	beginning of the test runs. For both regular and irregular waves: H = 0.8, 1.0 and 1.2 m, T=5 s. The ABS and the TSS measurements and their relations are compared explicitly.
Beach and Sternberg, 1996	Field Duck, NC	0.170	OBS, Pressure sensors	Wave breaking: Plunging Bores and spilling Unbroken waves	Mean wave height is 0.9 m with a period of 9s. The beach in the vicinity of the deployment site had an average slope of 1:60 and is composed of fine sand with a mean diameter of 0.17 mm. Offshore, the depth was 18 m. Wave height 0.4-0.5m and periods of 10-12 seconds. Suspended sediment concentration was measured at each location Several concentration drafts with respect to the height in the water column are given
Bolaños, Thorne and Wolf, 2012	Field Near-shore site off Santa Cruz, CA in Monterey Bay	0.255	ADV, ABS, ARP, LISST	Waves, currents, bedforms and suspended sediments *Breaking waves = not significant process, irregular*	Mean water depth of 4.5 m and the vertical sediment suspension was measured in the first meter above the bed. The local mean tidal range was about 3 m The ratio for the wave height to the water depth was less than 0.3 40 days of experiments The experiments were taken in the sea and the measurements are not taken under a specific wave type, but the average of all kinds of waves is taken.
Cacchione, Thorne, Agrawal and Nidzieko, 2008	Field	0,200	ABS, ACP	Under waves and currents Sand ripples Not precise where it was measured	15-day period measurements were taken at a near-shore site off Santa Cruz, CA in Monterey Bay. Obtained estimates of the concentration at 1 cm above the bottom, C_{a1}. Predictions for the concentration at 1 cm above the bottom:C_1. Reference concentration C_0 is given by Nielsen's models
Cáceres and Alsina, 2012	Wave Flume, CIEM, Barcelona	0.250	PPT, ADS, ADV and OBS	Inner surf zone and swash zone	Most of the instruments were deployed close to the shoreline in order to obtain suspended sediment concentration, velocity, bore heights and swash thickness in the inner surf and swash zone. OBSs were located in the same cross-shore location and vertical elevation with respect to the bed level but close to the opposite wall --> measurements in the region between 3 and 7 cm above the bottom.
Deigaard, Fredsøe and Hedegaard, 1986	Comparison with	Differs			Near-bed mean concentration is almost the same under the spilling breaker as under non-breaking waves, as already noticed by Nielsen.
	Laboratory	0.120		Spilling breakers Non-breaking waves	Bed slope 1:12, measurements taken 3m "downwave" of the slope
	Field measurements.			Spilling breaker Plunging breaker	The turbulence generated in the water surface by broken waves has the same effect as the current, *i.e.*, that more sediment is carried in suspension away from the bed, while the near-bed concentration is still determined by the wave boundary layer.

					Measured on several locations in Australia with TSS. Pl.br.: D50 = 0.17-0.18 mm and H = 0.70 m Concentrations between 0.001 and 0.005 g/L "The concentrations are slightly under predicted"
Masselink and Puleo, 2006	Field measurements	Not given	Pump sampling	Swash zone	Maximum suspended sediment concentrations occur at the start of the swash cycle at the bottom of the beach and settling lag enables suspended sediment particles to be transported to the top of the swash zone, despite the fact that uprush velocities may well be below the entrainment threshold.
Miles, 2013	Field, Sennen (Cornwall, UK)	Differs, see graph	EMCM, OBS, PT, ADV	Different waves	The beach had a slope of 8% and was approximately linear in profile. OBS's were placed at heights of 0.01, 0.03 and 0.05 m above the bed respectively
Ogston and Sternberg, 2002	Laboratory		OBS, D&A instruments, FOBS	The surf zone Plunging Spilling	Flow beneath waves can be separated into three components, mean, periodic (wave) and fluctuating (turbulence). Wave heights at the measurements locations ranged from 23 to 45 cm
	Field Duck	D75 = 0.18 No more grain size infor-mation	ADV	Under non-breaking and breaking waves	DUCK94 For the broken wave sediment concentration profiles, the maximum concentrations in the near bed region were greater than 80 g/L at 1.0 cmab and decreased with height above the bed at varying rates of decay. (Measured with FOBS) (cmab = centimeters above the bed) In the upper water, column sediment concentrations was typically uniform in the vertical and ranged from 0.3 to 1.0 g/L. → 2 important figures for comparison the data
Osborne and Greenwood, 1993	Field	Fine to medium sand Fine-coarsed		Rippled bed Irregular waves	Data were recorded from both a nonbarred, marine shoreface and a barred lacustrine shoreface, under both shoaling and breaking waves (significant heights of 0.25-1.50m; peak period of 3 and 8s) and in water depths of 0.5-5.0 m. The average median grain size of sediment on the bed varied from 0.21 mm (1 10 m station), 0.14 mm (85 m station), 0.17 mm (63 m station) to 0.25 mm (55m station) and three bars were present on an average slope of 0.015
Thorne, Williams and Davies, 2002	Laboratory Delta flume of Delft Hydraulics	0.330	ABS, Pumped sampling	Rippled bed Regular and irregular waves	A sediment bed of thickness 0.5 m and length 30 m was placed approximately halfway along the flume. The sediment used was a medium quartz sand. The flume is 230 m long, 5 m wide and 7 m deep. Mean concentration profiles were averaged over 17 minutes for typical cases of regular and irregular waves. Measurements were collected at nominally 0.05, 0.07, 0.10, 0.13, 0.18, 0.25, 0.4, 0.65, 1.05, and 1.55 ma above the mean bed level. Ten liter samples were collected and dry weighed; finally, a correcting multiplication factor of 1.35 was applied to the measured concentrations on the basis of the findings of *Bosman et al.* (1987).

Schretlen, Ribberink and O'Donoghue, 2010	Laboratory GWK wave flume in Hannover, Germany	0.21-0.26; 0.25 is used	Pumped sampling, ABS and more	Non-breaking full scale velocity-skewed surface waves	Sediment concentration profiles showing large vertical gradients in the sheet flow layer are similar in oscillatory flow tunnels and wave flumes. Sheet flow occurred in the experiments Figure 3 on page 6 can be used to explain the profiles of the suspended sediment. It shows that the flow near the bottom is increasing because of onshore streaming induced by the wave Reynolds stress and this stirs up the sediments. 1:20 sloped sand beach

VIII. Error analysis

Errors can be divided in systematic and random errors. Systematic errors are errors that have a systematic source, so it is not attributable to accidental effects. The random errors represent the spread in the data around the real values. In Table 7 is shown where errors could occur and the error is calculated where one was found. The subsequent headings in the table are further explained beneath the table. Because the systematic errors were corrected as much as possible, they are not taken into account in the error analysis. Nevertheless, it is shown where errors could occur.

Table 7: The processes that could create errors and their calculated error

Random errors:	Error [%]:	Possible systematic errors:	Error [%]:
a. Air bubbles in suction system	-	i. Intake velocity	-
b. Sand that is left behind in the 17 L bucket	-	j. Friction within the tubes	-
c. Sand that is flushed away when draining the 17 L buckets	-1	k. Sand left behind in the tubes	-
d. Discharge measurements of the water collections. The time is insecure and so the water intake velocity too	-	l. The suction nozzles can be stuck because they get buried in the bed	-
e. The reading off of the value in the volume meter According to Bosman *et al*.(1987)	+1.12 +5	m. Height of the cart above the water can affect the sediment collection	-
f. The height above the bed differs during the sand collection. Average is taken in calculations	-	n. The difference in size of the plunging waves	-
g. Are the tubes of the volume meter perfectly clear	-	o. Bosman's β-calibration	-
h. The many non-sand parts that are on the bottom of the flume and are collected with the TSS			
Error due to 1 mm height difference (Bosman *et al.,* 1987)	+10		
Total random error*:	11.3%	Total systematic error:	-

*The total error is calculated by taking the square root of the square sum of the errors.

a. Air bubbles in suction system

Air bubbles are present because of the plunging waves and the generated surf bore. The air bubbles are of influence on the intake velocity. This error is corrected by calculating the amount of retrieved water and by measuring the time. With these values, the air bubbles in the system are corrected. If there was too much air pumped up, the pumps pumped clockwise for a few seconds to clear any barriers and then it was changed again to pump up water again. The time that was taken to perform this action was measured and corrected after the run.

b. Sand that is left behind in the 17 L bucket

After the measurement the buckets will be cleaned in the process of determining the concentrations. The remainder of sand in the buckets will be flushed this way. Still, some sand is left behind, what can be checked by swiping your hand on the inside of the bucket. This amount of sediment is very small and because it happens every run, the loss of sediment will be neglectible. Only in the first test runs there was some loss in sediment due to this issue.

c. Sand that is flushed away with the draining of the 17 L buckets

The buckets will be drained after pumping up and the collecting of a sample. If some sediment remains suspended in the bucket, it is possible that it will be flushed away when draining. The lighter particles, like leafs and paint particles, are flushed the fastest. Sand particles and dust is harder to notice when they are suspended in small amounts. Because this was the quickest and most secure way to remove the water from the samples, this technique was used. Although it was not possible to measure the loss of sediment, it is estimated to be 1%. Looking at the difference in dry weighing and the use of the volume meter, which consist of more or less the same problem, the same error is taken as there.

d. Discharge measurements of the water collections and time is insecure and the water intake velocity too

There are different peristaltic pumps and every pump has a different intake velocity. That is why a timer is used to get an estimate of the time that the water was pumped up. The amount of collected water and sediment is weighed before using the volume meter. In the weighing there is an error as well, because it gives roughly a volume. The scale has an accuracy of 50 grams and the bucket with water and sediments weighed 14000 grams. So the measuring error in the intake velocity is low and thus ignored in the error analysis.

e. The reading off of the value in the volume meter

The reading off error is described by Bosman *et al.* (1987) as a random error of 5%. With one measurement the dry weight and the result with the volume meter were compared. The difference of this calculation was 1.12%. When the error of more measurements is calculated this way, the average error will become higher. If more measurements are conducted with the TSS and the volume meter, more of these comparisons have to be made to get a more solid estimation of the error.

f. The height above the bed differs due to sand transport over the bottom

The height error may be both systematic (due to maladjustment or due to a slightly transversely tilted bed in the flume) and random (due to the bed mobility). The height above the bed is measured with the Acoustic Backscatter Sensor (ABS). This sensor determines the sand concentrations in the water column and by looking at this data, the bed elevation could be determined. The height above the bed is measured before a run and after the run the height is adjusted by taking the average bed level in the run. By looking at the distances between the ABS and the suction nozzles, the absolute height could be determined. The error was reduced in this way, because accurate data of the bed level was determined. Still the changing bed levels are different from what Bosman *et al.* (1987) found in their measurements and so this error is probably higher. The calculation of this error has to be made when more data is available or when the other instruments are analyzed and provide more reliable data.

g. Are the tubes of the volume meter perfectly clear before and after a measurement?

This error is corrected 1) by flushing the tubes sufficiently after a measurement and 2) the error is smaller than the error caused by the reading off.

h. The many non-sand parts that are on the bottom of the flume and are collected with the TSS

They were eliminated using a sieve. Still some small parts are present in the samples, but this amount is small and lies within the measuring error of Bosman *et al*. (1987).

i. Intake velocity

The intake velocity of the pumps was around the 2.36 m/s or 1 L/min. If the velocities were lower than 1.6 m/s, they were ignored. The explanation for this can be found in paragraph 4.1. Also when the pumps were pumping up air, the measuring time was corrected what brought the intake velocity back to a sufficient value.

j. Friction within the tubes

Friction within the tubes is not used in the error analysis. The friction drag was taken into account in the calculations for the intake velocity.

k. Sand that is left behind in the tubes that are attached to the pumps

Sand is left behind in the tubes and to reduce this error, some actions were taken. The first action was to make sure that after a run the tubes are cleared of water, by inverting the pumping direction. The second was to pump clean water through the tubes towards the flume to remove the remaining sand. This was executed only three times in total and only when the water in the flume was drained. Otherwise it was not possible to see when the tubes were cleared and the flow could cause deformations in the bed. The amount of sediment that is left behind depends on the location of the nozzle. For the lowest nozzles, more sediment could be trapped in the tubes than for the highest nozzles. The highest nozzles pump up less sediment. To reduce the larger insecurity for the lowest nozzles, pumps 1, 2 and 3 were lifted onto a brick of ±15 cm high. Adding this extra height caused less water to be left behind in the suction tube after the pumps were turned off.

l. The suction nozzles that got stuck because they were buried in the bed

This problem occurred often. For the nozzles where this happened, the data was ignored or the intake discharge was corrected with the time that no water was sucked up.

m. Height of the cart above the water can affect the sediment collection due to head loss

The sediment that is pumped up with the Transverse Suction System travels through 6 meters of tube. In the tubes, the water and sediment suffer from friction what causes the sampling to slow down. The error of this process is estimated to be neglectible, because in the calculation of the needed intake velocity this was taken into account. The intake velocity was 2.36 m/s which correspond to 1 L/min. As can be seen in chapter 4 (figure 13), the intake velocities are close to this value and values that are too extreme are ignored in the calculations.

n. Difference in size of the plunging waves

The plunging waves are increasing in strength with the rising of the breaker bar. The wave height is in every measurement 0.85 m, but at the plunging point the height of the plunge is insecure. The pressure sensors measure the pressure created by the height of the water column on both sides of the instrument. At the plunging point, the wave height on one side of the pressure sensor is higher than on the other side, so the average wave height will be somewhere in the middle of the wave. Further the breaker bar extended the shoaling process what caused the waves to increase together with the increasing bar. In the results the effect of this increase is taken into account.

o. The β calibration factor

The β calibration factor is a factor that is introduced to calculate the true mass of the collected sediments. It takes into account the random errors that occur in the sample collection and is not sensitive for different grain sizes. Bosman *et al*. (1987) found that the use of the β calibration factor indicated that a systematic error of 3%. This percentage is taken into account in the calculation for the random error caused reading off the volume meter.

IX. All the results, figures and tables

In this Appendix an overview of the measured sediment concentrations is given. Then the concentrationplots with the height above the bed are given. They are ordered to the position in the wave. In section B the concentrationplots postioned in the breaker zone are described in three figures and in section C the results of the allocation of the data to a Rouse or an exponential profile is given.

A. The concentration profiles

In the figures on the next pages, the concentration is plotted over the height and they are sorted by their position in the wave. The tabels next to the figures contain the following data:

- The absolute height above the bed, derived from the ABS data. The backscattered signal of the first 10 seconds and of the last 10 seconds are taken and transformed into two heights. The absolute height is calculated by averaging these two values and is then adjusted to the distance between the nozzles.
- The concentration per nozzle.
- The intake discharge per nozzle.

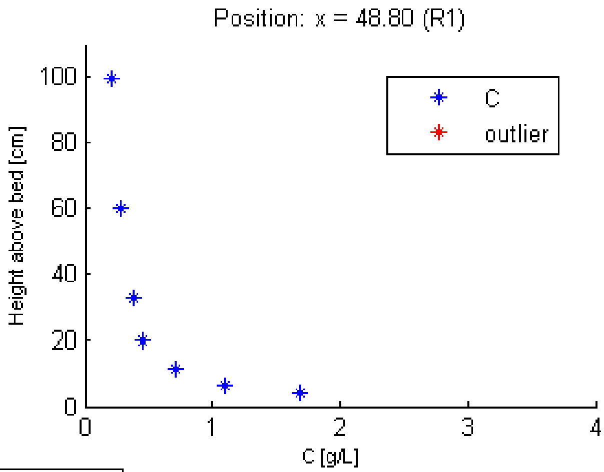
Underneath, in Table 10, an overview of the concentrations per run are given. The data shown in red are extreme values and are ignored in the data analysis.

Table 8: The concentrations in [g/L] per nozzle per run

Nozzle:	Run1	Run2	R3	R4	R5	R8	R10	R12	R14	R16	R18	R20	R22
1	1,682	1,278	3,253	2,598	1,322	9,344	-	-	-	-	-	-	-
2	1,090	1,324	1,576	2,142	1,093	43,032	3,736	3,407	1,002	1,002	0,806	1,887	1,629
3	0,706	1,175	1,520	1,320	0,850	1,917	0,210	2,563	0,654	0,602	0,729	1,117	1,431
4	0,454	0,962	1,051	0,960	0,612	0,821	0,187	1,713	0,460	0,460	0,658	0,838	1,300
5	0,384	0,818	0,823	0,820	0,480	0,433	0,175	1,166	0,423	0,423	0,607	1,105	1,187
6	0,286	0,597	0,593	0,584	0,415	0,349	0,129	0,717	0,445	0,445	0,560	1,052	1,371
7	0,210	0.508	0,405	0,547	0,249	0,248	0,154	0,551	0,475	0,475	0.712	1.076	1,242

Position x = 48.80 (corresponds to Run 1):

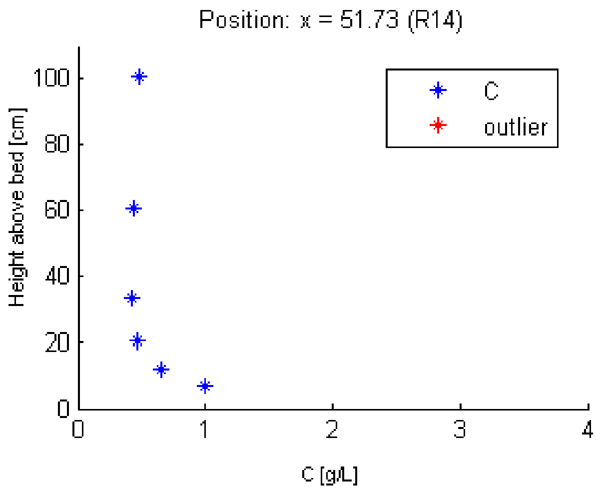
It was not necessary to remove data here. As can be seen the pumped samples are monotonically decreasing with height above the bed. The measurement was taken before the plunging point and the breaker bar was not formed when this data was obtained. The results are in line with the prediction of Schretlen *et al*. (2010) and Ahmari *et al*. (2011) for non-breaking waves. That is because the force of the plunge was low in the beginning of the experiments.



X=48,80			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	4,01	1,682	1,36
2	6,41	1,090	1,36
3	11,41	0,705	1,33
4	19,71	0,454	0,97
5	32,51	0,384	1,17
6	59,81	0,286	1,03
7	99,81	0,210	1,08

Position x = 51.73 (corresponds to Run 14):

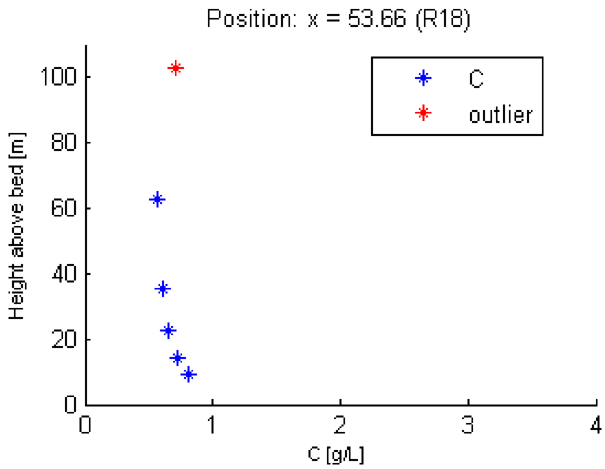
Nozzle 1 was defect, because of a sand obstruction in the tube that is connected to the pump. Further, the data shows that the concentrations of nozzles 4, 5, 6 and 7 are more or less the same, which indicates that the sediment is equally distributed over the height. This measurement was taken seawards of the plunging point, before the breaker bar. The breaker bar was better formed in this run, what caused the wave to be higher and thus the flows under the waves increase. As can be seen the concentrations higher in the water column increase.



X=51.73			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	4,79	NaN	NaN
2	7,19	1,002	1,32
3	12,19	0,653	1,13
4	20,49	0,460	0,97
5	33,29	0,423	0,98
6	60,59	0,444	0,95
7	100,59	0,475	1,03

Position x = 53.66 (corresponds to Run 18):

Nozzle 1 was defect, because of a sand obstruction in the tube. The data of nozzle 7 is ignored, because it was above the water level most of the time. The small amounts of water that were pumped up was not representable, because less water in the tubes the chance of sand staying behind due to friction with the tubes is higher. Again, the forming of the breaker bar causes the concentrations to be higher than in run 1. Also, the concentrations are well sorted over the height, which can be attributed to the fact that the measurements were taken under the plunging point.

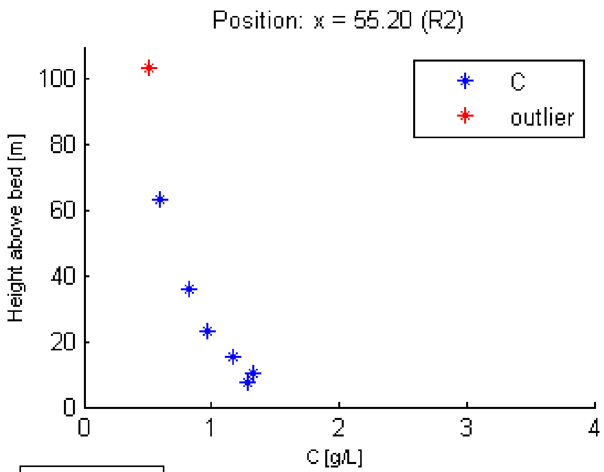


X=53.66			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	7,07	NaN	NaN
2	9,47	0,806	0,98
3	14,47	0,729	0,73
4	22,77	0,658	0,95
5	35,57	0,606	0,96
6	62,87	0,559	0,92
7	102,87	0.712	0.16

Position x = 55.20 (corresponds to Run 2):

Nozzle 7 was above the water level most of the time and therefore this data is ignored. Even though nozzle 2 and 3 have almost the same concentration, I did not ignore this data. That is because the measurmement showed no irregularities. The retrieved volume, the discharge and the concentrations for both the nozzles were sufficient.

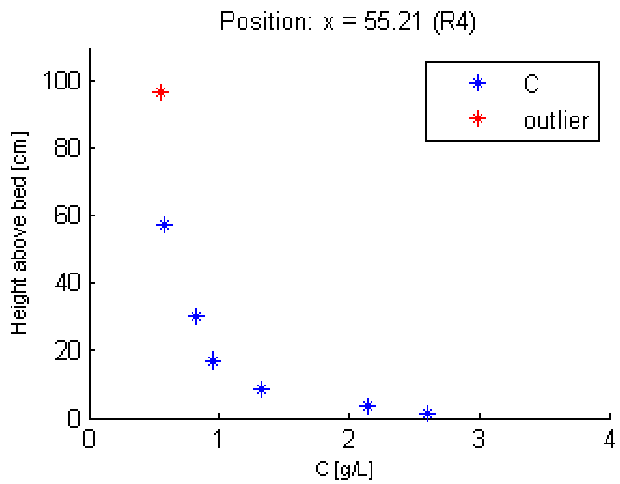
The concentrations in this run lie higher than in run 1. That is because of the position in the wave where the measurements were taken. The breaker bar was not fully formed yet, so in later runs with the same condition will show a higher concentration gradient.



X=55.20			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	7,70	1,278	1,24
2	10,10	1,324	1,23
3	15,10	1,174	1,40
4	23,40	0,961	0,96
5	36,20	0,818	1,08
6	63,50	0,597	0,98
7	103,50	0.508	0.70

Position x = 55.21 (corresponds to Run 4):

The concentrations near the bottom increase. In this run, the pumps retrieved enough water. The discharge was near or above the 1 L/min and therefore the concentrations are (given the random and systematic error) reliable. The data of nozzle 7 was ignored, because of the low discharge. The curve is monotonically decreasing with height above the bed. The results are close to the results of run 2 that is described above. That is because of the position in the wave where the measurements were taken and the small rise of the breaker bar between the two runs.



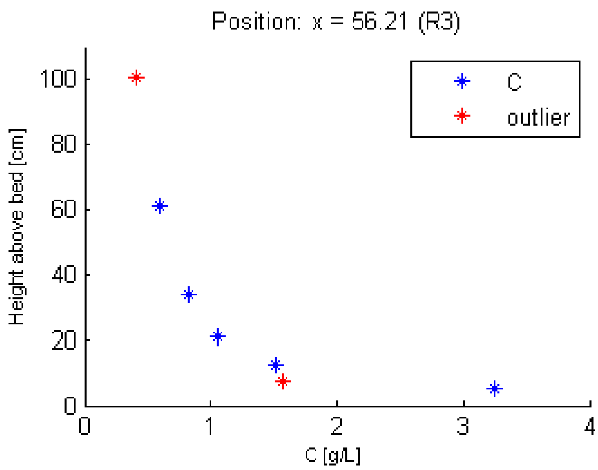
X=55.21			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	1,30	2,597	1,18
2	3,70	2,141	1,07
3	8,70	1,320	1,31
4	17,00	0,960	0,97
5	29,80	0,820	1,09
6	57,10	0,583	0,97
7	97,10	0.547	0.64

Position x = 56.21 (corresponds to Run 3):

Here the data of nozzle 2 is ignored, because of the significant lower concentration in relation to

nozzle 1. This is strange, because the distance between these nozzles is only 2,40 cm. The retrieved water was also much lower (± 2L) than with nozzle 1 and ± 7 L lower than nozzle 3, which can be appointed to the stuttering behaviour of the pump in the last 4 minutes. Nozzle 1 did not work well the first 4 minutes, but has a more reliable concentration because it pumped up ±10 L of water. Also, if the discharge of nozzle 1 is corrected by 4 minutes, it shows a good intake velocity.

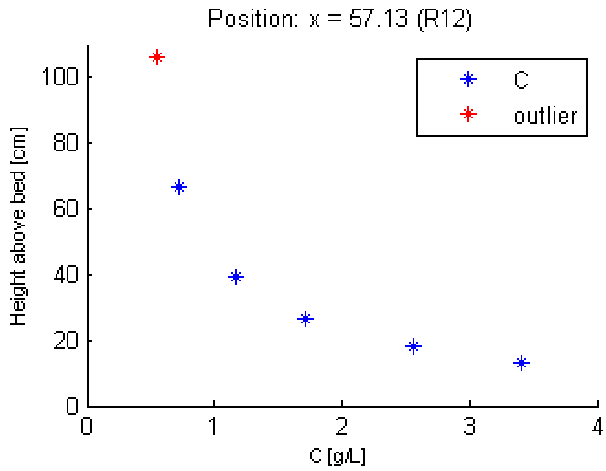
Like in runs 1, 2 and 4 the ***Figure*** shows an increasing concentration closer to the bed, what indicates a relatively low sediment suspension towards the upper part of the water column. When breaker bar increases to an equilibrium point the turbulence and currents will become stronger, what probably results in a more even sediment suspension.



X=56.21			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	5,16	3,252	1,63
2	7,56	1.576	0.98
3	12,56	1,519	1,42
4	20,86	1,050	0,98
5	33,66	0,823	1,06
6	60,96	0,593	0,98
7	100,96	0.405	0.37

Position x = 57.13 (corresponds to Run 12):

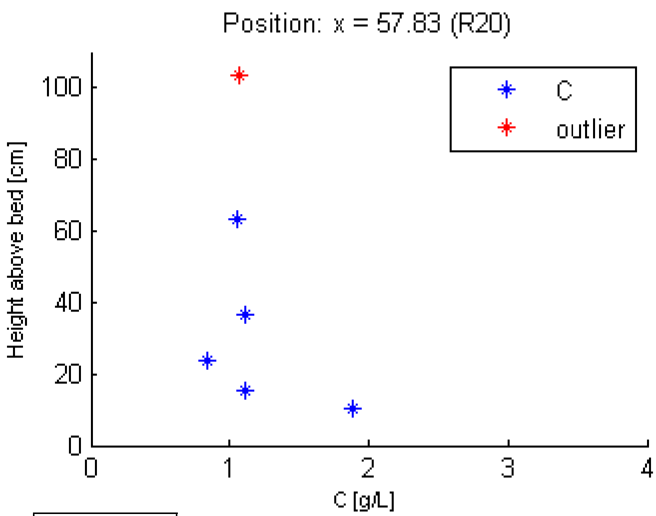
Nozzle 1 was defect, because of a sand obstruction in the tube. Even though pump 2 (nozzle 2) went on and off after 7 minutes, it managed to pump up 7.6L of water. Still the value is ignored, because of the low discharge that is not reliable enough when looking at the necessary intake velocity calculated following Bosman *et al*. (1987).



X=57.13			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	10,66	-	-
2	13,06	3,406	0,90
3	18,06	2,562	1,06
4	26,36	1,712	0,80
5	39,16	1,166	0,98
6	66,46	0,717	1,04
7	106,46	0.551	0.68

Position x = 57.83 (corresponds to Run 20):

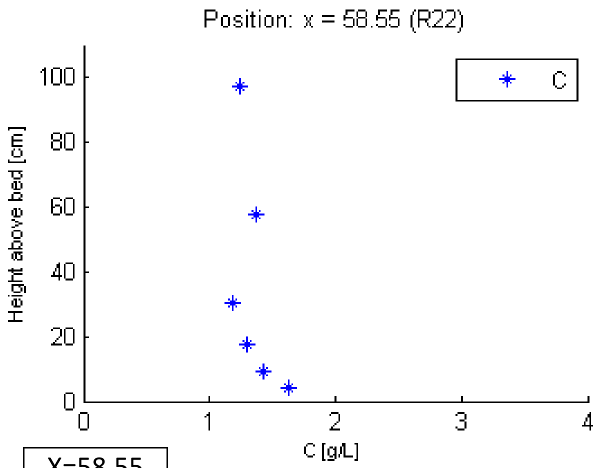
In this run many bubbles were formed. The bubbles and the turbulence in the water explain the sediment distribution that is shown in the ***Figure***. Nozzle 4 has compared to the other nozzles in this run a low discharge but is not ignored because it still has a sufficient discharge. When I look at the data of run 12 (see above), this run delivers different concentrations. This can be explained by the forming of the breaker bar, which was higher than in run 12. The higher bar caused a stronger plunge, what causes more turbulence, bubbles and sediment mixing. Nozzle 7 was most of the time above the water, so its data is ignored.



X=57.83			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	7,80	-	-
2	10,20	1,887	1,04
3	15,20	1,117	1,05
4	23,50	0,837	0,83
5	36,30	1,105	1,00
6	63,60	1,052	0,80
7	103,60	1.076	0.25

Position x = 58.55 (corresponds to Run 22):

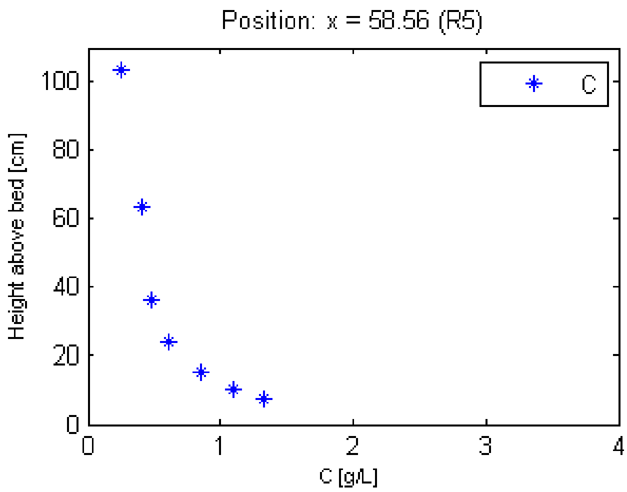
Nozzle 1 was defect, because of a sand obstruction in the tube. Nozzle 2 and 4 are corrected with the time, because of pumping up air a few times. There were many bubbles on the point of measuring what caused the sediment to be quite equally distributed over the height.



X=58.55			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	1,71	-	-
2	4,11	1,629	1,21
3	9,11	1,431	1,28
4	17,41	1,300	0,93
5	30,21	1,186	1,04
6	57,51	1,370	0,85
7	97,51	1,241	0,86

Position x = 58.56 (corresponds to Run 5):

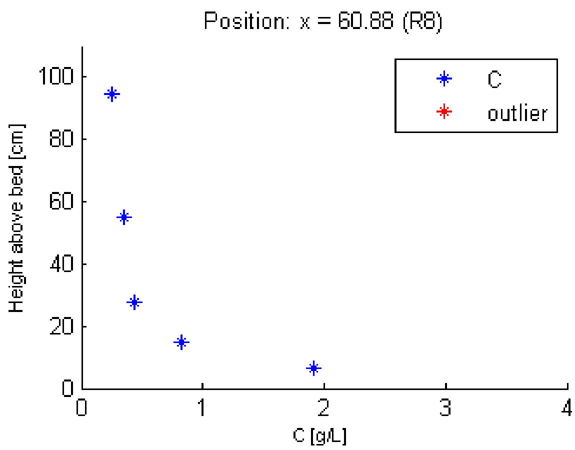
This run is the same as the one above, exept that the breaker bar was less high than in run 22. This is the reason that the sediment is transported less in the height. No data was ignored in this run.



X=58.56			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [L/min]
1	7,78	1,322	1,38
2	10,18	1,093	1,29
3	15,18	0,850	1,29
4	23,48	0,611	0,97
5	36,28	0,480	1,15
6	63,58	0,415	0,96
7	103,58	0,249	1,14

Position x = 60.88 (corresponds to Run 8):

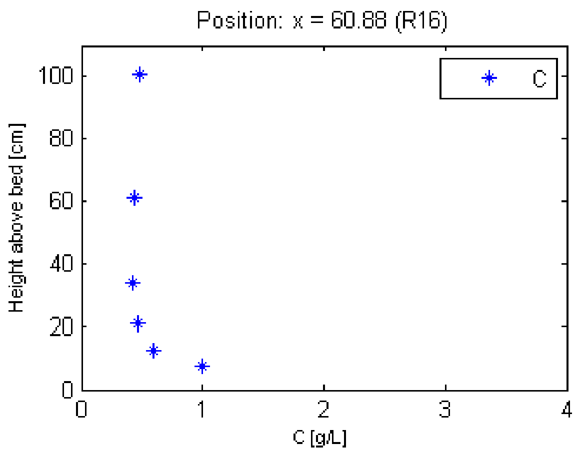
This is the run where nozzle 1 got stuck. Nozzle 1 and 2 were buried in a ripple (see the table). Pump 2 pumped up a part of the ripple, which caused a very high concentration. Both the data of nozzle 1 and 2 are ignored. Further, the concentrations over the water column are increasing near the bed. The measurement was taken in the surf zone.



X=60.88			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [m/s]
1	-1,00	9.344	0.67
2	1,40	43.032	0.92
3	6,40	1,917	1,40
4	14,70	0,821	0,95
5	27,50	0,433	1,16
6	54,80	0,349	0,97
7	94,80	0,248	1,06

Position x = 60.88 (corresponds to Run 16):

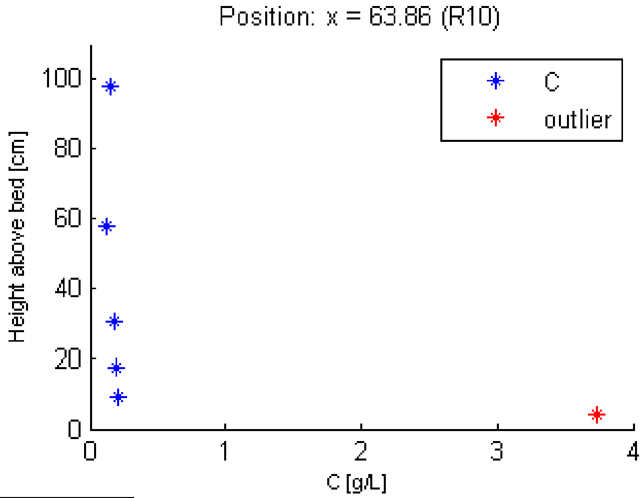
No data were ignored in this run. The sediment was evenly distributed over the water column, what can be attributed to the position of the nozzles in the surf zone. According to Beach *et al*. (1996) the curve with the increasing sediment concentrations in the upper water column was expected.



X=60.88			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [m/s]
1	5,18	NaN	NaN
2	7,58	1,002	1,32
3	12,58	0,602	1,13
4	20,88	0,460	0,97
5	33,68	0,423	0,98
6	60,98	0,444	0,95
7	100,98	0,475	1,03

Position x = 63.86 (corresponds to Run 10):

Nozzle 2 was ignored in this run, because of its high concentration. In this run was found that the concentrations were very low, but that they were evenly distributed over the height. The concentrations were probably very low because the measurements were taken far shoreward of the plunging point.



X=63.86			
# Nozzle	Height above bed [cm]	C [g/L]	Discharge [m/s]
1	1,94	NaN	NaN
2	4,34	3.736	1.57
3	9,34	0,210	1,37
4	17,64	0,187	0,97
5	30,44	0,175	1,10
6	57,74	0,129	0,98
7	97,74	0,154	1,07

B. Three comparisons in the breaker zone

In paragraph 4.3.2 the differences in concentrations between runs in the breaker zone are discussed. The role of the changing bed profile on the sediment concentration in the breaker zone was described. Beneath the same measurements in the breaker zone are given to determine the role of the changing bed profile, but here the less measurements are compared in one figure what increases the visibility of the changes.

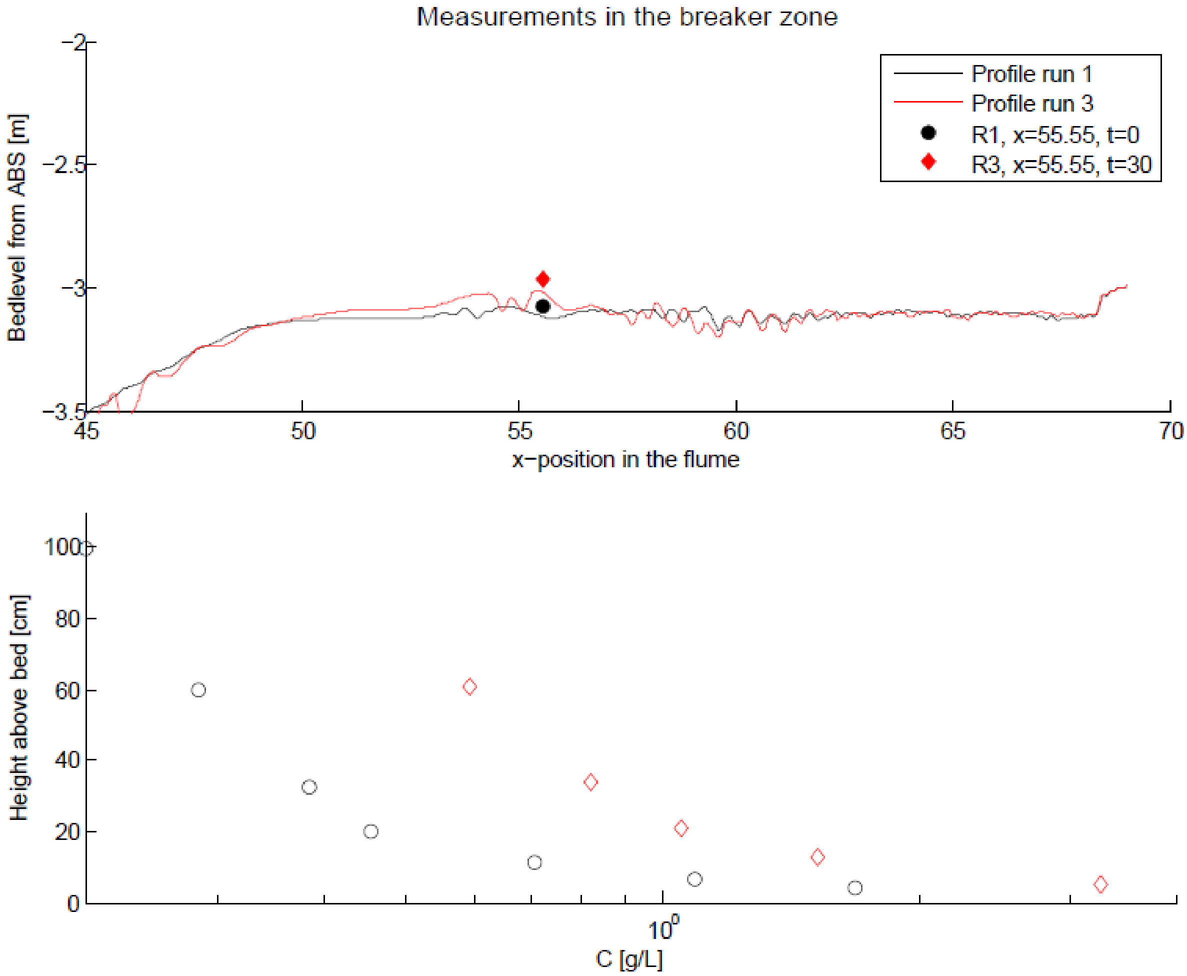


Figure 26: Two measurements in the breaker zone compared

In figure 26 can be seen that the bar was not formed in the beginning, but that there are differences in the measured concentrations. The reason that this happened can be explained by the changing conditions during the run. In the measurements shown, the waves did not plunge at one point, but the plunge moved shoreward during a run. Measurement 3 encountered the same problem, but the measuring point was in the breaking zone all the time.

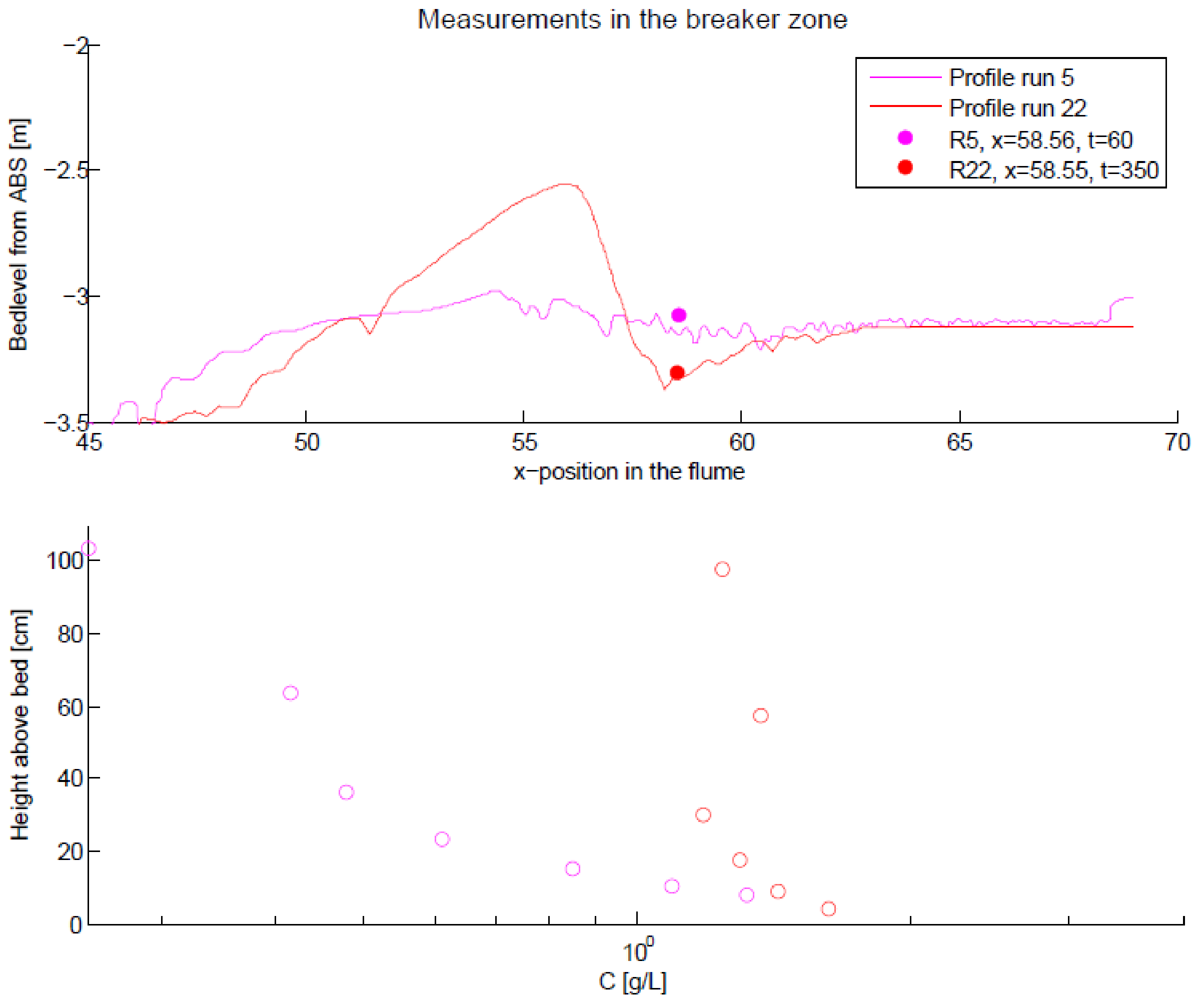


Figure 27: Two measurements in the breaker zone compared

By the comparison of run 5 and 22, a clear difference in concentrations can be noticed from which can be concluded that the height of the breaker bar is of influence of the sediment distributions over the height of the column. The stronger plunge causes more sediment to lift up and the concentrations over the height are more evenly distributed.

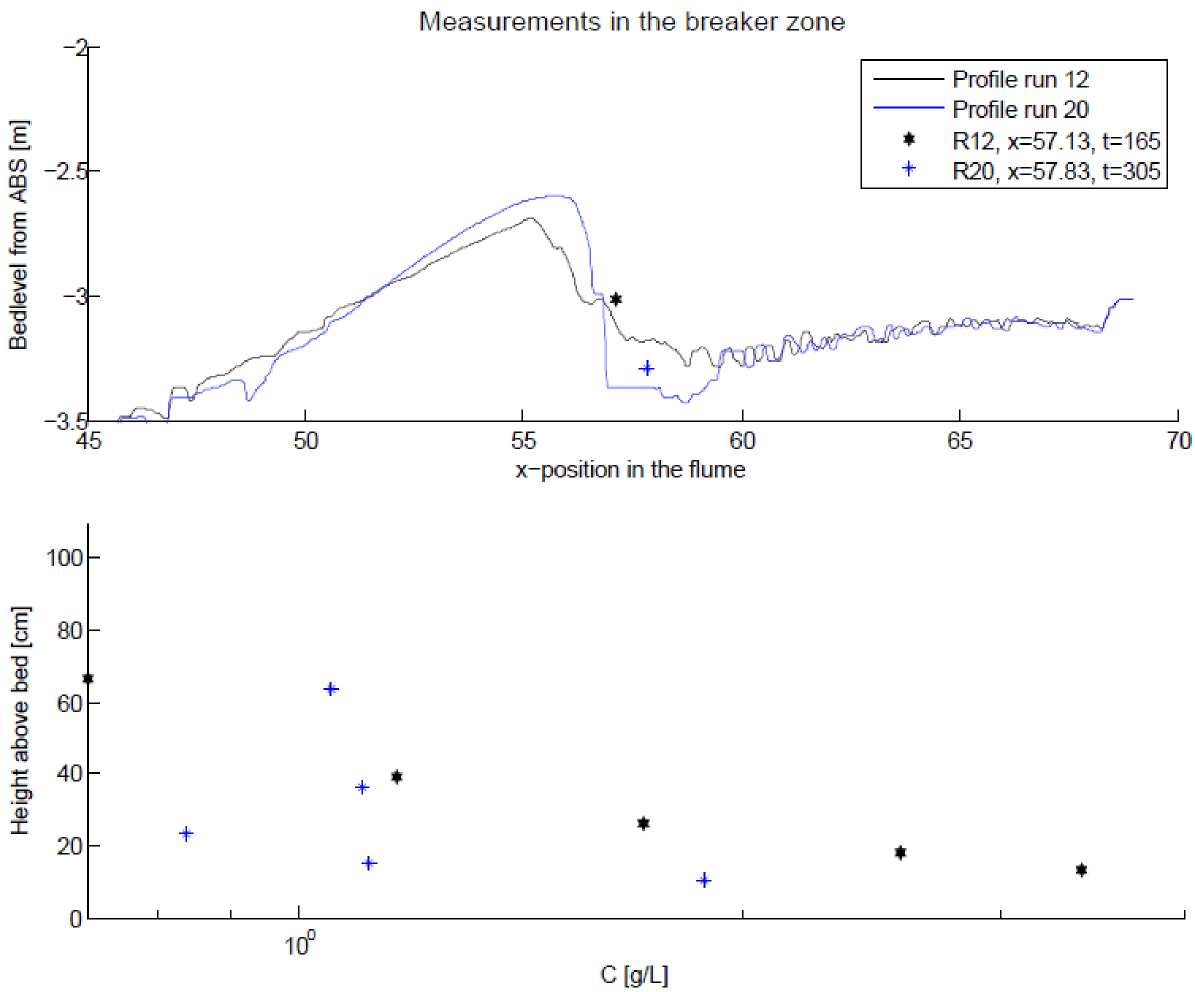


Figure 27: Two measurements in the breaker zone compared

When the wave is pushed up the slope and the height of the wave increases, the water supply will become less and so an undertow that comes from the shore towards the face of the wave occurs. In measurements 12 and 20 this undertow passes the point of measuring and the figure shows that it is nearly vertical at the point of measuring. This causes the sediment to suspend with a more evenly distribution over the vertical.

C. Allocating the results to a Rouse or an exponential profile

Fitting results of only the lowest 4 nozzles. A lot of correlation coefficients are 1.0 what seems strange. It is not, because often the lowest two nozzles were buried and were ignored in the data processing. The effect of this is that the fitting will be done through only two points, what is very insecure and does not give accurate results.

Table 9: The parameters of the fitting results with the lowest 4 nozzles

Run:	Best fit with a profile of:	Position in the wave:	Size of breaker bar:	Rouse; C_a	Rouse suspension number:	Rouse correlation coefficient:	Exponential; C_0	Exponential; l_s	Exp. correlation coefficient:
1	Rouse	BZ	Small	5.334	0.868	**0.999**	2.359	0.099	**0.971**
2	Rouse	BZ	Small	2.254	0.254	**0.909**	1.543	0.519	**0.957**
3	Rouse	BZ	Small	12.652	0.829	**1.000**	4.916	0.120	**0.986**
4	Rouse	BZ	Small	2.966	0.353	**0.968**	2.799	0.138	**0.985**
5	Rouse	BZ	Medium	5.393	0.685	**0.999**	1.900	0.197	**0.990**
8	Rouse	SZ	Full size	12.713	1.019	**1.000**	3.686	0.098	**1.000**
10	Rouse	SZ	Full size	0.313	0.179	**1.000**	0.238	0.729	**1.000**
12	Rouse	BZ	Full size	15.000	0.610	**1.000**	6.709	0.191	**0.999**
14	Rouse	BBZ	Full size	4.474	0.761	**0.999**	1.532	0.159	**0.982**
16	Rouse	SZ	Full size	5.311	0.831	**0.989**	1.581	0.152	**0.958**
18	Rouse	BBZ	Full size	1.356	0.232	**1.000**	0.923	0.658	**0.990**
20	Rouse	BZ	Full size	15.000	0.916	**0.984**	3.658	0.145	**0.961**
22	Rouse	BZ	Full size	2.032	0.157	**1.000**	1.720	0.592	**0.974**

In figures 28, 29 and 30 the fitting results of the exponential and the concave (Rouse) shaped profiles through the raw data are shown. The runs are arranged over time, so run 1 to run 22.

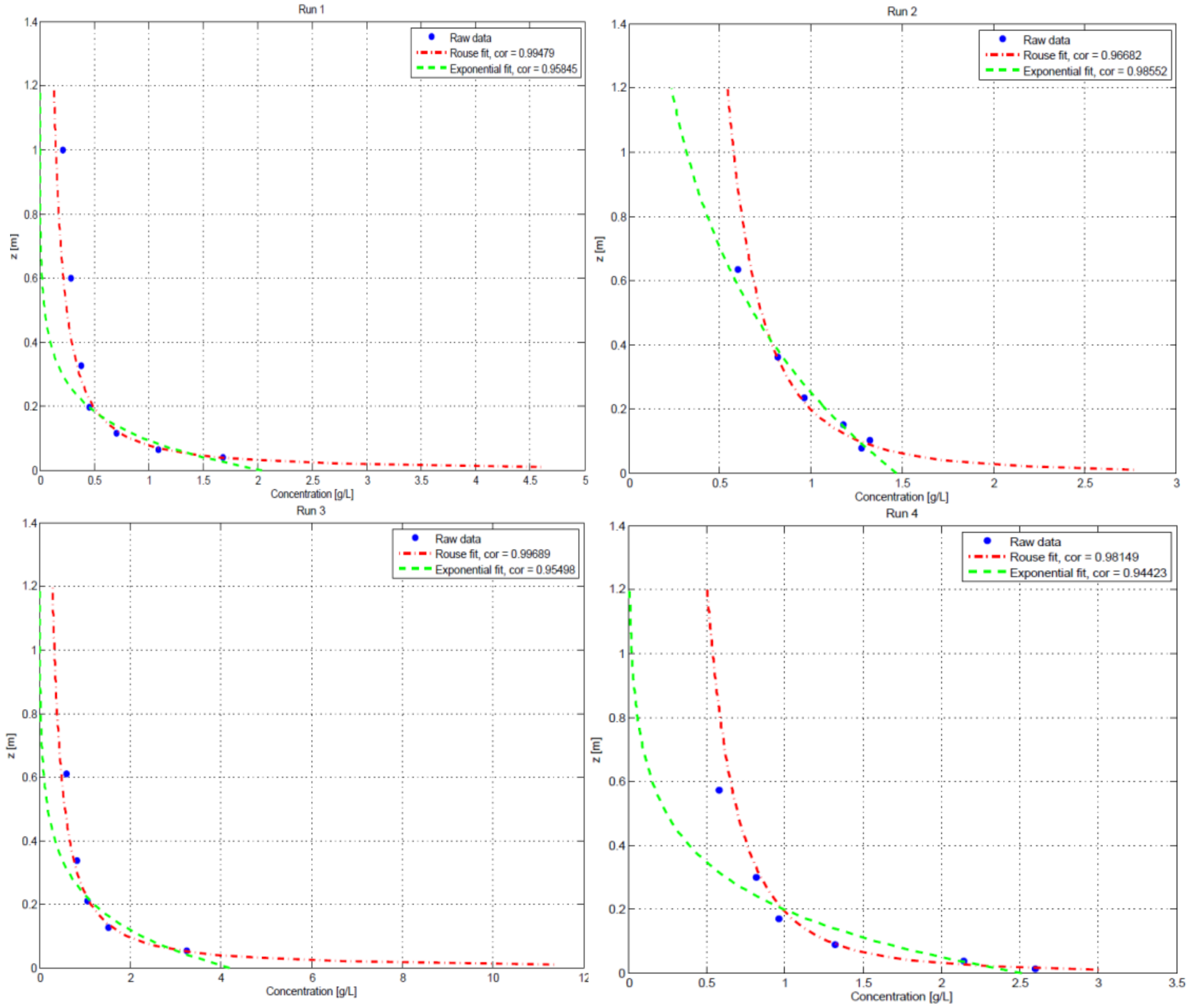


Figure 28: Allocating a concave Rouse or an exponential fit through the raw data

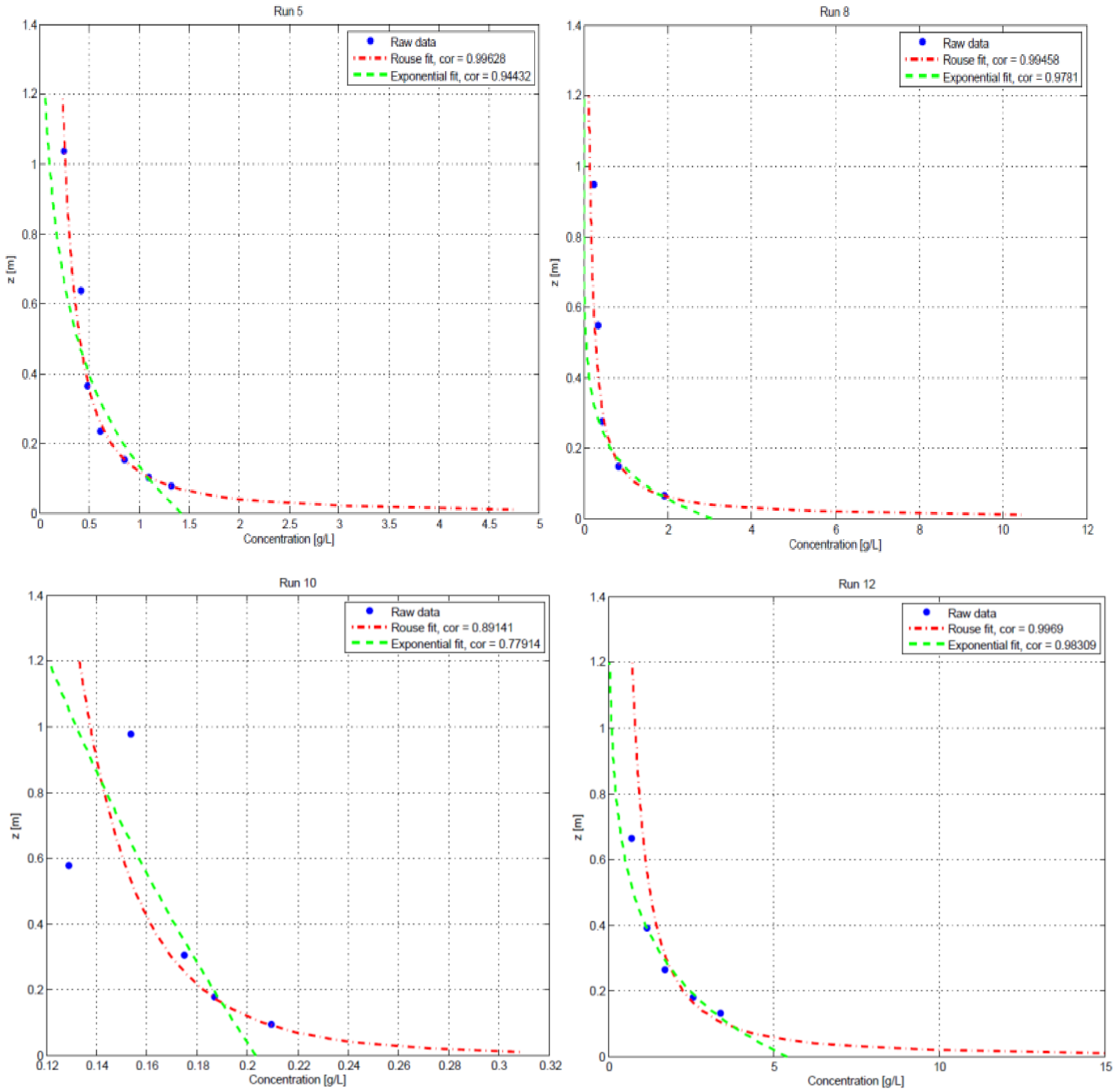


Figure 29: Allocating a concave Rouse or an exponential fit through the raw data

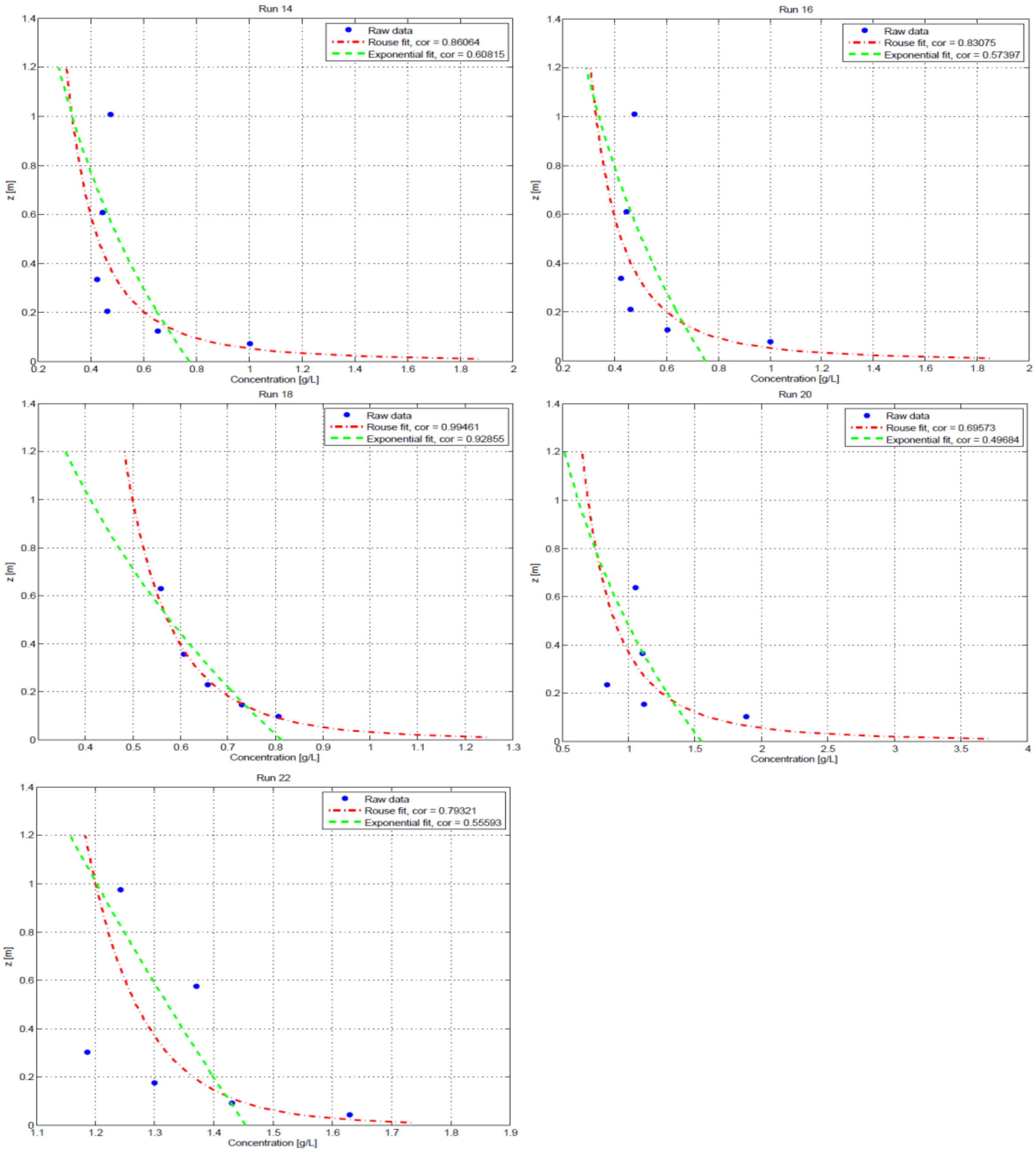


Figure 30: Allocating a concave Rouse or an exponential fit through the raw data