2014

Universiteit Utrecht

Patrick Michielsen

[TURBIDITY CURRENTS LINKED TO LEVEE COMPOSITION; AN EXPERIMENTAL APPROACH]

An experimental approach of turbidity currents is presented in order to relate the internal composition of bounding levees based on their particle size with the turbidity current responsible for its formation and how various conditions influence both their structures. It is shown that turbidity currents internal structure, mainly its concentration profile/particle size profile, is significantly altered by changes in boundary conditions e.g. angle of slope and initial sediment composition. Furthermore experiments show three stages in the formation of submarine levees. 1) A coarse steeply fining upward frontal lobe. 2) A well-mixed broad levee only slightly fining upward relative equal in height as the body of the passing turbidity current. 3) A narrow steeply fining upward top section of the levee created from the highest layer and therefore finest particles of the turbidity current and its subsequent settling of particles during the waning stage.

Table of Contents

1. Introduction

Submarine channels have been shown to cover large sections of the deep oceans floor. These channels are the main contributors in the transportation of sediments from the continental margins to the deeper marine environment. The general accepted theory is that these have been formed by turbidity currents. These currents pass through the channel developing it further by erosion and deposition within the channel. The upper part of the suspension spills over the edges of the channels where the sediment present in these overbank flows is deposited, creating levees bounding the channel on both sides. Experimental data of currents developing these levees and understanding of the processes behind their development, architecture and composition are limited. However levees created by those turbidity currents are gaining in importance in the hydrocarbon industries for their potential to be good reservoirs [*Mayall & O'Byrne, 2002; Weimer & Slatt, 2007 Kane and Hodgson,2011*]. For this reason they have been studied extensively in the last 20 years and due to this our understanding of the morphology and stratigraphy of deep marine channels has advanced significantly. Unfortunately, this cannot be said about the turbidity currents themselves since direct measurements are rare. Understanding of turbidity currents however is a vital part of understanding the deposits left behind by them. Those companies desire predictive models for the 3D architecture as well as the internal composition of those features. Such models rely on understanding of the dynamics and processes that are the cause of formation of features such as levees to increase their accuracy in predicting internal composition and overall architectures.

An important aspect for these predictive models is the grain size composition of submarine levees. Several authors have done research on this topic and tried to establish a link between the properties of a turbidity current and their levees based on current height, current velocity, diameter and size distribution of suspended particles and structure of the suspended-sediment concentration profile of the flow. Because measurements on natural currents are limited some authors have resorted to the use of numerical models [*Straub et al., 2008*], whereas others have used field observations and data of seismic mapping [*Pirmez and Imran, 2003; Skene et al., 2002*.]. These have led to theories about the connection between the turbidity current and the architecture and composition of their levees.

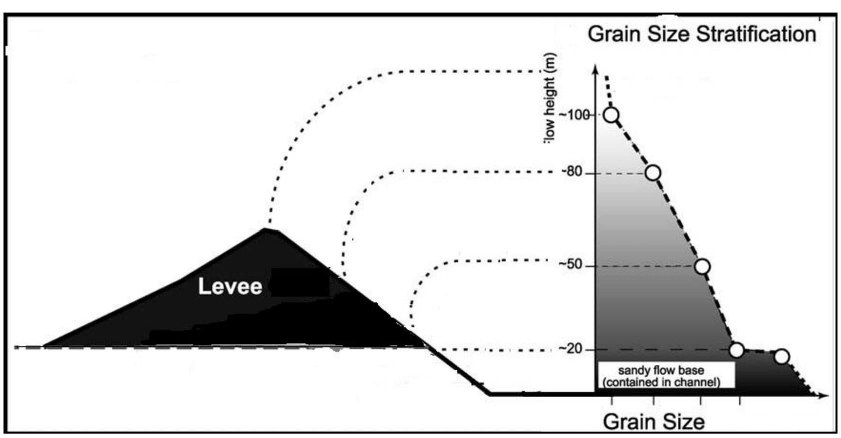


Fig. 1) ***The particle size stratification within the turbidity current in the channel is an analogue for the vertical particle size profile of its levees. Modified from Pirmez et alz, 2003***

This study will experimentally test whether the particle size profile of a turbidity current directly links to the particle size profile of its bounding levees, as proposed by Pirmez &Imran(2003). In other words can the particle size profile of a turbidity current predict the vertical particle size segregation in its levee (Fig1.)

The above described hypothesis can be divided in two separate parts, one being the turbidity current and the other being the levees that are formed as a result of them. In the best interest of this research the experimental work on these will be done separately. The first part of the experiments will focus on the dynamics and processes within the turbidity current which lead to a vertical concentration profile. 2D flume experiments will be carried out in order to analyse the turbidity current. Measurements on flow velocity, flow height, vertical sediment concentration and vertical particle size composition will be taken as well as derived values for Froude and Reynolds numbers. All of these parameters have an influence on the dynamics of the turbidity current and are of influence on the architecture and developments of the slope channel and bounding levees in the 3D situation. The results of the 2D flume experiments will therefore be compared to the 3D situation in order to obtain links between the internal particle composition of the turbidity current and the development of bounding levees and their composition.

The second part of the experiments will focus on the bounding levees, which are formed by the turbidity current passing over a slope. This will be done in the 3D Eurotank facility, which is set up in order to carry out successive runs of turbidity currents and see the development of the slope channel and bounding levees. These levees will be sampled and analysed on particle size composition with height and compared to the values obtained in the 2D flume experiments for the turbidity current composition. When comparing between both the 2D and 3D experiments it is of vital importance that both experiments are run under equal or very similar circumstances for the comparison to hold any significance. Therefore during the 3D experiments the same parameters will be measured as were obtained during the 2D experiments; flow velocity, flow height and calculated Froude and Reynolds numbers. The comparison between the both hopefully leads to a link between the internal composition of a turbidity current and the vertical particle size composition of their deposited levees. A link between these two will contribute to a better understanding of the processes involved with the formation of submarine levees. This will in turn lead to a more accurate predictability of levees architecture and composition based on properties of turbidity currents themselves.

2. Experimental setup

2.1 2D flume experiments

The 2D experiments will be carried out in a flume tank 4 metre long, 0. 26m metres wide and 0.5 metre deep (Fig2.). A wall was placed within the flume reducing the width of the flow to 0.1m. This wall extended along the full length of the flume and was 0.3m high. The placement of this wall has a dual purpose; first of all it reduces the width of the current so it can be run at lower discharges and is more like a “2D” current. The second reason has to do with the influence of the turbidity current when it enters the flume. The whole flume is a completely submerged closed system, this means that there is no outflow of water possible during any stage of the experiment. When the turbidity current enters the flume and flows down the slope towards the

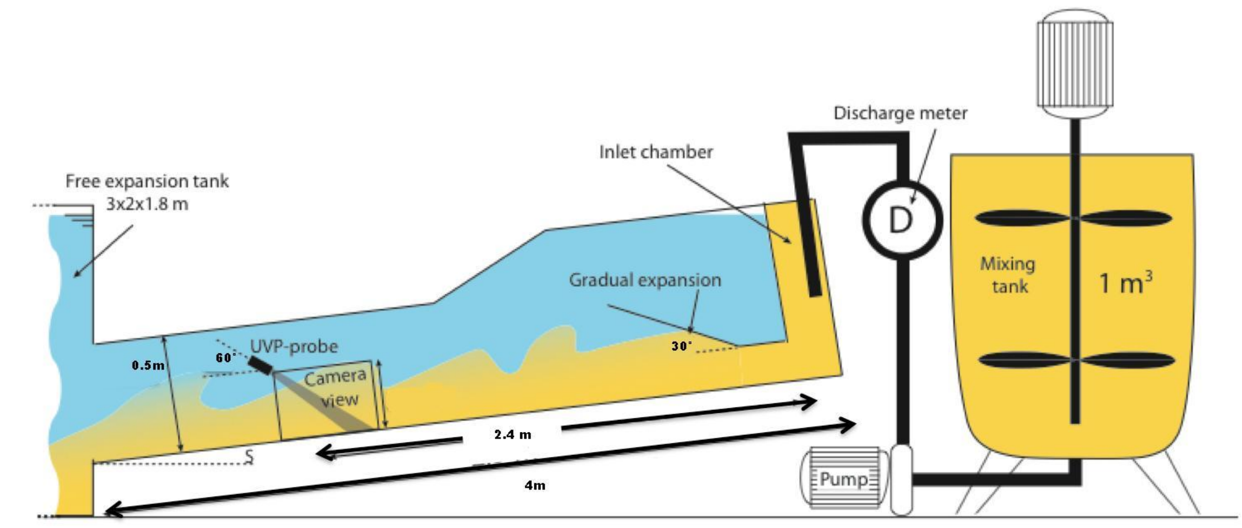


Fig. 2) Sketch of experimental setup of the 2D experiments. From Ramirez Bernal, 2013

free expansion tank it creates a backflow of water in the opposite direction, this backflow could interfere with the top layer of the turbidity current and have a significant effect on the development of the turbidity intensity, flow height and concentration profile with height. The wall that has been placed reduces this effect since the water of the backflow can more flow in the opposite direction on the other side of the wall with less resistance then the side of the turbidity current therefore not interfering with the current itself. In natural scenario this effect of backflow does not occur since the system is not enclosed to such small dimensions and therefore no interference will occur. The flume can be varied in angle ranging from 0-15°. The floor of the flume had a thin layer of sand glued on top of it to create natural roughness. The median particle size of the glued sand was 170 micron, which falls within the particle size range of the mixture used during the experiments.

The sediment is mixed in a $1m^3$ large mixing tank with the water to achieve a homogeneous suspension and from there pumped into the inlet of the flume. The pipe contains a discharge metre [Krohne optiflux 2300C] and the discharge meter and pump are connected via a NI

Labview control environment; this system can be been set at a certain discharge. If the discharge drops below this set value the system sends a signal to the pump to increase its power in order to stay above the threshold level set. the system checks the discharge value every 200 milliseconds and can therefore automatically regulate the discharge to keep fluctuations throughout the experiments to a minimum (~1m^3/h variation) and maintain a steady current. Before entering the flume the sediment-water mixture passes through an inlet chamber to reduce the formation of density waves within the tank. At the exit of the inlet chamber (0.3 m long, 0.1m wide and 0.06m high) the flow gradually expands (30°) to minimise the rapid expansion of the flow due to entrainment of ambient water.

2.1.2 Data collection

During the experiments measurements of flow velocity, flow height and turbulence intensity are taken by two ultrasonic velocity profile measurement probes [UVP DUO MX, 1Mhz]. These were installed at the distance of 2.4 metres from the exit of the inlet chamber to ensure a steady flow of the passing turbidity current. Those were placed at a distance of 0.15m from the bottom of the flume, one of them at an angle of 60° looking into the flow, to measure the horizontal velocity and turbulence of the flow. Corrections should be made on velocity data because they are not measuring the velocity in the direction parallel to the bed due to their 60 degree angle. The second UVP device is placed at a 90° angle with the bed to measure the vertical variations in turbulence and current velocity. Just in front of these UVP-probes a high-speed camera filmed the turbidity current through the side of the flume at a rate of 100 frames a second, during later experiments increased to 200 frames a second. The video data obtained from these cameras was used to estimate the flow height of the flow. Four siphon tubes with an inner diameter of 0.8mm were placed at respectively 1, 2, 4, and 8 centimetres above the floor of the flume, samples were extracted through these tubes in order to measure both the vertical concentration profile as well as the vertical particle size distribution of the turbidity current. For all the experiments these measurements were taken of the body of the turbidity currents since these are during the steady flow stage of the experiment and therefore give the most reliable results. For two runs of the series an automated arm with two siphon tubes attached to it at 5 cm apart was used. This arm moved up and down once over the course of a single experiment taking continuous measurements on concentration and particle size from the bottom of the flume to 15 cm above it. By using this method the bottom 15 centimetre of the flow were measured twice (once the arm going down and once back up) during a single experiment. This results in 20 samples (2 for each centimetre) with an overlap covered by both siphons from 5 to 10 centimetres from the bed. By analysing all of these samples based on concentration and particle size a far higher resolution could be obtained as compared to only the 4 data points of the previously used method.

The mixture of sediment used during the experiments consists of four different sizes of quartz sand, the D50 of these four different sizes are 103, 135,170 and 210 micron respectively. These four particle size are used in a 2 [103µm]: 3 [130 µm] : 1 [170 µm] : 1 [210 µm]ratio, as can be seen in on the right hand side of fig.3 this gives a range from approximately 125 to 260 micron with a continuous profile of particle sizes. The range is used because it covers a larger spectrum of particle sizes as compared to earlier experimental work on turbidity current most notably by *Cartigny, 2012 & Baas, 2008* giving the opportunity for comparison between results at a later stage.

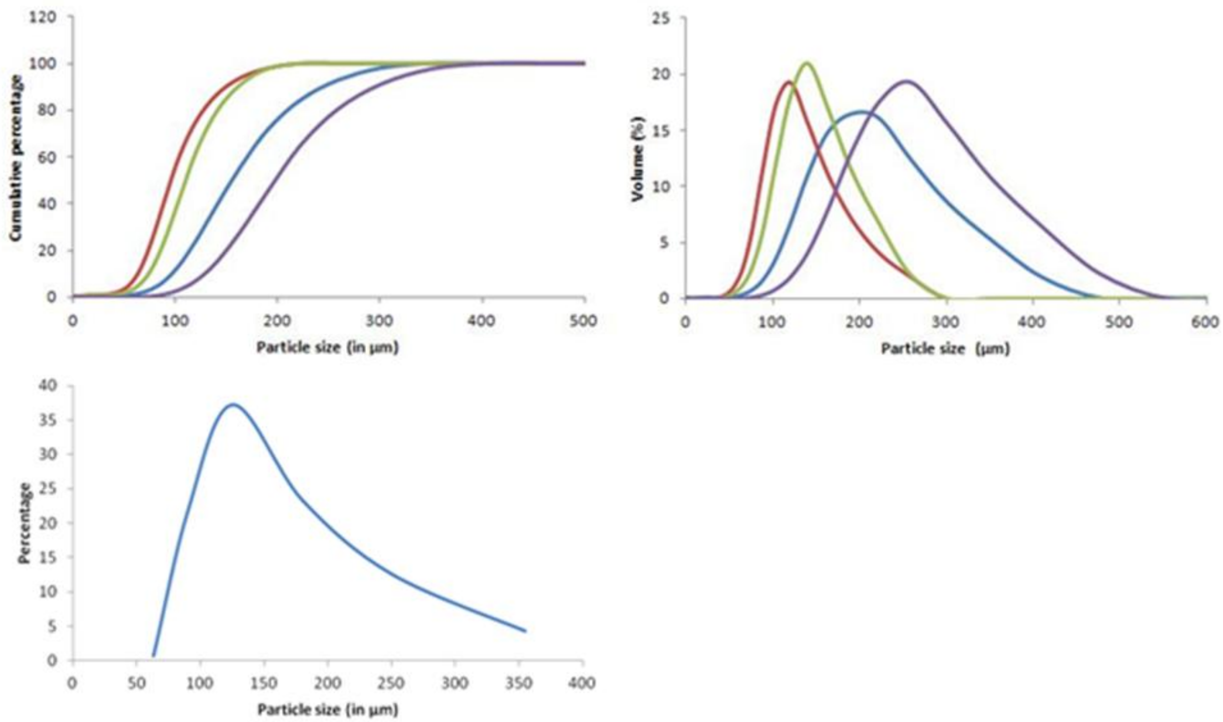


Fig. 3) A cumulative plot of the 4 different quartz sands used (Left). A distribution plot of the quartz sands used in the mixture with a ratio of 2 [103µm]: 3 [130 µm] : 1 [170 µm] : 1 [210 µm] (Right). A composite plot of the mixture used based on the four different types of quartz sand.

2.1.4 Data analysis

2.1.4.1 Scaling

Since experimental work on turbidity currents is performed on a different scale to the natural processes, it is important to make sure the experiments carried out are still comparable to these natural turbidity currents. This is done using dimensionless parameters like the Froude, Reynolds and bulk Richardson numbers. In order to calculate these dimensionless parameters, a few key aspects of the flow need to be derived. The important among these are the depth averaged flow velocity (U_{mean}), the depth-averaged volume suspended sediment concentration (C_{mean}) and the flow height (h). All three of these can be determined by analysing the UVP data and concentration measurements collected during the experiments. There are various methods for determining the values of U_{mean} ,h and C_{mean}, for this study the proposed method by Parker et al. 1986 was used. Both the average values for the velocity of the current as well as the average concentration of suspended sediment are dependent on the flow thickness. The complexity is however determining the upper boundary of the current. The method issued by parker (1986) and later enhanced by several others (Garcia&parker,1993; Islam&Imram,2010) works around this problem by calculating the averages without setting a number for the flow height. This method derives the average flow velocity, flow height and average suspended sediment concentration using three equations based on the concentration profile and the velocity profile.

$$U_{mean}h = \int_0^\infty u(z)dz$$

$$U_{mean}{}^2 h = \int_0^\infty u(z)^2\, dz$$

u(z) is the averaged local velocity and z is the distance from the bed. The integral is calculated from the base of the flow (bed) to infinity. This upper limit represents a level of z for which the velocity has reduced to insignificantly small to be still part of the current. In our case the upper limit is the maximum height above the bed at which the UVP-probes still made velocity measurements (between 12-15 centimetres). By dividing the second equation by the first the U_{mean} can be derived, once this is know the flow height (h) can also be calculated from these results.

A third equation is used to calculate the depth-averaged volume suspended sediment concentration (C_{mean});

$$U_{mean}C_{mean}h = \int_0^\infty u(z)c(z)dz$$

The c(z) in this equation is the local concentration of volume suspended sediment for every step of z. This can be determined using results of the concentration measurements taken during the experiment as described in the methods earlier. Plotting these concentration values for the various heights, a logarithmic best fit line can be plotted through these. The values for the concentration, as with the velocity, become insignificantly small above a certain value for z which is then taken as the upper boundary of the turbidity current (Garcia& parker, 1993; Islam & Imram, 2010). Using these values the dimensionless parameters can be the derived by the following equations;

$$Fr' = \frac{U_{mean}}{\sqrt{RC_{mean}gh}}$$

In which R= $\frac{\rho s}{\rho} - 1$ with ρ_s (2.65 grams/cm^3) and ρ (1 grams /cm^3)being the density of the sediment and the density of the water respectively. g denotes the gravitational acceleration (9.81 m/s) and. U_{mean} is the depth average flow velocity and h the flow height of the turbidity current and C is the depth averaged volume suspended sediment concentration within the flow.

This equation has been adjusted from the standard Froude number equation to be able to apply them to subaqueous flow (Kostic,2010). The adjustment is needed since the process responsible for the current to flow is different. In open channel flows (rivers) the current moves due to the down slope gravitational pull on the water, as a result of this sediment is pulled with the water. In subaqueous flow the opposite occurs, here gravity works on the suspended sediment within the flow and pulls it down the slope. Water is dragged within the current as a result of this down slope movement of the suspended sediment. The Froude number is an important parameter when looking at natural occurring turbidity current, numerical models and experimental work since it gives an possibility to compare events on different scales when the Froude number is kept equal. The Froude number gives an indication whether the current is sub (<1)- or supercritical (>1), this has been determined to be the boundary between a depletive or bypassing/aggrading turbidity current (Pantin & Franklin, 2009).

Reynolds number is a comparison between momentum and viscous scales of the flow, and can give an indication of state of turbulence in a flow. A value of 2000 has been determined to be the boundary condition between laminar and turbulent flow. The following equation for the Reynolds number has been derived by

$$Re = \frac{\rho_t U_{mean}\, h}{\mu_s}$$

In this equation μ_s is the dynamic viscosity of the flow, this can be derived from Relation of Roscoe (1953) depending on the concentration of sediment in the flow

$\mu_s = \mu_a(1 - 1.35C_{mean})^{-2.5}$.

The dynamic viscosity of ambient water (μ_a) for water at 20° is $1.002 \cdot 10^{-3}$ Pa·S.

The final equation to compare the experimental work done with natural turbidity currents is the bulk Richardson number. This number is an indication of the stratification within the flow compared to its turbulence. A low Richardson numbers means low stratification of the flow and therefore a single system of turbulence as compared to a high number which is a signal for stratification within the flow.

$$Ri = \frac{g \quad RCh \cos S}{U^2}$$ S being angle of the slope

2.1.4.2 UVP data analysis

The data collected by the UVP probes during the experiment contains information about the behaviour of the flow in terms of velocity and turbulence. Properties of the flow which are interesting regarding this study are the maximum (U_{max}) and depth average (U_{mean}) velocities of each experiment. These values were derived from a time averaged velocity profile constructed from the UVP data and from this the maximum velocity is selected. The interval used for the time average velocity profile is the body of the turbidity current for which the discharge is steady and therefore gives the most reliable data of the quasi-steady phase of the turbidity current. The depth average velocity was also derived from this profile as it is the steadiest interval of the experiment and would therefore give the most reliable data. This method however gives difficulties during depositional runs because the distance from the probe to the bed varies with time. This shifting of the bed causes the top of the flow to pass above the UVP probe so no measurements on these can be made, resulting in too high depth average velocities. The same applies to deriving the flow height from UVP data which gives distinct break in the bypassing runs but can become hard to estimate in depositing runs due to the afore mentioned build up of the bed. For bypassing runs the flow height derived from the UVP data was compared to the recordings of the high speed camera to verify its accuracy. With the height and velocity data a number of other calculations can be made in order to obtain information on the passing current, these include shear velocity, Richardson numbers and dynamic viscosity of the turbidity current.

2.1.5 Experiment series

This study aims to link the particle size profiles of a turbidity current to the particle size profile of its deposited levees. Therefore it is important to understand the effect of various parameters on the turbidity current and how these influence the vertical particle size segregation. From others studies [skene, 2003; Straub, 2008] it has been derived that; current height, current velocity and the properties of the sediment within the current have a major influence on the final composition and architecture of the levees they deposit. These properties of the turbidity current are influenced by several parameters like; slope angle, initial discharge, initial concentration and the initial particle size composition of the current. The 2D experiments were conducted to better understand the effect of various parameters on the conditions of the turbidity current. Furthermore during these 2D experiments data of both the vertical concentration and particle size composition of the current will be collected. This data will be used as a predictive tool for the vertical composition of the levees during the 3D experiments.

The 2D experiments were divided into two series. The first series used a constant volume concentration and particle size mixture, whilst the other parameters (Slope and discharge) were varied (table 1). This was done in order to see the influence of these on the properties (flow height, current velocity, concentration profile and particle size composition of the flow). The slope was varied accordingly to obtain information on the equilibrium slope of the flow. The equilibrium slope is the slope at which the flow changes from depositional to erosive and is stated by various authors (Cartigny, 2012).

Runs #	Discharge (Q)	Slope (°)
2	20	10
5	20	8
18	20	6
19	20	8
20	20	10
21	20	9
23	20	10
24	20	9
25	15	12
26	10	10
27	10	12
28	10	11
29	15	10
30	15	9
31	15	8
32	15	7
33	25	6
34	25	5
35	20	7
36	20	6
38	20	5
39	15	9
40	15	11

Table 2) The characteristics of the second series of 2D experiments. These runs are all performed with an initial concentration of 13% and a constant discharge of 20 m^3/h.

The second set of experiments were carried out using only a single type of quartz sand instead of the above mentioned mixture and a set discharge of 20m^3/h (table 2.). These experiments were carried out to see the influence of different initial particle size compositions on the turbidity current and the equilibrium slope. The smallest particle size that has been used in the previous series (103 micron) has not been used as a single particle size composition during these experiments. The reason for this is that at a discharge of 20m^3/h the current will not become depositional and therefore would have an equilibrium slope of 0. The opposite applies for the 210 micron quartz sand which was still depositional at a slope of 12 degrees and in our setup steeper slopes could not be tested.

Run #	Slope (°)	particle size in micron		
		135	170	210
7	12			■
9	12		■	
10	11		■	
11	12		■	
12	12		■	
13	12	■		
14	10	■		
15	8	■		
16	6	■		
17	4	■		
22	3	■		

Table 1) The characteristics of the first series of 2D experiments. All of these were done with a constant initial volume concentration (13%) and a constant mixture of sediment (2 [103µm]: 3 [130 µm] : 1 [170 µm] : 1 [210 µm])

2.2 3D Eurotank

The second phase of this study was carried out in the Eurotank facility at the Utrecht University. The Eurotank is an 11.4 m long, 6.3 m wide, and 1.3 m deep flume that can be used to model the oceans floor. The floor of this flume can be modified in height to create relief, for our experiments a relief was created that simulates the continental slope to the oceans floor. This slope has an angle of approximately 12 degrees. The floor on the slope was covered by a sand mixture with the same range of particle sizes as the first part of the 2D experiments were done with 2 [103µm]: 3 [130 µm]: 1 [170 µm]: 1 [210 µm]. The slope created for these experiments is 5 metres in length and at its widest point near the bottom of the slope also 5 metres in width. The end of the slope is 10 centimetres above the horizontal floor of the tank; this is done in order to reduce the effect of back stepping of the lobe deposit at the bottom of the flume onto the slope. In our experiments the focus is on the creation of a channel bounded by levees on the slope and therefore the deposits of the turbidity current at the horizontal bottom are not important. The combination of sand and water forming the turbidity current is mixed using the same mixing tank as during the 2D experiments and through a series of tubes is pumped towards the Eurotank. To minimise the influence of air bubbles trapped within these tubes they were filled with water before the start of each experiment. From those tubes the mixture passes through an inlet box. This 1.5 m long box gradually widens from the initial diameter of the tubes to a 1 metres wide flow and ensures in this way an evenly spread out flow at the top of the slope. As with the inlet box in the 2D experiments it also reduces the effect of entrainment of water at the start of the slope by an inclined roof of the inlet box (20 degrees). The floor and walls of the inlet box have sand glued onto them acting as roughness comparable to the bottom of the 2D flume. This inlet box was placed on top of the slope under a slightly less steep angle than the slope itself and was partly buried. This was done in order to lessen the scouring effect as the current flows from the inlet box onto the sandy slope. The whole flume was filled with water to submerge the slope and inlet box completely, so no influence off the water surface would occur.

2.2.2 Data collection

Two underwater cameras were installed to capture the current as it flows down the slope. One at the bottom of the slope looking into the current and a second one captured the current from the side as it leaves the inlet box. These recordings were analyzed on inconsistencies of the flow during the experiment. As during the 2D experiments, ultrasonic velocity profile measurement probes [UVP DUO MX, 1 MHz] were installed to collect data on flow velocity, turbulence intensity and flow height. During the first set of experiments four of them were placed in a line down the slope with the first one being placed just above the end of the inlet box then the next at a distance of 1.3m from there, this way covering the entire length of the slope. For each experiment they were lined up with the centre of the inlet box, this to ensure the middle of the current was recorded. Height above the bed was set at 13 centimetres, this to make sure the bed was still visible in the recordings and additional deposition or erosion would still be visible. The last three consecutive experiments had the UVP's placed in an array parallel to the strike of the slope. Height above the bed was kept at 13 centimetres in order to be able to record the bed of the slope during the various experiments at all times. Four of them were installed at 25 cm spacing of each other starting at the centre of the flow towards the side of the slope, all facing upstream. A fifth UVP was placed right next to the second UVP and was facing perpendicular to the others towards the centre of the slope. This was done in order to record the change in direction of the flow as it got further away from the centre. The other four UVP's were measuring the difference in flow velocity and turbulence moving from the centre of the flow towards the sides. Also they recorded the deposition of sediment and hence the creation of levees and the effect this had on both flow velocity and turbulence in the second and third run. Data collected by those UVP measurement device were again used to calculated Froude & Reynolds numbers, mean velocity and flow height of the flow as elaborated in the data scaling section of the 2D experiments (page. 6-8). In the setup used for the 3D experiments it is not possible to measure the concentration and particle size composition of the turbidity current itself, therefore a different method has been used to estimate the average volume concentration of sediment within the flow. This method coins a expansion factor (ef) to compare the initial discharge with the measured flow discharge of the turbidity current. (*Hofstra, 2012*). ($ef = \frac{Q_t}{Q_i}$) with Q_i being the initial discharge and Q_t the discharge as measured during the experiment. Q_t is calculated from the flow velocity and the dimensions of the flow. Q_t=U_{mean} x flow height x width of the flow. Both the mean velocity and the flow height can be calculated as mentioned before by analyzing the data obtained from the UVP measurements. The width of the flow is assumed to be the width of the channel it creates, this can be derived by measuring the distance between the crests of the levees it created on both sides of the slope channel. By using this expansion factor on the initial concentration ($C_t = \frac{Ci}{ef}$) the concentration within the actual turbidity current can be estimated. This average volume concentration of sediment within the turbidity current can subsequently be used to derive turbidity density, shear velocities and both the Froude and Reynolds numbers.

Laser scanner photogrammetry using an automated positioning system designed for high-resolution surface scans was used to create a digital elevation model (DEM) of the slope before and after each run. Combining the digital elevation scan taken after the experiment with one at the start of it, shows the areas in which erosion or deposition of sediment has taken place. By doing this for all three consecutive experiments it shows the development and evolution of the slope channel and bounding levees under the influence of a passing turbidity current.

The evolution of both the slope channel and the levees were also studied in terms of particle size composition. Therefore at least two sets of particle size samples were taken after each run. One set would be down slope in line with the centre of the inlet box. These consisted of five samples each with a metre of spacing in between, in this way covering the whole slope. The second set of samples would be taken along a number of vertical sections at different distances from the channel axis. This is done to sample across the bounding levees to acquire data on changes in particle size within the levees. The spacing between samples going across the levee varies depending on the size of the formed deposition. On the runs with the best developed levees a third set of samples is taken, further down the slope again going across the levee. All samples taken were divided in two or more sections depending on the height of the levee. The particle size distribution of each sample will be analysed using the Mastersizer S long bed Version 2.18. These analysed samples show the variation in levee composition in vertical, down slope and perpendicular orientation and therefore all trends can be observed. The results of this compositional data obtained by the 3D experiments will then be used to compare with the predictive data that has been derived from the earlier executed 2D flume experiments.

2.2.3 3D experiment series

The 3D experiments carried out in the Eurotank flume focused on creating a slope channel bounded by levees. These levees were subsequently analysed on their architecture and composition and compared to results on particle size from the 2D experiments previously mentioned. Since the experimental work on slope channels is limited this is of major importance to increase the understanding of turbidity currents. In this study a series of eleven experiments were run trying to create a channel covering the full slope and formation of levees on either side of it. The first eight runs were performed varying the parameters in order to get a better understanding of the influence of each of them and obtain a better result in the following runs. The parameters involved are;

-*Geometry of the inlet box* : The importance of the inlet box is to make sure the discharge of the sediment-water mixture enters the tank as straight as possible, this in order to ensure a straight flow down the slope and no influences of “meandering” due to a skewed inflow. Furthermore the box was made with such dimensions to confine the flow as it enters the tank to reduce major influence due to entrainment of water. Roughness was also created within the inlet box by gluing sand to its bottom to act like an artificial bed and make the transitions to the actual slope smoother.

-*Discharge*: varied between 30 and 50m^3/h kept reasonably steady throughout each experiment. The higher discharge caused the turbidity current to entrain a lot of ambient water at the top of the slope causing it to swell to a large current with relatively low concentration of sediment, to counter this a lower discharge (30m^3/h) was used during the latter experiments.

- *Slope*: Equilibrium slope results from the 2D experiments were used. For the particle size composition and discharge this was estimated at 10 degrees. However due to the large scale of the 3D experiments had to be increased to 12 degrees to get bypass runs.

-*Sediment concentration*: A 13% volume concentration of sediment as was used during the 2D experiments. However since the size of the turbidity current increases significantly after entering the Eurotank the actual concentration drops to the point that all force of the current is lost. To increase the actual concentration of the turbidity current as is flows down the slope an initial volume concentration of 17% has been used for the last 6 runs.

-*Particle size composition*: The first six runs the before mentioned 2 [103µm]: 3 [130 µm]: 1 [170 µm]: 1 [210 µm] particle size composition was used. For the last 5 runs a composition of 1 [103µm]: 1 [130 µm] was used. The reason for this being that the first used mixture deposited early on the slope due to the higher fraction of large particle sizes. With the later used mix the smaller particles are kept in suspension easier throughout the current creating bypass.

-*Angle of the inlet box*: Scouring occurred at the transition point of the inlet box to the actual sandy slope. In order to reduce this, the inlet box was placed under a slightly shallower angle compared to the rest of the slope. To further minimise the scouring effect the inlet box was partially dug into the slope itself, creating an easier transition between the non-erodible inlet box and the sandy bed of the slope.

3. Results

3.1 2D experiments

For every experiment run various properties of the flow are derived from the collected data; these properties show the development of the turbidity current based on the initial parameters chosen. Some of these are of importance for scaling purposes like the Froude and Reynolds numbers and can also give insight in the intensity of turbulence. Other parameters, like flow velocity and initial discharge have an influence on the concentration profile and the directly linked particle size profile of the turbidity current. Table 3 below shows these parameters for the most important 2D experiments with an additional table for all experiments carried out available in appendix A.

Table 3 Flow Characteristics of experimental turbidity currents

Runs #	ρ_0	ρ_1	Q (m^3/s)	Umean (m/s)	H_b (m)	U* (m/s)	Fr	RE	Umax (m/s)
28	1085.8	1045.4	2.78 x10^{-3}	0.697	0.092	0.052	2.36	6.12 x10^4	1.077
30	1085.2	1060.3	4.17 x10^{-3}	0.819	0.095	0.055	2.23	8.22 x10^4	1.087
36	1083.2	1053.2	5.56 x10^{-3}	0.911	0.088	0.045	2.66	8.40 x10^4	1.141
33	1086.4	1074.6	6.94 x10^{-3}	1.064	0.094	0.050	2.55	1.07 x10^5	1.171

All these are erosive runs closest to equilibrium slope conditions to compare between different discharges. ρ_0 = Initial density of the suspension; ρ_1 = Density of the suspension at the measurement section during the experiment; Q = Discharge as measured through the inlet system; U_{mean} = Depth-averaged velocity of the quasi-steady body of the flow; H_b = Flow height of the body; U* = Shear velocity as determined by the flow height and the method proposed by *Kneller et al. ,1999*; Fr = Densimetric Froude number Re = Reynolds number of the body. From top to bottom the discharge per run increase with 5 cubic metre an hour. Starting at 10m^3/h (run 28) to 25m^3/h (run 33)

These runs have a discharges (Q) between 10 and 25 m^3/h in order to study the influence of this on flow properties of the turbidity current. A first observation that can be derived from this data is with an increasing discharge obviously the depth-average velocity of the body of the current increase too. A faster flowing current has a lower flow height, as a result of this the decrease in density of the suspension, as measured at the 2.5 metre point down the slope, is less compared to the initial value than for larger and slower turbidity currents. Shear velocity on the other hand decreases with a increasing velocity of the current. In other words, faster flowing currents seem to be more stratified based on shear velocities, however they have higher densimetric Froude and Reynolds numbers which indicates more turbulence occurs within.

The first set of experiments were carried out using a constant mix of *2 [103µm]: 3 [130 µm]: 1 [170 µm]: 1 [210 µm]* at a volume concentration of 13%. The other parameters of these high density turbidity currents were then varied in order to obtain the influence of them on the vertical concentration and particle size profile of the flow. The best comparison for runs with different discharges is those near the equilibrium slope, since conditions within these currents are similar. The equilibrium slope of turbidity current is the angle of slope at which the conditions for a flow changes from a non-aggrading to a aggrading run (fig. 4).

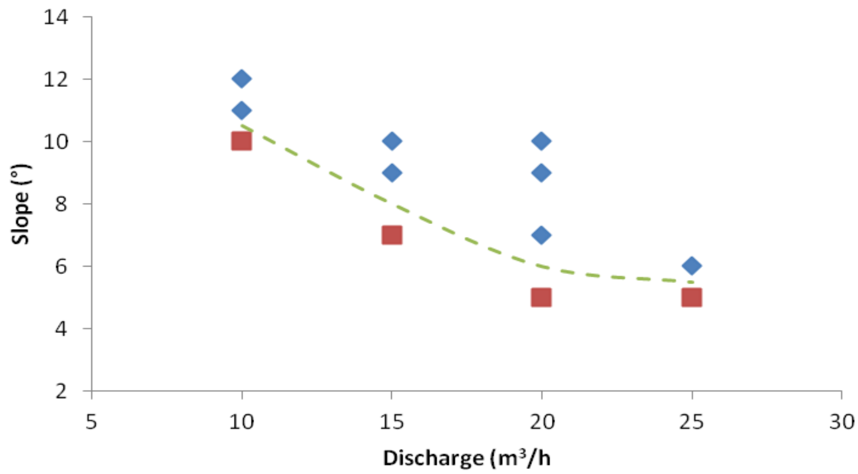


Fig. 4) Plot of the dependence of the equilibrium slope on discharge of the turbidity current. Aggrading runs (Red), Bypassing runs (Blue), dashed green line represents the equilibrium slope.

The relation between equilibrium slope and discharge shows a decrease in the steepness of the slope with increasing discharge. From a discharge of 10 cubic metre per hour there is a linear decline in the steepness of the slope from 11 degrees to 7 degrees if the discharge is increased to 20 cubic metre per hour. At a higher discharge the linear trend does no longer occur but flattens out to around a 6 degree slope for the boundary between aggrading and bypassing/depletive currents.

The concentration and particle size measurements for most of the runs were only sampled at four different heights above the base of the current this makes it difficult to draw any significant conclusions/ trends through these few data points. As mentioned before however for 2 runs the samples have been taken by an automated arm giving higher resolution data (10 data points). These can be compared with a low resolution run under the same circumstances in order to see whether the trends draw through these points are reliable (fig 5).

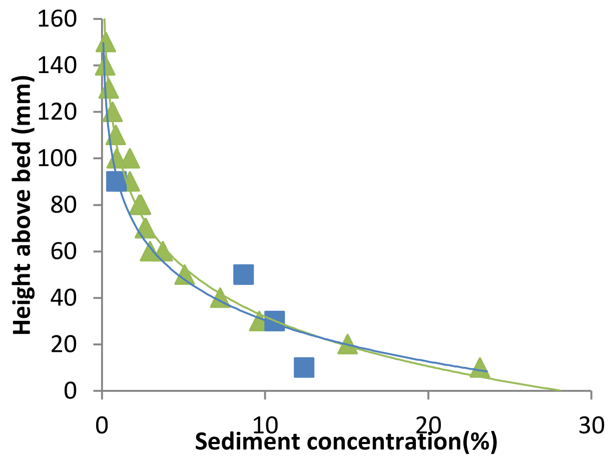


Fig. 5) a plot of the 2 experiments with the same boundary conditions using different methods of samling the concentration. With an automated arm (Green) and using stationary siphon tubes (blue)

The plot for the automated run (Green) shows a continious decrease in sediment concentration with height, best resembled by a logaritmic function. By applying a logaritmic function to the data obtained by the low resolution method (Blue), it gives a trend line closely related to the high resolution function. Based on this it is assumed that the concentration profile in all experiments is a continious decrease best represented by a logaritmic function and all other data is treated as such.

The first parameter that is looked at is the influence of discharge on the turbidity current in terms of concentration and particle size. Below is the vertical concentration profile per discharge for bypassing runs near the equilibrium slope.

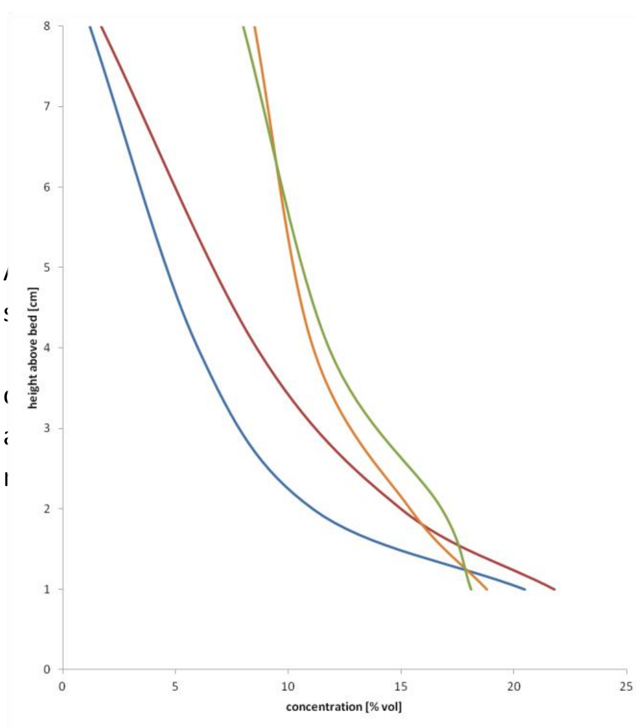


Fig. 6) vertical concentration profiles of bypassing runs per discharge. 10m^3/h (Blue) , 15m^3/h (Red) ,20m^3/h (Orange) and 25m^3/h (Green)

be seen in the graph [fig. 6] the concentration profiles differentiate more the further the distance to the bed is. They differentiate in such a way that near the top of the measured spectrum two distinct groups of discharge occur. These two groups of concentration profiles are similar to each other and no obvious trend can be seen amongst them. The runs with 10 (Blue) and 15 (Red) cubic metre per hour discharge start near the bed at a slight higher concentration but this declines rapidly to values of only a few percent the further the distance to the bed becomes. Experiments with the higher discharges (20m^3/h and 25m^3/h) have a slightly lower concentration (20%) near the bed however the decline in concentration with height is significantly less (10%) as compared to the low discharge runs.

A similar plot (fig. 7) is constructed for the variation in vertical particle size profiles for the four different discharges mentioned afore. The overall trend is an increase in particle size throughout the height of the turbidity current with increasing discharge, comparable to the result in the former concentration graph.

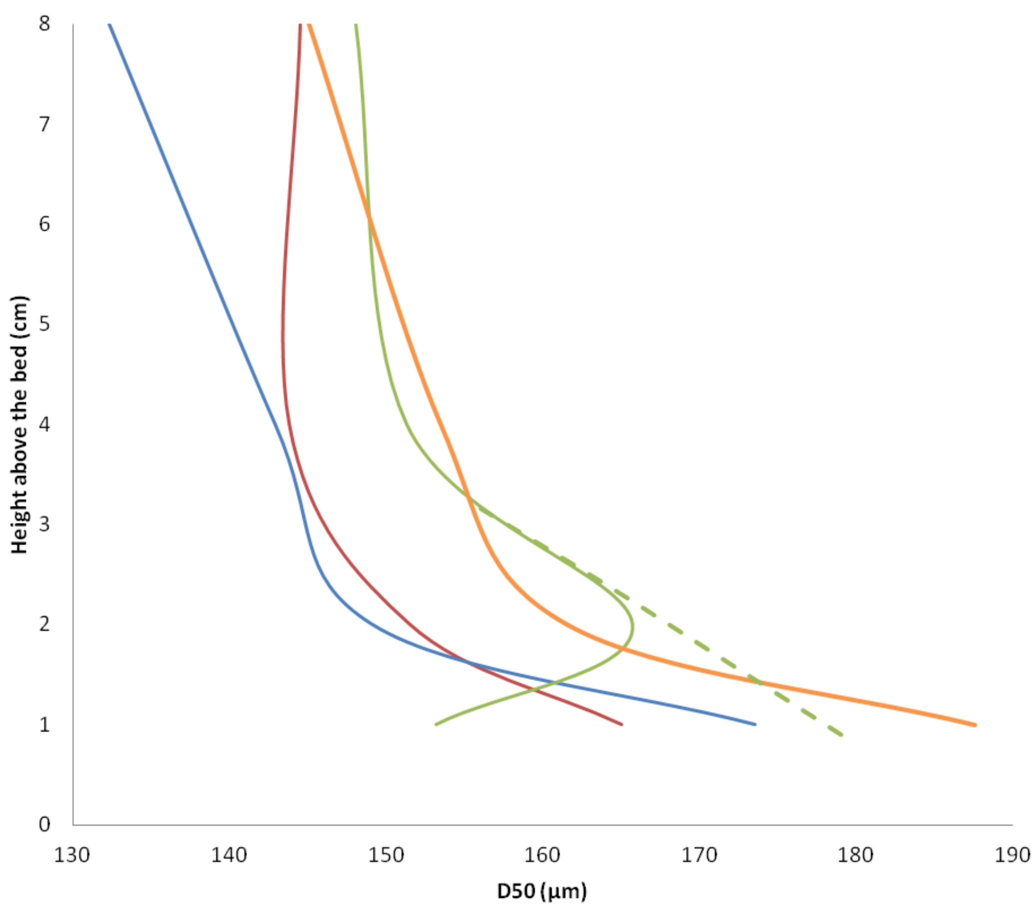


Fig. 7) Vertical particle size profiles for bypassing runs per discharge. 10m^3/h (Blue) , 15m^3/h (Red) ,20m^3/h (Orange) and 25m^3/h (Green). The dashed line represents an estimate of the particle size for the bottom centimeters to compensate for the unreliable data obtained during the experiment.

The profile for the 25m^3/h (green) experiment looks distinctively different compared to the other three profiles. This is mainly due to the lowest data point (1 centimetre from the bed) being considerably lower than the point at 2 centimetres. This particular run was not a complete bypassing one with some sediment being deposited mainly around the siphon tubes used for measurements on particle size. The bottom data point may therefore have been affected by the build up of sediment and is therefore unreliable. A dashed line was added to estimate the bottom data point of the high discharge run if it would follow the trend of the other runs. Using this estimate as most reliable point of the high discharge experiment it shows for all four experiments a sharp reduction in particle size close to the bed. The largest decrease in particle size can be observed in the experiments with a lower discharge. Above this initial steep decrease the reduction becomes less steep going from roughly 2 centimetres to the highest measured point of 8 cm above the bed. The overall shape of these particle size profiles is comparable to the concentration profiles mentioned. The standard deviations of the quartz sand used for the experiments ranges from 40-60 micron, this creates difficulties in replicating the exact particle size composition for each run. Although the exact values per experiment differ due to this, the overall trends observed can be derived from all experiments carried out.

In short the results of the experiments show a sharp decline in sediment concentration and particle size within the first few centimetres above the base of the current. The upper part of the flow has less of a decline in both of these. The profiles also show that stronger currents in terms of discharge are able to carry larger particle sizes higher within their current.

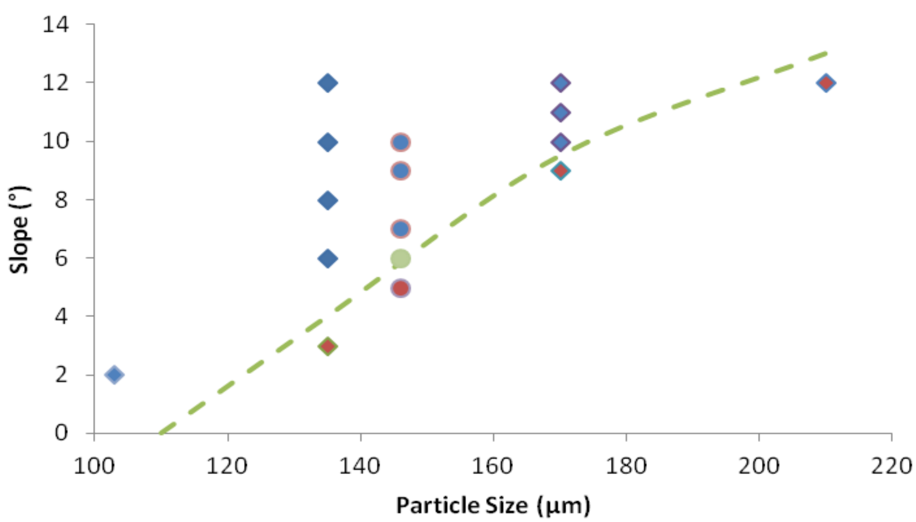


Fig. 8) Plot of the dependence of the equilibrium slope on particle size. For all experiments with 13% volume concentration sediment and a constant discharge of 20m^3/h. Bypassing runs (Blue) Depositional runs (Red), estimated equilibrium slope (green). Diamonds represent experiments carried out using a single particle size mix. Compared to the sediment mix used in the first set of experiments (Circles).

The second of 2D experiments investigated the effect of particle size on the properties of the flow like flow velocity, slope and concentration profile. Four different particle size samples were used in these experiments with a D50 of 103 µm, 135 µm, 170 µm and 210 µm respectively. These experiments were carried out using the same 13% volume concentration of sediment as in the first set of experiments and a constant discharge of $20 m^3/h$ in order to compare the results with the data obtained in the first set of experiments. The equilibrium slope for the different particle size samples was the starting point during these experiments, because experiments near the equilibrium slope are best comparable with each other. The equilibrium slope increase with increasing particle size, this means the slope becomes steeper in order to still get a bypassing run for large particle sizes (Fig. 8). The largest particle size (210 µm) turned out to be depositional even at a 12 degree slope, which is the maximum slope in our experimental setup and its equilibrium slope is therefore only an estimate. This shows a linear trend of increasing slope with particle size throughout the whole ranges of particle sizes, with the exception of the 210 micron particle size which isn't depletive under any of our experimental setups and the slope for this can therefore only be determined as at least 12 degrees and without and upper limit. The mix experiments of the first series have a mean particle size of 146 µm, plotting this in the graph (circles) of the single particle size experiments shows a good fit with the results for equilibrium slope. This shows that a turbidity current with mixed from quartz sand of different particle sizes does behave in the same way as a current with a single particle size quartz sand and the equilibrium slope can be determined using the D50 for the whole mixture.

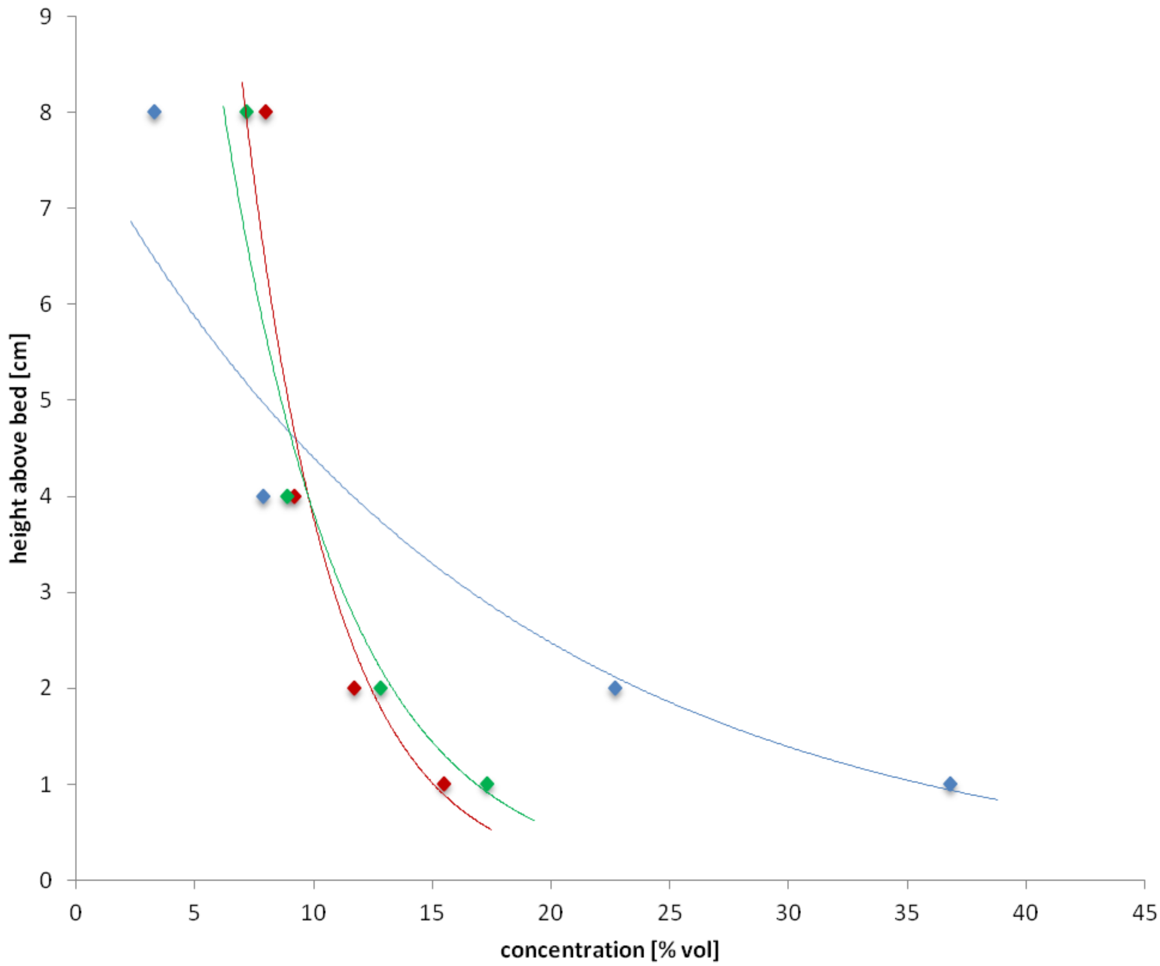


Fig. 9) a plot of the vertical concentration profile based on initial particle size composotion at a constant discharge of 20m^3 and a slope of 10 degrees. 170 micron (Blue) 130 micron (red) and the mixed composition (Green).

The initial particle size composition of the turbidity current itself also has an influence on the concentration profile. The discharge and slope for these experiments were kept at a constant value of 20m^3/h and 13 volume percent respectively, the only variable being the initial particle composition. A larger particle size ,as initial input results in a higher concentration of sediment near the bottom of the current and a larger decline in concentration in the higher levels of the flow. The smaller particle size experiments show a lower concentration near the bottom and less decrease in concentration vertically. The mixed sediment experiment was analysed in closer detail investigate a smaller range of particle sizes. The automated arm and siphons were used to collect ten samples at every centimetre starting at the bottom and subsequently analysed using the Malvern mastersizer. 3 groups of particle sizes; a small (below 120 µ m) medium (120-160 µm) and a large (above 160 µ m) set were investigated to see what composition of the turbidity current was over different heights. These three sets are picked because they represent roughly the D10, D50 and D90 of the initial composition used for the experiments. The small set (under 120 micron) shows a distinct increase in percentage going from the bed to 10 centimetres above the bed. The medium (120-160 micron) also increase with height but less distinct as compared to the smaller particle size group (Fig. 10)

The large particle size makes up over half of all the sediment in near bed conditions (0-3 centimetre) but decreases with height significantly to only one third of the sediment concentration at the top of the measured window. The composition at the top of the turbidity current resembles the best fit with the initial composition of the sediment mixture. looking at the full spectrum of particle sizes for this experiment it can be noticed that the smallest disappear going from high above the bed downwards and the opposite occurs for the largest particle sizes which can no longer be found within the 10 centimetre height samples. it is however important to relate the concentrations to the starting composition of the sediment mixture that builds the turbidity current. The smallest set of particle sizes crosses the concentration of the initial mixture around 6 centimetres from the bed. Closer to the bed the concentration is less than the initial composition and above the six centimetre mark the concentration is higher in comparison with the starting conditions. The opposite trend can be observed for the largest particle size set, where the near bottom conditions render a higher concentration of particles than the overall mixture transitioning to a lower concentration at a height of 8 centimetres above the bed. The set relating the closest to the D50 of the overall mixture behaves dissimilar to the other two. Like the smallest set it starts with a relatively low concentration near the bed as compared to its initial concentration. This increases with height to roughly 35 percent fraction of the total sediment volume at a height of 5 centimetres above

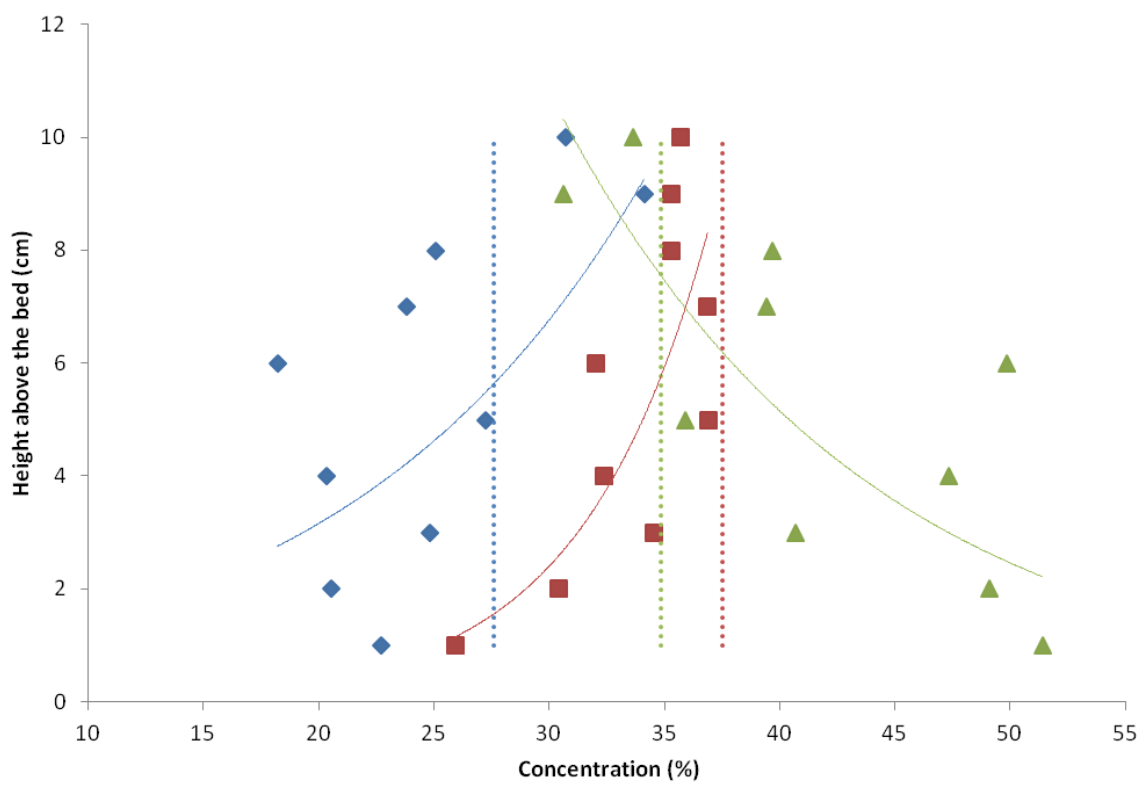


Fig. 10) Plot of concentration profiles for three sets of particle sizes; under 120 µm (blue), between 120 and 160 µm (red) and above 160 µm (green). dashed lines indicate the concentration for each set in the initial sediment composition

the bottom and from their no longer significantly increases. The initial composition value for this set of particle sizes is 37% and within the bottom 10 centimetres of the turbidity current this value does not get crossed, instead a concentration close to its initial composition is maintained throughout the turbidity current above 5 centimetres measured from the bed.

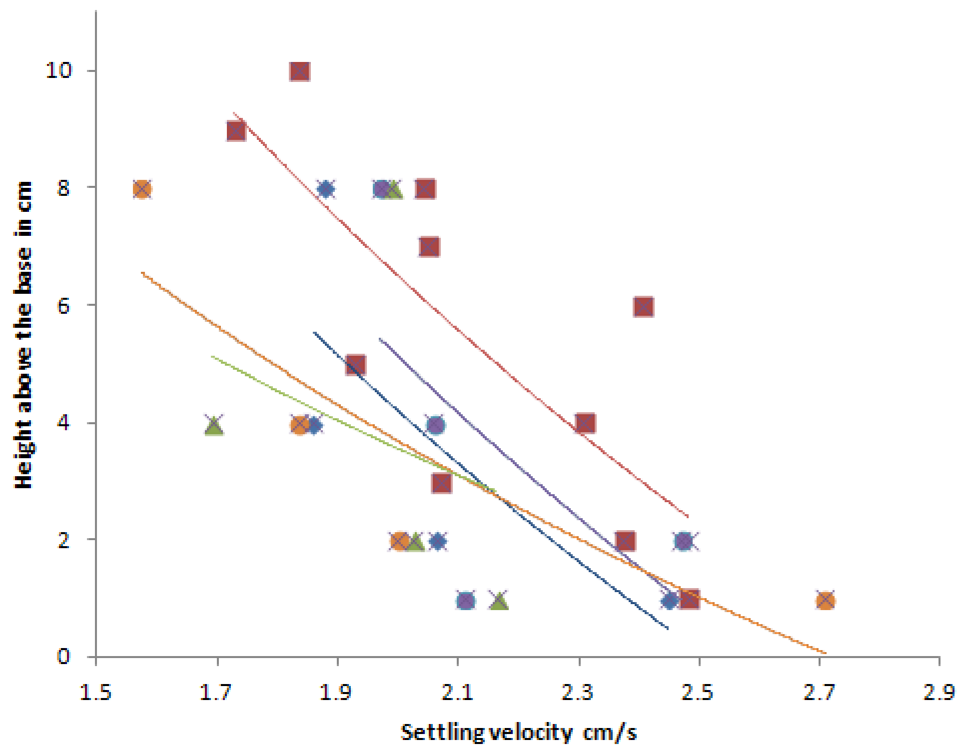


Fig. 11) Plot of the settling velocity with height above the base of the turbidity current for all bypassing runs at their equilibrium slope at discharges of 10m^3/h (orange) 15m^3/h (blue), 20m^3/h (green), 25m^3/h (purple) all with their respective logarithmic trend lines.

The vertical particle size compositions of the turbidity currents have been calculated to settling velocities to be able to compare these to studies by other authors (*Pirmez, Straub*) and the later conducted 3D experiments. The change in settling velocity with height throughout the turbidity current has been plotted for runs done at the equilibrium slope for their respective discharge. By plotting a logarithmic trend line through the data points, it gives an indication of the decrease in settling velocity over height which can also be seen as a decrease in particle size with height. A logarithmic function was chosen because this gives the best fit line in relation to the data points and since it was shown that the particle size with height profiles have a logarithmic best fit line as described earlier in this paper. There is a fair amount of scatter amongst the data since these have different discharges as input conditions. As mentioned before an increase in discharge leads to a larger turbidity current and therefore larger particles being transported within the suspension at a greater height above the base . This plot (fig. 11)shows however that the trend of decreasing settling velocity with height is not dependent on the discharge of the flow and remains roughly the same, the only exception to this seems to be the 20m^3/h runs which has a remarkably higher decrease in settling velocity with height compared to the others.

3.2 3D Experiments

Previous work of *Hiscott et al. (1997) and Pirmez & Imran(2003)* showed particle size succession within a levee could hold a connection with vertical particle size composition of the sediment within a turbidity current. Both of those studies consisted of analysis of cores taken from levees along the Amazon channel and found distinct spatial trends within the particle size composition of these levees. The most significant conclusions drawn from *Hiscott et al. (1997)* are; A) downstream depletion of the finer fraction of particles being caused by overbank spill and deposition. B) A overall decrease of particle size with height within levees. Leading to the hypothesis; that a relation between vertical composition of turbidity current and their levees could be derived. *Pirmez & Imran (2003)* continued this study in more detail and worked on a higher resolution as compared to *Hiscott et al*. This lead to a vertical particle size profile of levees, which shows trends in different phases of the growth of a levee. A phase consists of a series of turbidity current events in this representation. The overall profile still showed a fining upward sequence throughout the levee, however subsequent turbidity current events showed up as smaller sequences with a coarser particle size near the bottom and fining upward only to be followed up with again a coarser base of the next sequence before fining further. Original conditions of the turbidity current and properties such as channel depth and its evolution over time are unknown in research of these natural levees. The experiments conducted for this study are to form a slope channel bounded by levees and in that fashion look into the particle size succession and compare these to the results as shown by these former authors to verify the validity of our results and subsequently try to correlate these particle size successions of a levee with the known conditions of the turbidity currents creating them.

As mentioned before there is limited knowledge about the conditions for the initiation of a slope channel and its bounding levees and therefore various conditions were tried in order to start the formation of the slope channel. The slope was set at 12 degrees to make sure a bypassing/depletive turbidity current would be created under a discharge of roughly 30 cubic metre per second. From former experimental work on turbidity currents it was noted that the angle of the inlet box is of great importance in order to reduce scouring effect of the current as it flows onto the sandy slope. Over multiple runs these variables were tested and improved to be able to form a slope channel with bounding levees. After obtaining more of a constraint on the particular conditions needed for the formation of a slope channel with levees three consecutive turbidity current experiments were carried out to gain insight in the development and evolution of a slope channel/leveed system. The conditions eventually used for these were a slope of 12 degrees with the inlet box at slightly shallower angle (11 degrees) in order to account for a smooth transition from the non erodible inlet onto the sandy slope, this all at a discharge of 30 cubic metres per hour. The initial sediment concentration was 17% with a particle composition of 1 (103µm): 1 (132µm). The aims of these three experiments are to create a slope channel on both sides bounded by levees, this in order to investigate the development of submarine levees both architecturally as well as their compositional structure. The flow characteristics for these consecutive turbidity currents are depicted below and give a starting point about the development of a slope channel and bounding levees during these flows.

Table 4) Flow parameters of 3 consecutive 3D experiments

Runs #	ρ_0	ρ_1	Q (m^3/s)	Umean (m/s)	H_b m	U* (m/s)	Fr	RE	Umax (m/s)
49	1112.5	1032	$8.33x10^{-3}$	0.547	0.059	0.058	1.44	$3.32 x10^4$	0.930
50	1109.2	1028.1	$8.33x10^{-3}$	0.593	0.063	0.056	1.51	$3.81 x10^4$	0.966
51	1113.1	1022.5	$8.33x10^{-3}$	0.693	0.075	0.054	1.62	$5.26 x10^4$	1.138

All these runs are carried out with a 12 degrees slope and under equal and constant discharges. ρ_0 = Initial density of the suspension; ρ_1 = Density of the suspension at the measurement section during the experiment; Q = Discharge as measured through the inlet system; U_{mean} = Depth-averaged velocity of the quasi-steady body of the flow; H_b = Flow height of the body; U* = Shear velocity as determined by the flow height and the method proposed by *Kneller et al. ,1999*; Fr = Densimetric Froude number Re = Reynolds number of the body of the turbidity current U_{max} = Velocity maximum.

The parameters for the three consecutive runs were equal in terms of discharge, slope, composition of the initial sediment mixture and starting concentration of the sediment-water mixture. The results of these experiments are shown in the table above (table 4). Some remarkable observations can be derived from these results; first of all there is an significant increase in the mean velocity of the current with each following experiment albeit the discharge remains equal. The thickness of the flow however also increased with each experiment, meaning the turbidity current becomes faster and at the same time larger at the point of the UVP measuring probe located in the middle of the channel (UVP probe 2).The variables of interest within this table are both the Reynolds and Froude number since these are distinctly different as compared to the 2D runs carried out before. The values for the densimetric Froude number of the 2D runs varied between 2.2 and 2.6 and were in indication of supercritical flow, the turbidity currents in the 3D experiments are still supercritical although their Froude numbers are a lot closer (between 1.4 and 1.6) to the boundary level of 1 dividing sub- and supercritical flows. This can also be seen in the Reynolds numbers, which are only half of the values of the 2D experiments indicating a less turbulent flow, although these still are above the boundary value (Re >2000) for turbulent conditions.

Below (Fig. 12) is a digital elevation map of the deposits after all three experiments were carried out and shows the developed levee bounded slope channel near the lower half of the slope. The blue line represents the transect across the right-bounding levee that was used as sample location. The bounding levee on the left of the main slope channel is less developed as compared to the right and also shows indications of being breached higher on the slope, whereas the right levee more uniformly developed and does not show indications of an incipient avulsion altering its architecture. For this reason the right bounding levee was picked to be used for the sampling transect. The position of the transect along the right bounding slope was also chosen as a result of the development of a scour near the top part of the slope. The Sediment-water mixture is pumped into the inlet box at a set discharge of roughly $30 m^3/h$ and develops into a turbidity current as it enters the tank. Since the turbidity current near the exit of the inlet box is still influenced by the momentum supplied to the current at the inlet it needs time to develop in a self-sustaining turbidity current with a velocity and other properties that are in agreement with those. Low on the slope this effect has subsided and is therefore a better location for the sampling transects. Another reason not to use a transect higher up the slope is the development of a scour near the exit of the inlet box, this scour significantly influences the flow of the turbidity current and this effect had to be reduced to a minimum in order to get the result of an uniform flow down a slope.

The bounding levee itself was sampled on three locations; first of all the highest point of the levee with the other samples taken at 25 centimetres on either side of the top of the levee. These positions are roughly halfway the levee slope on both sides to cover the most important part of the levee. These samples give the particle size composition of the levee on all of the above mentioned points with a half a centimetre resolution in height and will later be compared to the 2D experiments. During these experiments measurements were done on the Turbidity currents velocity with the use of UVP-devices (black dots on the map). The data collected from these devices can be converted in vertical velocity profiles over time for each run and position in relation to the main channel. They measure from the original bed up to a height of 13 centimetres above it and are therefore also used to obtain information on the depositional rate with time. These values are in indication for the development of the turbidity current in terms of height and confinement in between levees and relationships between those and the vertical particle size composition of the bounding levee will be determined.

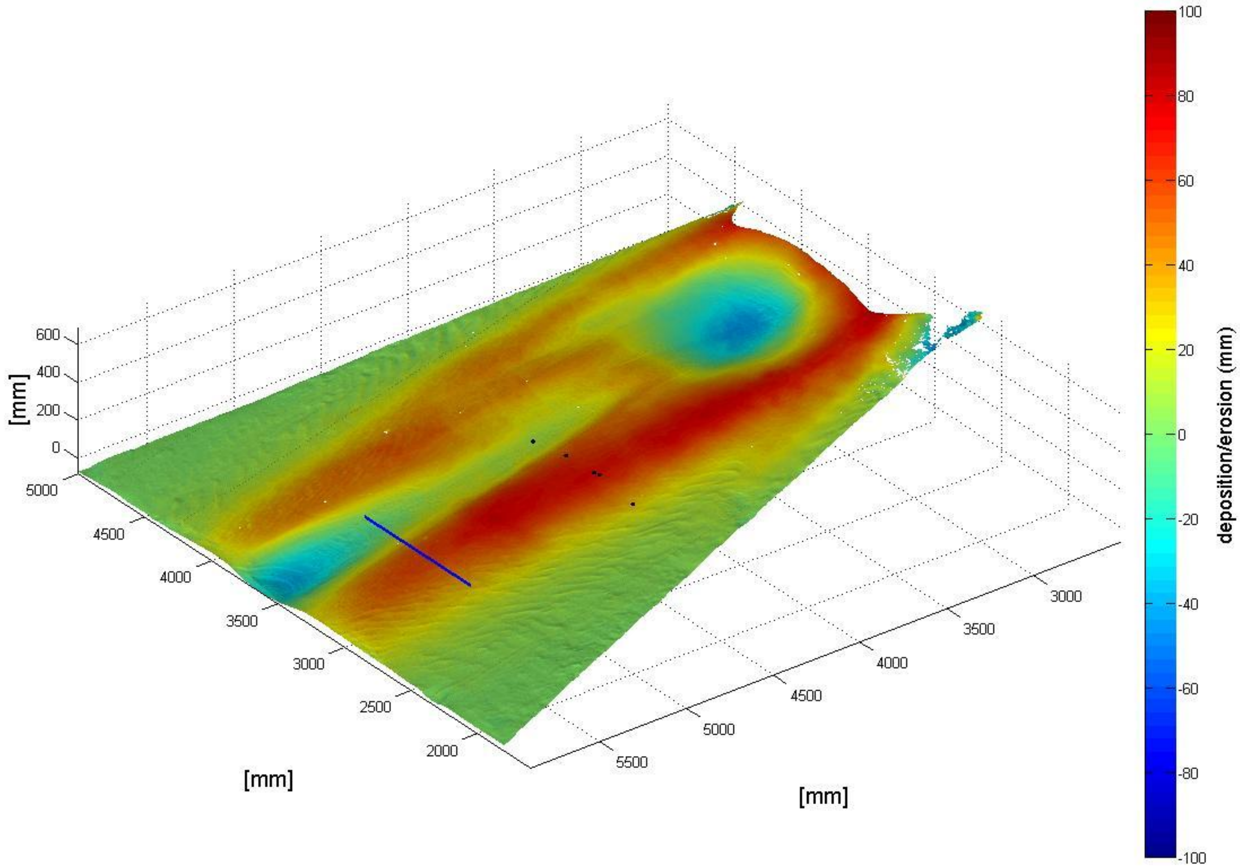


Fig. 12) A digital elevation model (DEM) of run 51 combined with the difference in deposition and erosion compared to the initial slope. the five UVP measurement devices represented by the black dots and a blue line to indicate the transect along which samples for particle size of the levee were taken.

From the analysed particle size samples along the transect, four vertical profiles are constructed and these have been combined with the cross-section of each separate run along at the same spot. The levee shows a decrease in particle size with height above the bed for all locations. However there are distinct differences between the locations. The samples taken from halfway up the slope of the levee on the channel side start with the largest particle size composition of all locations, but has a distinct reduction in particle size with height to eventually the lowest D50 of all samples at the top of its deposit. The middle of the levee shows a more seesaw pattern with height. It consists of three sequences each with a larger particle size near the base and then a similar decreasing trend over the next few centimetres before the start of a new cycle. These starting point of these cycles coincide with the starting point of a new run, in other words each separate run consists of a fining upward trend followed by a slight coarser particle size near the bottom of the new run and again a fining upward trend. Despite these cycles the overall trend along the whole vertical profile is still decreasing in particle size. This trend is similar as shown by *Pirmez & Imran (2003, fig 10)* of a levee along the Amazon channel. The back slope of the levee does not show this distinct trend of decreasing particle size with height, but remains more or less steady for most of its vertical succession and only the top half a centimetre shows a decline in particle size. The sample taken near the surface for all of the three locations covering the levee show a relatively large decline in particle size compared to the overall trend for each location. This could be a resemblance of the waning phase of the last run, when the flow decreases in velocity and the smaller particles in suspension start to drop down and deposit on top. Another interesting observation that can be derived from these results is that during the first run (blue line) the particle size does not decrease as much for the first centimetre above the bed for both the left slope and the centre of the levee locations and to a lesser degree for the right slope of the levee. This 1 centimetre level coincides with base of the channel for that particular run, and only after that the particle size drops significantly. The samples taken from the centre of the slope channel show smaller particle size near the surface as compared further down. The particle sizes of deeper down the bed are similar to those of the original slope. The top centimetre of the bed in the middle of the channel consists of a finer particle size as compared to the D50 of the original slope, this can either be caused by vertical segregation of particle sizes during the formation of the original slope. This process may have occurred during the formation of the original slope used in the experiments. Since the sand mixture was introduced from the top of the slope, segregation of the different particle sizes may have occurred as a result of gravity whilst flowing down the slope.

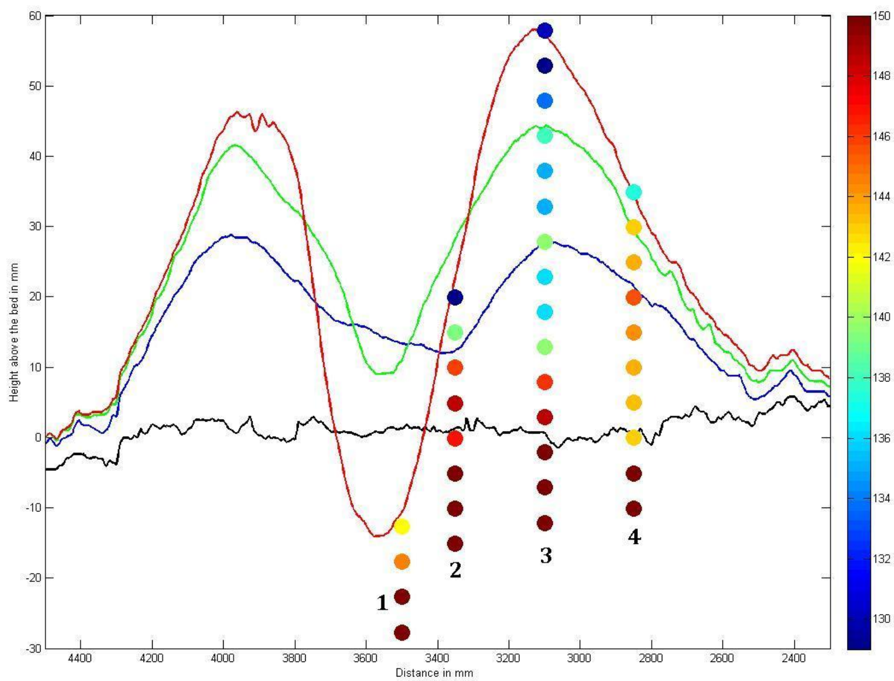


Fig. 13) Plot of vertical particle size profiles of 4 locations across a levee. channel deposits (1), halfway between channel centre and top of the levee (2), through the top of the levee deposit (3) and Halfway up the back-slope of the levee (4). Together with the architecture of the levees and slope channel after each of the 3 experiments; run 49 (Blue), run 50 (green) and run 51 (red). The black line indicating the initial slope before all of the experiments.

Another cause of the lower particle size in the near bed sand can be the of erosion into the initial slope with a subsequent infill with finer particles during the waning stage of the turbidity current.

As mentioned these results show similarities with the work done by earlier authors the same analysis is applied for these to compare the data with each other in more detail. The particle size samples have been converted into settling velocities using the analytically derived formula by *Ferguson & Church (2006)* and divided into the three sequences/runs derived from the particle size analysis and the cross section of the levee (fig 14.). These settling velocities per run where then compared with their height above the initial slope.

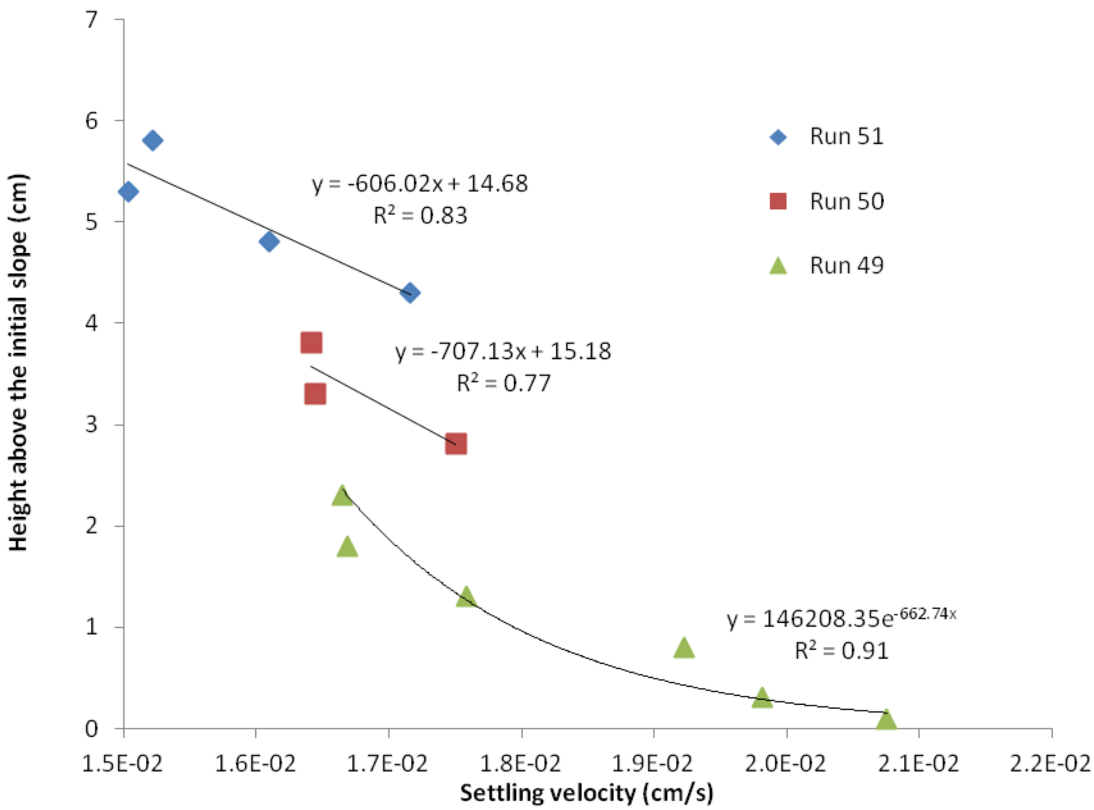
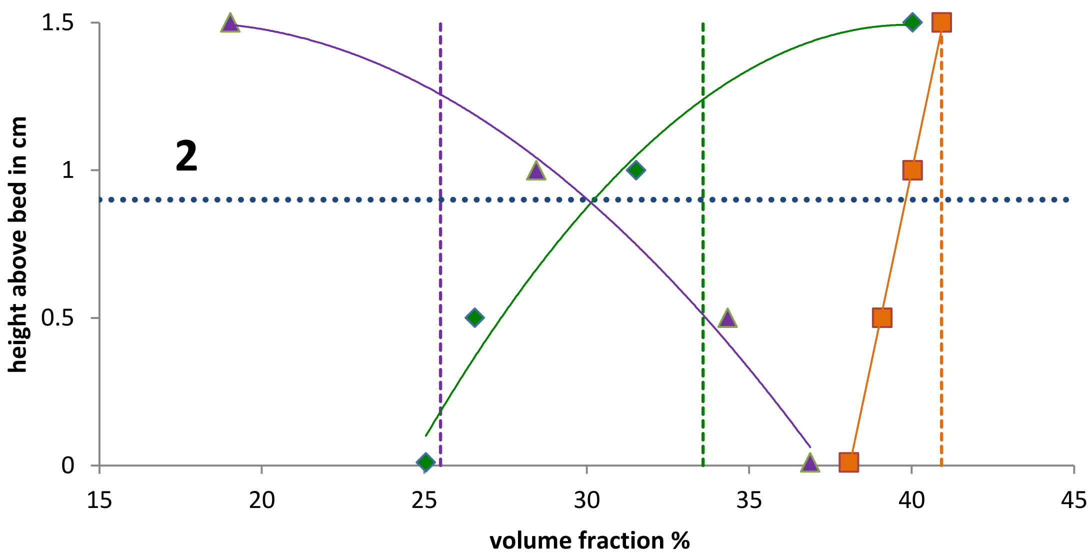


Fig. 14) Plot of the settling velocity versus height above the initial slope of the experimental setup.

The three runs each show a gradual decrease in settling velocity and therefore particle size with height. A second observation that raises from these results is the increased particle size near the base of every run. Both the second and third experiment have recorded a larger particle size as their first deposition as compared to the last data point of the run before, this even though it is at a slight higher level from the initial slope. Plotting trend lines through these data points to get an indication of the rate of decrease in particle size with height of all the various runs yields the last two runs to have a linear trend of decline, whereas the first has a better fit with an exponential trend line plotted through its data points. The rate of upward fining is similar for the last two runs (50 & 51) with a decrease in settling velocity with height of -1.41×10^{-3} and -1.65×10^{-3} cm/cm/s respectively. The rate of decrease in settling velocity for the first run (49) has been divided in two section to highlight the differentiation of the rates near bottom and higher above the initial slope. This gives a decrease rate of -0.8×10^{-3} cm/cm/s for the data points higher above the initial level of the slope, whereas the near bottom average decrease in settling velocity gives -1.2×10^{-4} cm/cm/s. The rate of decrease in settling velocity becomes lower with height above the base of the flow. In particular this effect is shown for the first run which has a distinct sharp decrease in settling velocity near its base, before any effect of levees and/or formation of a slope channel are in place. Analysis of the vertical particle size profiles as shown above is based on the D50 of each sample. This D50 value however is only an average value for the whole sample and not very detailed, therefore a comparable examination as in 2D experiments has been conducted.



T

Fig. 15) Plot of vertical concentration profiles of halfway up the levee on the channel side (position 2 in fig. 10). For three sets of particle sizes; under 120 µm (green), between 120 and 160 µm (orange) and above 160 µm (purple). The vertical dashed lines are the volume fraction of the initial mixture per particle size bracket and the horizontal dotted line represent the architecture after run 49 (blue)

T

The particle sizes are arranged in three range groups, in order to get a more detailed view on the segregation of particle sizes throughout a levee. These groups again represent roughly the D10, D50 and D90 of the initial composition and are; below 120 µm, between 120 and 160 µm and above 160 µm respectively. The results of these can be compared to the trends derived from the 2D experiments in which not the deposits were sampled but the turbidity current itself, to see whether a relationship exist between the vertical particle size profiles of turbidity currents and of their depositing levees. Vertical particle profile (fig 15) for the left side of the levee deposit, position 2 from figure 10, shows concentrations of roughly 40 percent for the D50 bracket (orange). This concentration is stable throughout the whole profile with only a small increase from bed to the top of the deposit at a height of 1.5 centimetres from the bed. This constant value is also similar to the volume fraction of this particle size bracket of the initial mixture. The relative proportion of the >160 mu fraction near the bottom of the bed is 38 percent which is over 10% larger as compared to its initial fraction in the mixture, from there a decreasing trend of concentration towards the top of the deposit at 20 percent, with the concentration decrease becoming increasingly bigger. The exact opposite trend can be derived from the volume fraction of the <120 micron bracket, where there is a progressively increasing rate of concentration from a value of 25 percent and crosses its initial mixture value of 33 percent at a height of 1.1 centimetre above the bed above this the increase continues to a value of near 40 percent which is similar to the volume fraction for the 120-160 micron bracket at that height.

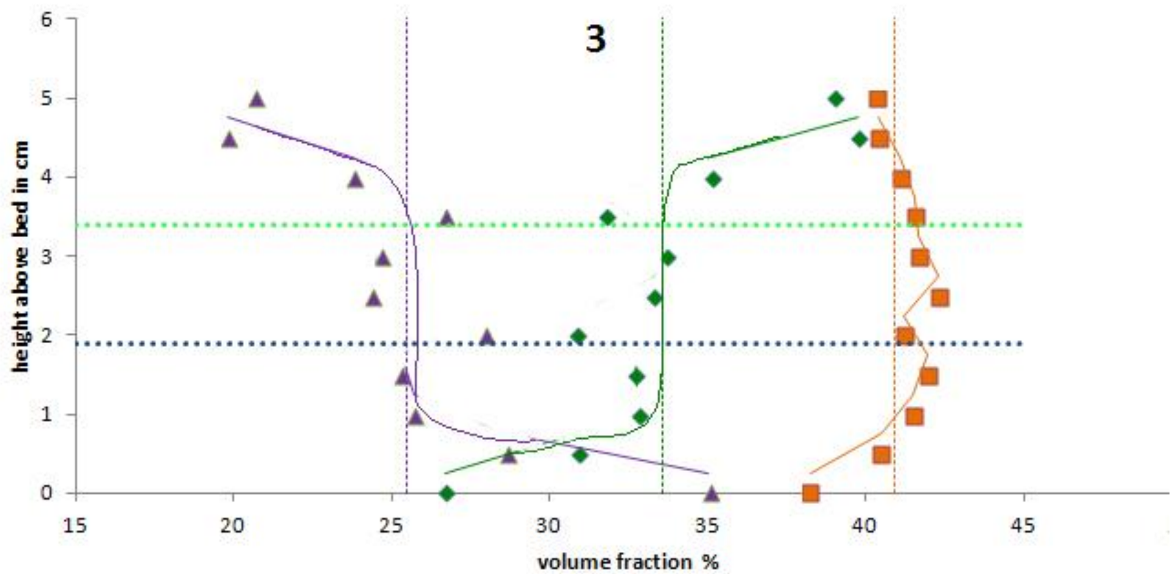


Fig. 16) Plot of vertical concentration profiles of crest of the levee (3 in figure 10).For three sets of particle sizes; under 120 µm (green), between 120 and 160 µm (orange) and above 160 µm (purple) The vertical dashed lines are the volume fraction of the initial mixture per particle size bracket and the horizontal dotted lines represent the height of the levee after each run; run 49 (blue) and run 50 (green) with run 50 being marked by the highest measured data point.

The analysis for the crest of the levee (fig.15) shows a similar trend, with the medium particle size range portraying only small variations in volume fraction with height above the bed. A slight increase from 38 to 41 percent in the lower part of the levee (0 to 2 cm above the bed) , from there on a slight decrease back to roughly 39 percent volume fraction at the top of the levee. Again this value is close to the value of the initial volume fraction before the experiment. The large particle group again shows a steep decrease with height near the base of the flow, going from 35 volume fraction to 25 within the first centimetre above the base. The three centimetre above this are fairly steady in terms of volume fraction, with only the first data pint of each run shown to have a slight higher fraction, the last centimetre shows a marked decline in the fraction of the larger particle size again. The opposite again is the case for the small particle range which starts with a low volume fraction near the bed and has a steep increase close to the bed followed by a steady phase in the middle of the levee and only near the top a further distinct increase to nearly 40 percent volume fraction The volume fractions of all three particle size ranges are very similar near the bottom of the bed and at the top of the levee as compared to the fractions particle sizes of the first sampled area halfway up the slope of the levee (fig. 15).

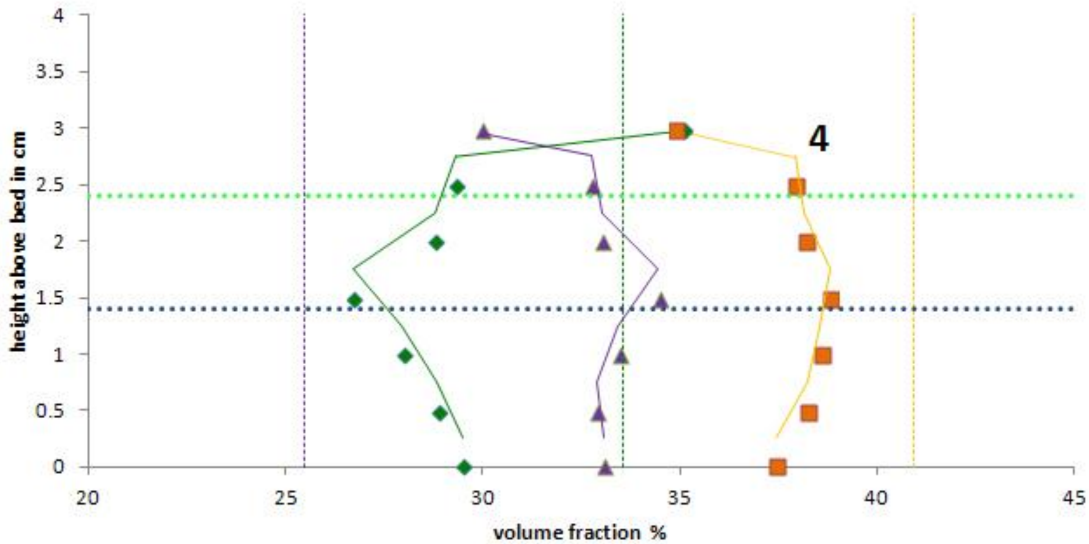


Fig. 16) Plot of vertical concentration profiles of halfway down the back slope (4 in figure 10).For three sets of particle sizes; under 120 µm (green), between 120 and 160 µm (orange) and above 160 µm (purple) The vertical dashed lines are the volume fraction of the initial mixture per particle size bracket and the horizontal dotted lines represent the height of the levee after each run; run 49 (blue) and run 50 (green) with run 50 being marked by the highest measured data point.

The back slope of the levee (fig. 16) shows a distinct different vertical succession for the three particle size brackets. The volume fractions for all of these do not deviate significantly throughout the height of the levee. The D50 fraction is the largest at approximately 37 percent followed by the above 160 micron fraction and the below 120 micron fraction at 32 and 30 percent respectively. Only two minor changes occur throughout the levees height; The smallest and largest particle size groups deviate at 1.5 centimetre above the bed where the fraction of above 160 micron increase whereas the opposite happens to the below 120 micron group. This deviation coincides with the first data point of the second experiment and is similar to the larger particle size for the first data point of a new experiment as seen in the composition of other parts of the levee. This however does not occur at the start of the third run of the experiment, with no distinct increase in particle size for the base of the composition at this location of the levee. The second deviation is at the top of the levee where the fractions of above 160 and the 120-160 micron group have a sharp five percent decline in volume fraction and as a result the below 120 micron bracket demonstrates a near 10 percent increase in volume fraction. There is however a striking deviation of all these particle size brackets when compared to the initial volume fraction of the mixture. In the former two graphs the 120 to 160 micron bracket showed very similar volume fractions as the initial mixture, at this location however the samples levee has a volume fraction of this bracket that is lower by a few percentages as compared to the initial fraction. The other two particle size brackets; under 120 and above 160 micron respectively, show an even larger deviation from their original fractions. The less than 120 micron bracket stays around 4 volume percent under its original value and the above 160 micron bracket is nearly 10 percent higher as compared to the starting mixture.

Suspension threshold

The lateral and vertical composition of the channel bounding levee have been analysed based on particle size. These give an indication of having a direct link to the vertical particle size profile of the turbidity current itself. Comparisons between the both cannot been given directly since there are no particle sizes profiles obtained of the 3D experiments due to interference with the flow and therefore negatively altering the formation of a slope channel and levees. However the deposition of sediment is related to the flow velocity of the current and measurements on these have been recorded. Assuming that in order to deposit sediment of a certain particle size the velocity of the current cannot exceed the velocity it needs to keep particles of this size in suspension, this is called the bedload/suspension threshold. This threshold gives the minimum velocity to keep a particle of a certain size in suspension and in order to deposit it, the velocity therefore has to be lower (Komar, 1985).

$$U = \frac{V_s}{\sqrt{C_d}}$$

Where U is the boundary velocity of this threshold, V_s is the settling velocity related to particle size and C_d is the drag coefficient. Per sample within the levee the D50 is taken as representative for the whole sample. This then yields values for maximum velocities in which these particle sizes can be deposited on the levee. This has been done for all samples taken from the crest of the levee since this gives the longest vertical profile for the velocity at a certain distance from the centre of the channel. It has been done for each of the three runs separately and subsequently compared to the velocity data obtained from the UVP measurement device at the levee crest (probe 4). Due to turbulence within the turbidity current the measurements of the UVP probes there is a large variation within the velocity data, including negative values for velocity or in other words flow upstream. In order to keep particles in suspension it is not relevant in which direction the current flows but only the velocity it does so with, therefore absolute values have been used. The body of the turbidity was taken as quasi-constant in terms of velocity and average values for velocity every 0.6 millimetre in height were derived for the full time interval the body of the currents passes. This gives velocity values that are averaged for roughly 70 seconds and any anomalies due to turbulence are straightened out. The objective of this analysis is to find the suspension threshold of the turbidity current passing over the crest of the levee. The significant part of the velocity profile of the whole turbidity current is only the section below the velocity maximum, since particles dropping down out of suspension above the maximum will be brought back into the suspension at the velocity maximum and only below this particles will deposit on the levees. The height of the velocity maximum varies slightly over the different runs but here is taken at 20 millimetre above the bed. The result of these derivations (fig 17) show a regular velocity profile for a turbidity current with the maximum velocity close to the base of the flow and from there a decrease with height. The velocity profiles across the three runs only show run 50 and 51 to have a similar trend and only the first experiment to have a turbidity current pass at a much higher velocity and therefore being able to keep larger

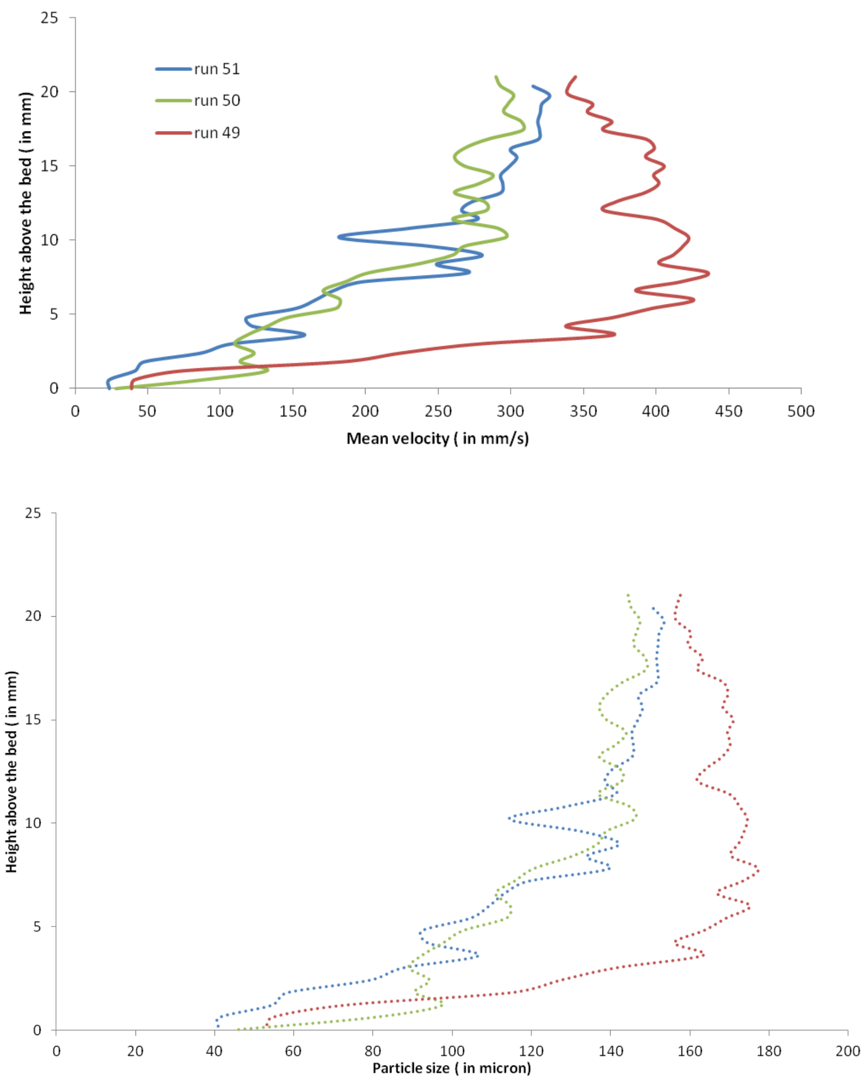


Fig. 17) A plot of the mean velocity of the lowest two centimeter of the flow for all three different experiments. Using the time interval of the quasi-steady body of the current. The lower plot shows the maximum particle sizes that can be kept in suspension at those velocities.

particles in suspension. Although the data is limited this is in agreement with the fining upward trend in particle size found within the sampled levees, since a lower velocity means the flow is only able to keep smaller particles in suspension. The development of the slope channel and levee system at the location of the sampled levee is however different compared to the location where the velocity profiles were measured. The location of the UVP devices shows deposition of sediment within the channel causing the distance between the base of the flow and the crest of the levee only to be influenced by the formation of levees, whereas erosion into the bed occurs in the channel at the location of the sampled levee and with that increasing the confinement of the channel by both deepening of the channel and build-up of levees and therefore direct relations can't be assumed.

Since there is deposition during the experiments that cause the bed to rise the data per run has been divided into three pieces all approximately 40 seconds long, in this way a more detailed picture of the velocity profiles of the turbidity current and subsequently leads to a better derivation of the suspension threshold for each of the experiments.

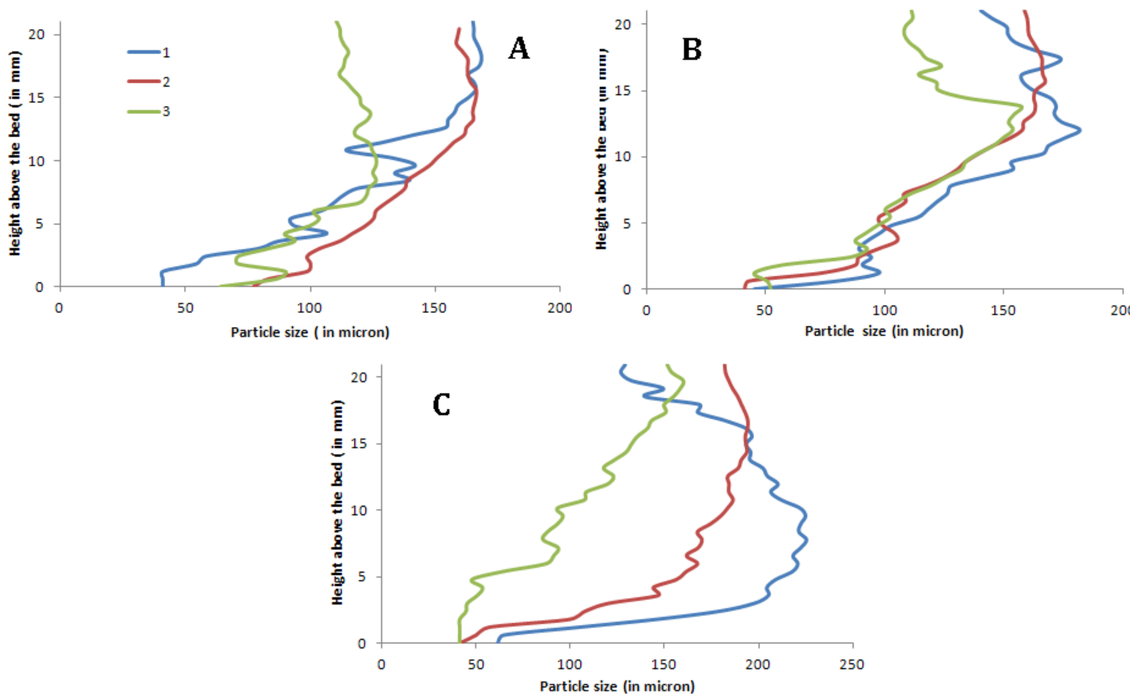


Fig. 18) The maximum particle size still of the bedload/suspension threshold for experiments 49 (A), 50(B) and 51 (C). all three experiments being divided into three sections of roughly 40 seconds, with 1,2 and 3 being the start of the body, the middle section and the end/tail of it respectively.

The first two experiments (fig. 18 A&B) show little differentiation between the three sections of the turbidity currents body, with the body of the turbidity current having a particle size of between 50 and 75 micron near the bed of the flow for the full measured time interval. This increases with height as this is to around 175 micron for the first part of the turbidity current (1&2). The deviation of the latter part (3) of the turbidity current starts around the 1 centimetre mark from where it no longer increase but remains steady throughout its top centimetre at roughly 125 micron. The second experiment even shows a sharp decrease in particle size above the 1.5 centimtre mark for the last part of the turbidity current as it shifts sharply from 150 to 125 micron. The third of the experiments(C) shows a distinct different profile of the suspension threshold for its two centimeters near the bed. The first part of the body still has a near bed particle size of its threshold of 50 micron but this increases sharply with the first five millimeters to reach a particle size of over 200 micron, then contrary with the other two experiments it steadily decreases above the 1 centimetre mark to a value of around 125 micron at the top of the measured section. In short this means the particle sizes of the threshold are higher than before in the lower part of the profile and lower in the top part of its profile. The middle part of the body is fairly similar to the other two profiles of the middle part of the body, starting at 50 micron with a steady increase to 175 micron around the 1.5 centimetre mark then tailing away slightly in the top half a centimetre just like the other two experiments showed. The last section of the body of the turbidity current here start at a similar point as before but doesn't increase a lot in the first 5 millimetres above the bed then increasing at roughly the same rate as before throughout the whole measured height interval and contrary to the other two experiments it doesn't become steady above the 1.5 centimetre mark but keeps increasing to a value of approximately 150 micron at the highest measured point.

These results show that during the experiments the particle size of the turbidity current does not decrease significantly even though there is sediment being deposited and the levees are building up higher as compared to the middle of the channel. The body of the turbidity current is a rather continuous quasi-constant state of a turbidity current with not much variation throughout its passing in terms of velocity and directly linked the suspension threshold whereas only for the latter part it slows down at the start of the waning face and smaller particles will be deposited. This indicates that during the passing of the turbidity current the decrease in particle size as the levee is building up isn't large in the first section of the body and only tails to smaller sizes near the end of the deposition.

Suspension threshold of the Sampled levees

The method for the suspension threshold has also been applied in opposite fashion to derive the maximum velocity of the flow in order to still be able to deposit the particles retrieved from the levees. this has been done in a further downstream location as the UVP measurements done above and although it therefore does not give a direct relation it still shows the velocity development of the flow going down the slope. The D50 of the measured samples from the

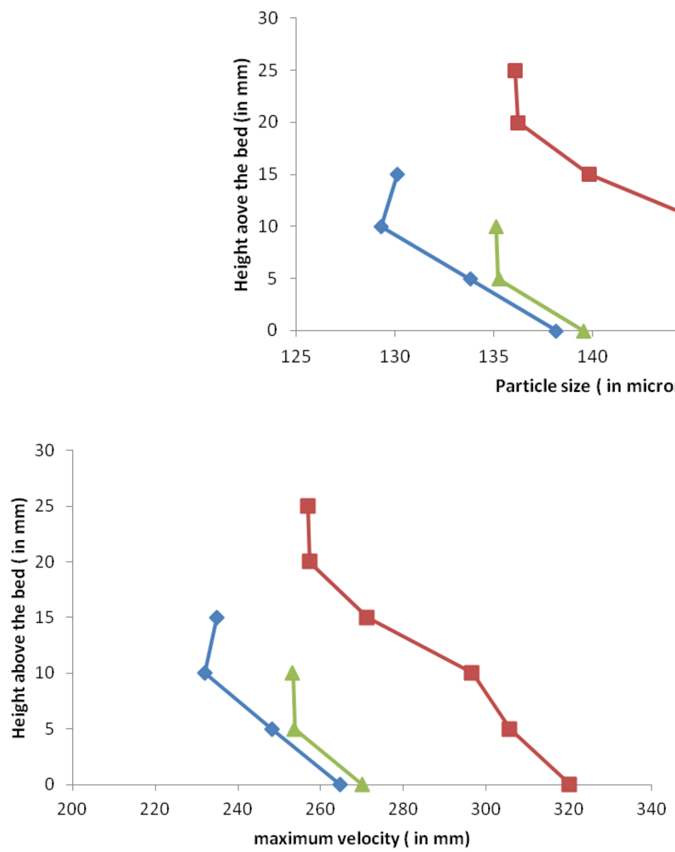


Fig. 19) The top plot showing the particle size per 0.5 millimetre of each experimental run obtained from their levee depositions. The lower plot shows the maximum velocity at which the above mentioned particle sizes would still occur within the deposits.

crest of the levee were taken to calculate the maximum velocity of the flow at the every 5 millimetre of deposition during each of the runs (Fig. 19). The distinct trend that can be recognised for each of the experimental runs are the steep decline in particle size deposited/maximum velocity from the start of deposition towards their penultimate measurement point and the very little difference between that point and the last of the measured samples. Previously notion of decrease in particle size per experimental runs again shows with it becoming clear that a first experiment has a distinct higher velocity as compared to both of the other runs particularly during the first 15 millimetres of its deposition. Above this the particle sizes/velocities are comparable with both the other experiments, with a slight decrease in both parameters with each subsequent experiment.

4.Discussion

4.1 2D Experiments

The initial velocity of the turbidity current has a large influence on the development of the flow further down the slope. A larger discharge transports more sediment into the system at a higher velocity, as depicted by the equilibrium slope (fig. 5) derived from the 2D experiments it is shown that this added amount of sediment within the system is kept in suspension due to the increased velocity and therefore they are still bypassing even on shallower slopes slope as compared to flows at lower velocities. From this figure the change in decrease of slope with discharge above the 20 cubic metre per hour mark stands out and might be an effect of methodological constraint of our setup and therefore could be less reliable, however this has no further influence on the experiments carried out since these are all done at discharges of maximum 20 m^3/h.

In conditions just above the bed (0-2 centimetres), the discharge does not seem to have a large effect on the concentration of sediment in suspension. This is most likely due to the overall shape of the velocity profile of a turbidity current which has the velocity maximum near the base of the flow and doesn't vary much with increasing initial discharge as can be seen in table 1. This velocity maximum is therefore sufficiently high enough to keep a large concentration of sediment in suspension. The change in discharge however has an influence on the average velocity of the current as has been derived using the method of *Parker (1986)*. An increasing average velocity has as an effect that a higher concentration of sediment is kept in suspension throughout the full height of the turbidity current (fig 6). This effect also influences the vertical particle size composition of the turbidity current. The higher average velocity also causes an increase in particle size being kept in suspension at a certain height above the bed (fig. 7). A sharp decline in particle size composition in the near bed conditions (below the velocity maximum) with above a more gentle decline in particle size with height. This is the trend for all discharges and does not change its shape with a changing discharge. The gently declining upper part coincides with the "cloud" part of the turbidity current, whereas the sharp declining section is part of the fast underflow.

This implies that a turbidity current becomes thicker with increased discharge and a higher average velocity, however the flow height for the experiments with increasing discharge do not show a significant increase in flow height (table 3) derived by using the method mentioned earlier as proposed by *Parker(1986).* The explanation for this apparent paradox is result of the measuring method. The main focus of this study is the relation of the turbidity current and the particle size composition of the levees it deposits, therefore the near bed processes and dynamics are of major significance. The UVP probes that measure the velocities throughout passing the turbidity current have been set up in such a way that the near bed conditions are focussed on, with the negative consequence that the top layer of the thicker turbidity currents falls outside the measured window (see fig for experimental setup). Since the method by parker relies on the velocity profile provided by those UVP probes to calculate the flow height, average velocity and average concentration these values are not calculated over the complete height of the flow. This incomplete derivation therefore gives an overestimate on the average velocity and concentration and an underestimate for the actual flow height. This directly highlights the complexity of deriving parameters from turbidity currents, because those derived parameters all have an influence on one another due to the assumptions a particular method uses. The flow height for example can be defined as the level at which the down slope flow velocity is equal to zero. The advantage of using value as a boundary between the turbidity current and the ambient water is that it can quite easily be retrieved from the data, however the ambient water just above the actual turbidity current is dragged along down the slope with the flow as a result giving an overestimated flow height for the turbidity current. The method used here as proposed by *Parker (1986)* uses the integral of the velocities measured in order to determine what values of velocity are still significant enough to be counted as being part of the flow in order to determine the flow height. This would cancel out the low velocities caused by drag of ambient water or backflow due to the experimental setup out of the actual as part of the turbidity current and bases the flow height on this. From this assumed flow height the other parameters like average velocity and average concentration are calculated. As mentioned before there is a possible error in those estimates due to the experimental setup and the measurement range of the UVP probes. These errors are transferred into the calculation of both the Froude and Reynolds numbers for the different flows as both of these depend on parameters mentioned before (flow height, average velocity and concentration).

A similar measurement issue is present amongst the concentration data, which has been measured from the flow during the experiment by four siphon tubes at different height in the flow. Through these four data points a best fit line has been plotted and the equation of this best fit line is used in the calculation method of Parker for the average concentration of the whole flow. Due to the limited number of data points (four) measuring the concentration and particle size, the resolution of the data isn't very good and local variation within the current in terms of concentration/particle size may therefore not be measured. The accuracy for this method has been tested by doing and experiment in which the conditions of the flow were the same but now the amount of measurements taken with height was increased to 10/ one measurement each centimetre by using an automated arm. Although the best fit line of both these methods is rather similar (fig. 5), the spread in the siphon technique is larger compared to the automated arm technique. The advantage of the automated arm is a higher resolution in the data points and therefore a more accurate estimate of the vertical concentration and particle size profile can be given. However the advantage of having a moving arm is at the same time also its disadvantage, because of the movement of the arm the amount of time for each measurement per height is a lot lower as compared to the stationary siphon tubes. This shortened measurement time could be influenced by turbulence within the flow, creating either a wrong estimate of the average concentration/ particle size at a certain height above the bed. A second issue with the movement of the automated arm is that the measurement isn't actually at a fixed height above the bed but rather is smeared out slightly by the moving of the measuring tube, which leads to smoothing of the measured concentration/particle size between each point. A better solution to obtain a higher resolution in the concentration/particle size data points would be either;

-An increase in the number of fixed siphon tubes with height, since more measurements means a higher accuracy of the actual profile. *Disadvantage: an enhanced interference with the flow and could therefore also have an effect on measurements by nearby siphon tubes.*

-An automated arm that stops every centimetre for a separate measurement, therefore no longer smearing out the measurement due to movement and instead measuring accurate concentration/particle size samples and not interfering a lot with the flow. *Disadvantage: the experiment has to last a lot longer which means a quasi-steady body part of the flow needs to be maintained for a considerable longer amount of time in order to have sufficient measuring window which reduces the effect of turbulence.*

4.1.2 Influence of particle size

The initial sediment mixture of a turbidity current can have a large impact on their overall structure and as a consequence on the depositions they leave behind. The 2D experiments show that mixtures with a larger initial particle size have a steeper equilibrium slope (fig. 8). Since the experiments with the 210 micron size particles were all depositional, the only the conclusion given is that the equilibrium slope for this size is steeper than the maximum 12 degrees of the experimental setup. By extrapolating the equilibrium slope for the other particle sizes this gives a linear relation that would assume the 210 micron equilibrium slope to be at 15 degrees. The larger particles need a higher velocity of the flow to be kept in suspension, the earlier mentioned suspension/bedload threshold. Since all experiments are carried out using the same initial conditions in terms of initial volume concentration of sediment and most importantly a equal discharge the only way the velocity is kept above this threshold is steepening the slope of the setup. This can be traced back in the velocity profiles (appendix), for example by looking at the runs for the 130 micron experiments. The maximum velocity and with that the average velocity of the whole profile, increases from the depositional experiment (run 22) to the bypassing or even erosive runs 17-14 as the slope becomes steeper. Measurements during depositional experiments are complex since they have a build up of sediment on the bed during the length of the experiment which changes the depth of the "new" bed to the UVP measuring devices with as a result inaccurate velocity measurements. Calculation of the suspension/bedload threshold velocity for particles of 130 micron it results in a value of 0.439 m/s, comparing this value to the velocity profile obtained it shows that those velocities only occur very near to the bed and well below the velocity maximum and is therefore the explanation why no deposition takes place in these experiments. Since velocity profiles are complex for depositional experiments it is difficult to explain how this profile would differ to the ones that are bypassing. The velocities for the whole profile (maximum and average) would be lower as compared to the bypassing ones due to a shallower angle but would still be sufficiently high enough to maintain above the suspension/bedload threshold which would suggest the particles are kept in suspension. The equation for the velocity threshold does not take turbulence into account which is a significant process in turbidity currents and due to this large fluctuations in the local velocity of the flow occur which in term can lead to deposition of particles. A second consideration that has to be taken into account is the fact that the 130 micron particle size in this example is only the D50 of the sediment mixture used, in other words half the amount of particles in the mixture used is actually larger than 130 micron and would therefore need higher velocities to be kept within suspension. So Although the velocities seem to be sufficiently fast enough to keep the average particle size of the mixture this could still lead to deposition of the particles above this size. A disturbance of the bed by deposition of particles has an effect on the turbulent flow for some distance behind it, whilst also increasing the roughness of the bed. This may work as a positive feedback system leading to enhanced deposition of particles that under normal conditions would have stayed in suspension.

This similar effect also shows by looking at the vertical concentration profile of the experiments with various particle sizes in their initial sediment mixture. Increasing particle size of the initial composition results in a higher concentration of sediment near the base of the flow with a steeper decline with height as compared to smaller particles. Larger particles can only be kept in suspension at higher velocities and will therefore occur nearer to the base of the current and not migrate up into the “cloud” that forms near the top of a turbidity current when smaller particle sizes are used. Their settling velocity is higher and therefore fall to the faster flowing lower region of the turbidity current quickly. This suggests that turbidity currents with a larger average particle size become smaller in size as compared to ones with finer material within them.

For the mixture consisting of the four types of quartz sand with different particle sizes, as been used in the first series of experiments mentioned above (p.) the concentration profile was looked at in more detail by dividing the particle in three groups based on their size. This gives a more precise account of the variation in particle sizes with height of a turbidity current. It shows vertical differentiation of particle sizes, which are in agreement with the earlier found results. The larger particles, in this case above 160 micron have the highest fraction near the bottom of the flow and decrease significantly with height. As is to be expected the smaller (below 120 micron) particles display the opposite trend of making up only a small portion of the sediment near the base of the flow but become more frequent higher in the profile. This indicates that turbulence causes the smaller particles to move to the top part of the turbidity current relatively quickly and due to their low settling velocity and the still present turbulence maintain at this height. The large particles are less likely to be transported to this top layer since a higher velocity is need to prevent them from settling to lower levels and velocity decreases quickly with height within a turbidity current. The trends for both the small (below 120 micron) and large (above 160 micron) particles can be explained in this fashion, however the group that covers the particles between these two behaves slightly unusual. It is rather identical to the small particle size group in terms of increase with height, although this increase is smaller. Near the bottom of the flow the fraction of "medium" sized particles is far below their initial fraction within the mixture and although they do increase towards that initial fraction percentage it never exceeds it, which seems strange. The reasoning for this apparent strange result lies in the results should be interpreted, this only shows the fraction of each of the different groups of the total sediment concentration at a certain height in the turbidity current. Since the overall concentration of the sediment decreases with height as well complicates it. For example by look at the concentration at the 4 centimetre above the bed data, the concentration measured here is 7.25% and of this the fraction for the three groups (below 120, 120-160 and above 160 micron) are 25%,35% and 40% respectively. Meaning this values are very low compared to values close to the bottom of the flow, where a lot more sediment is in suspension to begin with.

Instead of looking at how particle sizes are distributed throughout a turbidity current it is worth recalculating those in settling velocities. Settling velocity values are easier to work with in terms of relating them to velocity of the flow. Comparing all experiments conducted with bypassing conditions there is quite a spread due to the different starting conditions of each experiment (discharge, angle of the slope etc.), however the trends of decreasing settling velocity with height all seem to be rather similar. The range of decrease of settling velocity is between 0.8 and 1.1 cm of height above the bed per cm/s decrease in settling velocity. Comparing this to rates of settling velocity decrease with height from turbidity levees along the Amazon channel (*Pirmez, 2003)*it shows the decrease to be relatively quick but still in the same order of magnitude as found in those natural occurring levees. A possible explanation for this could be that the numbers obtained by Pirmez come from levees formed by depositional turbidity currents, whereas our experimental values come from bypassing turbidity currents. As seen in earlier analysis of our experimental data it is shown that in order to deposit sediment the turbidity currents have to be slower and as an effect of this they reach higher above the bed since the top layer of the current swells and the overall rate of decrease of settling velocity decreases with it. This is in agreement with the one experiment in fig. , with a discharge of 20 cubic metres per hour, this experimental run deposited a small amount of sediment and is therefore not completely bypassing but was still classed as such. The trend in decrease in settling velocity however is completely different compared to the others with a fining upward trend of 0.54 cm/cm/s which is quite close to the values obtained in the study along the Amazon channel. Although data on actual depositional experiments is lacking due to the limits of our experimental setup, the hypothesis can be made that those turbidity currents have an even lower rate of fining upward due to reduction of velocity and therefore more mixing of the smaller particles throughout the full height of the flow. This lower rate of fining upward in particle size with height would then be recorded within the levees deposited by those turbidity current, which is the objective for the 3D experiments carried out.

In a natural situation a turbidity current growing in size will spill from the channel onto the levees and the rest of the slope and thereby becoming much wider. This difference in behaviour between 2D and 3D experiments/natural situations makes it complex to compare between them. By looking at the velocity profiles constructed from these experiments they are in agreement with the general accepted profiles of turbidity currents with a steep increasing velocity from the base to the maximum at a few centimetres above the bed and from there a decline towards lower velocities.

4.2 3D Experiments

4.2.1 setup and initial conditions

The initiation of a slope channel with bounding levees still is poorly understood and reconstruction of those natural occurring systems in experimental setups remains a challenging and complex study (Baas, 2008 Rowland 2004). The aim is to create an turbidity current that remains an erosive current along the full length of the slope, the erodible bed in this case is of major important as has been suggested by Rowland (2004). The equilibrium slope at various discharges and/or particle size compositions are known from the 2D experiments carried out and are a useful guideline for the angle of the slope in the 3D experiments. However the scale of these 3D experiments is much larger compared to the 2D ones and the discharge and initial concentration of sediment had to be adjusted accordingly in order to achieve a eroding current. Even though those 2D experiments gave an good indication of the initial parameters that had to be met the first series of experiments showed the conditions in which slope channels with bounding levees form is limited. The main difficulty during the experiments is the transition from the non erodible inlet of the setup to the erodible sandy slope. Due to the force with which this happens the flow has the tendency to form a scour in front of the inlet box , since the flow has to pass through the scour hole it slows down with in such extent that it deposits large quantities of its sediment at the top of the slope instead of being bypassing along the slope. In this fashion the current creates a lobe with a scour hole in the centre much like the deposits in earlier experimental work by Rowland and baas and very little deposition down the slope with no indication of a slope channel/levees.

The issue of a scour near the top of the slope remained a problem for the full extent of the experimental series however conditions were found to keep this to a minimum, this resulted in three consecutive experiments conducted without making changes to the initial conditions are the architecture that was created on the slope. The digital elevation model of the slope after those three experiments conducted shows a system consisting of the afore mentioned scour near the top of the slope, with lower down the slope a straight channel on both sides bounded by levees. The focus for this study remained on the particle size composition of the levees and how these relate to the turbidity current itself. Therefore samples have been taken across the levee deposit and from the base of the slope channel itself with a resolution of half a centimetre in depth. Obtaining concentration/particle size samples directly from the turbidity current, as has been done in the 2D experiments would give a direct comparison between the profiles of levees and the turbidity current. This however cannot be done without interfering with the flow of the turbidity current which would alter its internal structure and as a result of this the formation of the slope channel and levees , which has therefore not been carried out.

After the experiments samples were taken from the section of the levee that was assessed to be the best developed and unaltered by other processes or flows, this means not too close to the scour near the top of the slope, since influence of this scour hole would still be recorded downstream in the flow and not on the right hand side of the flow since the deposit seems to be altered by a secondary flow. A direct link of the samples taken from the levees and the velocity data provided by the UVP probes would have been ideal in order to find a relationship between the current and its deposits. The UVP measuring probes in place to record the flow velocity and turbulence of the current are unfortunately not close to the area of the levee where the samples are taken from. The probes have been places before any of the three experiments was conducted therefore the exact location for those probes is difficult to pick. Since three consecutive runs were conducted those probes couldn't be moved to a different location since any comparison in velocity data would then lose its value.

Comparing the parameters from these 3D experiments to the ones earlier obtained in the 2D experiments it shows that although the discharge and concentration of sediment in the 3D experiments is higher; the velocities, flow height, Froude and Reynolds numbers are lower. This all has an influence on the development of levees and their particle size composition, because slower and less high turbidity currents have less of an ability to maintain the particles in suspension. The area over which the flow can spread is a lot larger as compared to the enclosed 2D experiments which reduces both the velocity and the flow height of the current, subsequently affecting both the Froude and Reynolds numbers. This larger spread of the flow also reduces the average concentration of the flow since there is more space for it to accommodate the particles. Confinement of the flow focuses it more into the developed channel increase both its average and maximum velocity. The velocity maximum of the experiment with the highest confinement due to the levees is similar to the ones achieved in the 2D experiments. The flow height also increases since the flow less easily spreads across the whole width of the slope due to the formation of the levees, although this increase is small compared to the increase in height of the levees. The levees build up quicker in height than the increase in average flow height meaning the situation is nearing its equilibrium status.

4.2.3 Transect across slope channel and levees

The transect across the slope (fig) at the same location as the particle size samples were taken shows the development of the system per experiment and shows the differences due to confinement of the turbidity current. The first turbidity current had no confinement and spread wide across the slope with deposits over its full width, but does also start to form 1 cm high levees on either side of a main channel. The following experiments are erosive in the middle of the channel causing the channel to decrease in width and at the same time increase the height of its levees causing more confinement of the flow. This confinement is the cause of the earlier mentioned increase in the velocity with each experiment . The total height of the levee after the three experiments are carried out is 7.2 centimetres, measured from the middle of the channel to the crest of the undisturbed right hand levee. This is close to the flow height (7.7 cm) of the turbidity current as determined before by the UVP measurements probes and is another indication that overspill becomes less and the system is likely to be close to its equilibrium status. This can also be traced back in the fact that the deposits of the last experiments are less in volume and it no longer build the levee outward but in height so overspill is already limited. The portion of the turbidity current near the top of its flow height that does still overspill is low in concentration as found by the earlier constructed concentration profiles and would only contain small particle sizes.

A overlay of the results of the samples measurements shows an overall decreasing particle size with height for the inner to crest section of the levee, with D50 particle sizes for the unconfined first turbidity current being over 150 micron decreasing to just under 130 micron for the crest of the levee. This is in agreement with the hypothesis derived from the earlier conducted 2D experiments, that turbidity currents transport larger particle sizes near the bottom of the flow and a decrease in both concentration of sediment and particle size with height. A second distinct observation that can be made from the particle size data is that the first data point of every subsequent experiment on the levee is larger than the last of the previous experiment, this is an indication that the particle size profile of a levee is not solely related to the height above the base of the flow. Possible explanations for this are; the waning phase deposits particles which eventually have dropped out of suspension from much higher level than the height they are sampled from in the levee now, or the initial head of the turbidity current is much larger as compared to the body that is following it and does spread over the levees when it passes down the slope depositing larger particles than would be expected looking at the height above the base alone.

Centre of the slope channel

A more thorough analysis of the four sampled locations was conducted to create a detailed view on the variation and trends in particle sizes both horizontal and vertical across the deposited levee. Starting from the channel bed, which is at a lower level as compared to the initial slope before the experiments due to the erosive nature of the second and particularly third turbidity current. Particle size samples from this eroded channel bed however show a smaller D50 particle size (145 micron) at a depth of a centimetre below the surface as compared to the D50 particle size(160 micron) of the initial slope. This is an indication that during the final experimental experiment the current eroded deeper down into the slope, only to be filled with finer grained particles during the waning stage of the flow. This complicates determining the actual height of the levee during the run and subsequently it creates a mismatch in comparing the height of the turbidity current and its vertical particle size profile to the height it lines up with in the deposited levee on the overbank. Since the evolution of the bed can only be recorded after the experiment has been conducted, this is not taken into account and it gives as mentioned a slight underestimation of the height of the levee at time of deposition. Instead the reference level that has been taken to determine the height of the levee is measured from the initial bed. As stated by pirmez et al. (2003) this results in some smearing of the results of the deposits because the actual deviation of the base of the channel from the reference initial slope is not taken into account but this has only a small effect on the overall particle size profile.

Inner slope of the levee

The second location where particle size samples were taken is halfway up the inner section of the levee. This location has undergone sedimentation during the first two experiments followed by erosion by the last one. Once again the complexity of the development of the bed during the passing of the turbidity current raises and it is hard to determine whether the particles closest to the surface at this location are deposited during the waning phase of the third experiment or during the quasi steady body phase of the second experiment. The middle of the channel has undergone some deposition during the waning phase of the last experiment and by comparing those particle sizes to the ones close to the surface at the second location it is most likely that the top half a centimetre was deposited during that same waning phase and most of the particles deposited during the second experiment has been eroded. The bottom three samples taken from this location have been deposited during the first experiment and very little variation in particle sizes are present in this lowest centimetre, this might be due to a different process of deposition during the initial experiment with an unconfined flow. Not only looking at the D50 value for each sample bit divided in three brackets of particle sizes and their fraction of the concentration with height shows decrease of larger particles near the top and the opposite for the fine particles as was predicted by the 2D experiments. The measurements near the bottom (0-0.75 cm) do however change far less as compared to those from higher up succession at this location, again as an indication that the initial stage of the unconfined flow might have been different as a confined flow, albeit the figure () does not represent this as neat and another analysis must be conducted in order to be able to verify this.

Levee crest

The levee crest has recorded all three experimental runs in its vertical succession, which therefore gives the most complete covering data about the variation between experiments and with height above the base of the flow. Overall the particle size decrease with height as could be assumed from the 2D experiments and derived from the few data points on the inner slope of the levee. A detailed view of those results shows however that although the overall particle size is decreasing with height, the deposits at the bottom few millimetres of each consecutive experiment are coarser as those deposited before that. This is represented more clearly by the settling velocities with height representation of each experiment. This shows a linear relation for the second and third experiments, those that have been influenced by confinement of the flow in a levee bounded slope channel. The rate of decrease in settling velocity with height has a linear best fit for these two experiments and are 0.63 and 0.55 cm/cm/s for the second and third experiments respectively. Those values are considerably lower as compared to those found in the erosive/bypassing experiments in the 2D setup (around 1cm/cm/s), thereby confirming the hypothesis made that for depositional flows those fining upward rates would be considerably lower. The values found for these second and third confined experiments are still above the values derived from the Amazon channel by *Pirmez (2003)*which were between 0.22 and 0.47 cm/cm/s. The scale of the Amazon channel levees however is hundred times larger as compared to our experimental levees and measurements there are taken of sets of turbidity currents instead of a single one which could fade out the small scale fining upward trend within a single flow. Both results from the levee deposits and the particle size profiles in the 2D experiments have shown that the upper layer of the turbidity current consist of the finest particles and variation in particle size in this top layer "cloud" is low. Pirmez states that most of the particles in the Amazon channel levees consists of silt and this small particle size can be kept in suspension all throughout the turbidity current reducing the fining upward trend seen in our experiments with sandy particles.

The first experiment carried out on a then pristine and unconfined slope has a different trend in fining upward of its particle size. As the plot (fig) shows the best fit line for this succession is a logarithmic equation which indicates a different process in deposition of the sediment. In more detail this succession can be divided into two sections, one for the bottom centimetre and the other for the later sediment (1-2 cm) deposited during this experiment. The second part is fairly similar to the trend in the other two experiments and can be represented as a linear best fit line that is steeper than the other as expected with a reduction of 0.75 cm/cm/s more towards the values of the 2D experiments. Since some build up of levees already starts during the first experiment the later stages of the flow will have undergone some influence of the confinement due to channel-levee formation, the sediment deposits at the top of the levee after the first experiment are therefore most likely a result of the same processes of overspill deposition as the second and third experiments, with the difference that the levees are not as developed yet. The near bottom deposits during the first experiment are significantly larger in particle size and have far greater fining upward trend as compared to all the rates. This can be explained as unconfined flow covers a broad section of the whole slope and this width is basically the channel so velocities at the location of the later formed levees are higher, and are reduced quickly as even the smallest of levees start to build up giving the high rate of fining upward in this bottom part of the levee. The particle size values near the base of the levee for the different locations they have been measured at are in small range meaning that they most likely have been deposited as a frontal lobe for the first part of their deposition, on top of which the later levees have been deposited and the slope channel has eroded in. The theory of a frontal lobe forming on an unconfined slope first with only after that the incision of a channel and the development of levees has been proposed based on outcrop and bore hole data by *Morris et al. (2014)* in which he writes " This suggests that, where there is useable accommodation, external levées initiate through formation of a frontal lobe, followed by propagation of the channel and increased flow confinement and the development of an external levée by flow overspill." this rapid rate of decrease in particle size near the base of the flow can also explain the little sandy particles found throughout the Amazon channel levees as those would only be deposited in the early stages of confinement outside the main channel/ during the formation of the frontal lobe, assuming there was enough accommodation space for this to occur.

In more detail the fining upward trend for the crest of the levee look shows a different trend as compared to looking at just the D50 values. During the first and last experiment there is a significant change in the fraction each of the particle size groups occupies in the whole concentration. The first experiment, shows a sharp decrease in the larger of the larger particle fraction and the opposite in the small one for the first centimeter. This is similar to the high decrease in particle size of the near bottom conditions mentioned before. The latter part of the first experiments and the whole of the second experiment do not show significant changes in the fractions for each group as they remain relatively steady around their values in the initial sediment mixture. This is difficult to explain since the D50 particle size during the second experiment does decrease with height as seen before (fig). The trend of fining upward as derived before is only based on three data points in the whole succession for the second experiment. The first data point is significantly larger in settling velocity/particle size, as is the first data point for every experiment, with the other two being rather similar and in this way under estimating the fining upward trend. The third experiment shows a large increase in the small particle fraction as the height above the base of the levee is increased which has as an effect only a small amount of large particles are this high in the suspension.

This shows the levee is build up out of three sections based on the succession in settling velocities/particle sizes, with these three sections each related to a different part of the turbidity current.

-The first section is near the bottom of the bed with the slope still being pristine. A wide frontal lope deposit with approximately a thickness of a centimeter in the middle and decreasing in height towards the edges. The overall particle size is the coarsest of the whole succession but shows a steep decreases with height but laterally is similar across a larger area. Velocity of the flow is here the most important process influencing the particle sizes that the deposit consists of.

- formation of the slope channel and bounding levees. Confinement of the flow causes it to accelerate in the centre of the channel causing erosion into the frontal lobe while at the same time the formation of levees on the side where velocities decrease. The fining upward trend of this section of the levee is small and relates most likely to the body of the turbidity current. Although velocity still has an influence here the most important factor for the low fining upward trend in this part of the levee is turbulence. Above the velocity maximum the body of the flow is highly turbulent mixing a wide range of particle sizes throughout and resulting a this low fining upward trend for the middle part of the levee.

-The top of the levee again shows a larger decrease in particle sizes comparable to the first phase, with these particles depositing from the upper part of the flow with less turbulence mixing the different particle sizes and therefore the relation to the velocity profile being the most important process to determine the fining upward rate of the particles once again. This “cloud” of fine grained particles no longer builds the levee laterally in thickness but only in height.

Back/outer slope of the levee

The back slope of the levee shows vary little variation in particle sizes with height and across experimental runs. A possible explanation for this could be the remainder of an incipient avulsion, although it can be traced throughout all experiments and might therefore be unlikely. A second explanation could be a secondary flow caused by overspill further to the top of the slope. Due to the scour hole that forms at the top of the hill the turbidity current is not confined within levees for the initial part of flowing down the slope and can thereby spread across the full width of the slope. This would be an scenario of part of the flow spilling over the edge of the scour and to the back slope of the levee creating a secondary flow on that side of the levee instead of the main developing channel. Deposits on that side of the levee are therefore not settling from the main channels overspill but directly out of a secondary flow accommodating for the higher particle size then would be expected at the distal part of the system. This effect has been neglected for the course of this study and the focus has been on the inner to crest section of the deposited levees.

4.2.4 velocity influence on deposition

The relation between the composition of the levee and the turbidity current are largely influenced by velocity of the flow, since this velocity is one of the processes that keeps particles in suspension. The bedload/suspension threshold (komar, 1985) can give an indication of the maximum velocity that the flow can have and still deposit a certain particle size. This assumption was used to gain insight in the flow conditions at the location of the sampled levee and in the opposite manner to relate the UVP prober velocity data to predicted particle sizes deposited. The UVP data for the levee crest shows a faster average velocity for the first experiment, with a particular notable rapid increase from the base to 0.75 cm in height and from there a more steady velocity. This first rapid increase is most likely the result of the flow being unconfined at the stage of the experiment. The other two runs are similar in terms of average velocity and do not show this rapid increase in velocity near the base since they are no longer part of the main channel. Deposition of particles has been measured throughout the full length of these two experiments, with the velocities measured indicating a particle size deposition between 130 and 150 microns. At the location of these UVP probes there is a deposition in the centre of the channel for all three runs, therefore the height measured from the levee crest to the base of the channel does not increase significantly and as a result this does not lead to decrease in particle sizes with height of the levee deposit. This is another sign that the processes are different for an unconfined flow as compared to one influenced by bounding levees.

Deposition of sediment at the location of the UVP probes influences the measured results of the velocity which could affect the average velocities and lead to the wrong interpretations of the velocity changes during the experiment, to reduce this effect the average velocity is looked at in greater detail on a shorter time interval. The quasi-steady body of the turbidity current during each experiment is divided into three sections with an equal time interval and the distance to the bed taken into account by deposition, giving a more accurate view of the changes in average velocity over time without being interfered with by the depositions. This shows that the first two experiments are similar with the average velocity of the body not changing much over the complete interval. The average velocity for these experiments is roughly around 150 mm/s with only the last time interval of the body showing signs of decrease in velocity as it starts to enter the waning phase near the end of it. The explanation for this could be that during these experiments the distance from the base of the channel to the crest of the levee does not change significantly. The levee is forming during these experiments but at the same time there is also deposition of sediment within the channel therefore the height the crest of the levee has within the turbidity current doesn't change much. This is different in the final experiment which shows a higher velocity during the initial part of the body with velocities around 200mm/s but these are quickly reduces during the second and third interval measured. As concluded in other analysis already the confinement of the turbidity current increases its velocity which could be the reason for the initial higher velocity; however contrary to the other two experiments this increase of velocity results in erosion in the channel. This erosion has as a result that the distance from the base of the flow to the crest of the levee increase and the velocity measured at the crest of the levee is from a higher section within the turbidity current as the time passes. The higher above the base the lower the velocity of the turbidity current as is recorded within the levee in the last experiment, as is also recorded in the earlier mentioned particle size analysis.

Sampled levee

The equation applied to the particle sizes derived from the analysed samples, maximum velocity at which these particles are still deposited. The particle sizes used in this equation is the D50 particle size of the samples, which is assumed to give the value of the average flow velocity of the turbidity current. It shows the average velocity of the first experiment is far higher compared to the other experiments as has been determined before by the UVP probe data at the upslope location and the analysed particle size data. The suspension/bedload threshold velocities that this gives are in a similar range as found in the earlier determined average flow velocities from the UVP data. The first experiment has an average velocity range between 320-260 mm/s, this is overall slower as compared to the measured UVP velocities. An explanation for this is the first part of the experiment on a pristine unconfined slope the velocities of the flow were much higher with most of the levee formation only beginning further down the slope as the current slowed down and deposited its sediment in a frontal lobe, with deposits near the UVP probes only forming in the second part of the experiment. This therefore gives a higher average velocity of the flow further up the slope as compared to the down slope development of a frontal lobe and subsequently the initiation of levees. The second experiment ranges from 270-250 mm/s and are velocities similar to the average flow velocity found earlier, an indication that the flow doesn't undergo much change as it flows down the slope during this phase. The last experiment gives average velocity values of the turbidity current (250 -230 mm/s) that are below those recorded by the UVP probes (250-270). The velocity values from the UVP probes for the second and third experiment are similar due to the deposition of sediment within the channel and as a result the difference in height between the base of the channel and the crest of the levee only changing marginally. The distance between the top of the levee and the base of the channel at the sampled levee location does increase between the second and third experiment due to erosion in the channel, which as a result decreases the velocity at the crest of the levee and the deposition of smaller particles.

5. Conclusion

The experiments carried out in2D setup have shown that the internal structure of turbidity currents is dependent on a combination of initial conditions. The experiments in this study have shown that the concentration profile is influenced by a combination of the angle of the slope, the initial sediment composition of the flow and the initial discharge. The angle of the slope and the discharge influence the thickness (flowheight) of the flow. An increase in thickness has a direct relation to the concentration profile of the turbidity current with a higher concentration of sediment being found at greater height as compared to flows of reduced thickness. This increased concentration at higher levels above the base also have an effect on the particle size that is kept in suspension, these currents are able to maintain larger particles within suspension higher above the base of the flow, which has an effect on the composition of the bounding levees they form in natural/3D situations. The initial sediment composition has a similar effect with flows of larger particles having an increased concentration of those near the bottom and currents with a smaller particles size able to keep these smaller particles in suspension at higher levels above the base. A combination of these boundary conditions determines whether a turbidity current will have a erosive or depositional nature, and whether levees will be formed.

The 3D experiments show that the formation of slope channels with bounding levees as seen in nature only form under specific boundary conditions of which the most significant are the angle of the slope and the initial sediment composition and concentration of the flow. Subsequent experiments under equal conditions have shown development of the slope channel and levees to consist of different stages. The first stage is the flow over the then still pristine unconfined slope, this results in the deposition of a thin frontal lobe near the bottom of the slow migrating upward with time. Once this frontal lobe has cause some disturbance to the slope levees start forming outside the main flow. These early levees are still broad and have a low height compared to the thickness of the entire flow. Subsequent currents enhance the earlier formed levees and more confined channel comes in place. The levees start building up in a more vertical narrower fashion as compared to the earlier stage and this has increased confinement and subsequent increase in velocity and erosion within the main channel as a result. Both these processes increase the distance between the crest of the levee and the base of the main channel resulting in less overspill of the top layer of the turbidity current across the levees causing even less horizontal buildup of the levee, it seems reasonable to assume that a equilibrium state exists between the buildup of the levees and erosion at the base, as the flow eventually will no longer reach the crest of the levees and this also stop the enhancement in confinement of the main channel decreasing erosion in our experiments however this state has not been reached and would be a good starting point of further studies.

A fining upward composition is recorded in the overall bounding levee, as the distance between the crest and the base of the flow is increased and therefore a higher layer of the turbidity current is recorded for every subsequent run. A single turbidity current also has a fining upward trend in its deposits, with a coarse base as the head of the turbidity current passes and only deposits the largest particles, after this the body of the current passes, which is the well mixed and turbulent part of the turbidity current with several centimetres thick flow that does not decrease in particle size with height as much. The final part become the waning stage of the flow and is only the settling of the small suspended particles as the flow has actually already stopped, with a significant drop in particle size deposited as result. For subsequent runs these little single deposits stack creating a typical pattern for turbidity currents as has also been recorded in nature like the amazon channel for example (Pirmez, 2003). This pattern is a coarse base as the frontal lobe is deposited during the early stages and only close to the main channel, with a steep decrease in particle size, this is follow by a thicker section which is a well-mixed succession with little decrease in particle size with height, this thickness is equal to the thickness of the turbidity currents passing. The last section is the top of the levee which is more or less equal to the total height of the turbidity current and therefore only consisting of the smallest particles that reach these heights in suspension.

6. References

Baas, J.H. (2008) *The dynamics of turbulent, transitional and laminar clay-laden flow over a fixed current ripple.* Sedimentology 55 (3), pp. 635-666

Cartigny, M.J.B. et all (2012) *Concentration-dependent flow stratification in experimental high-density turbidity currents and their relevance to facies turbidites models.* J. sed. res.

El-ghawad, S. et al. (2012) *Three-dimensional numerical simulation of turbidity currents in a submarine channel on the seafloor of the Niger Delta slope.* Journal of geophysical research, Vol. 117

Ferguson, R. I., and **Church, M.** (2006), *A Simple Universal Equation for Grain Settling Velocity*, Journal of Sedimentary Research, 74(6) 933-937,

Garcia. M and **Parker, G.** (1993) *Experiments on the entrainment of sediment into suspension by a dense bottom current.* J. Geoph. Res.98(C3) 4793-4807

Hiscott, R. et al. (1997) *Turbidity-current overspill form the Amazon channel: texture of the silt/sand load, paleoflow from anisotropy of magnetic susceptibility and implications for flow processes.* Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 155

Islam, M.A. and **Imran, J** (2010) *Vertical structure of continuous release saline and turbidity currents.* Journal of Geophysical Research: Oceans115 (8), C08025

Kane, I.A. and **Hodgson, D.M.** (2011) *Sedimentological criteria to differentiate submarine channel levee subenvironments: Exhumed examples from the Rosario Fm. (Upper Cretaceous) of Baja California, Mexico, and the Fort Brown Fm. (Permian), Karoo Basin, S. Africa* .Marine and Petroleum Geology28 (3), pp. 807-823

Kostic, S. (2011) *Modeling of submarine cyclic steps: Controls on their formation, migration, and architecture.* Geosphere7 (2), pp. 294-304

Mayall, M and **O`byrne, C.** (2002) *Reservoir Prediction and Development Challenges in Turbidite Slope Channels.* Proceedings of the Annual Offshore Technology Conferencepp. 321-330

Mohrig, D. et al. (2006) *Controls on geometry and composition of a levee built by turbidity currents in a straight laboratory channel.* River, Coastal and Estuarine Morphodynamics: RCEM

Morris, E. et al. (2014) *Origin, evolution and anatomy of silt-prone submarine external levees.*

Pantin, H.M. and **Franklin, M.C.** (2009) *Predicting autosuspension in steady turbidity flow: Ignition points and their relation to richardson numbers*. Journal of Sedimentary Research 79 (12), pp. 862-871

Pirmez, D. and **Imran, J.** (2003) *Reconstruction of turbidity currents in Amazon Channel.* Marine and Petroleum Geology, 20, p. 823–849

Skene et all. (2002*) Quantitative analysis of variations in depositional sequence thickness from submarine channel levees.* Sedimentology 49 (6), pp. 1411-1430

Spencer, D.W. (1963) *The interpretation of grain size distribution curves of clastic sediments.* J.Sediment. Petrol., 33:180−190.

Straub, K. and **Mohrig, D.** (2008) *Quantifying the morphology and growth of levees in aggrading submarine channels.* J. Geophys. Res., 113

Weime, P. and **Slatt,R.M.** (2000) *Developing and managing turbidite reservoirs: Case histories and experiences: Results of the 1998 EAGE/AAPG research conference. AApg Bulletin 84 (4), pp. 453-465*