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Evolution of Unconfined Turbidity Current Deposits: an Experimental Study

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Abstract

Turbidity currents are submarine flows, which are responsible for the transport of sediments in turbulent suspension to deep areas of the ocean, creating major morphological features. Environmental hazards, such as breaking of submarine cables, and dispersal of pollutants, can be created by turbidity currents. Turbidite deposits contain important stratigraphic records, and are of importance to the fields of sedimentology, marine geology, benthic biology, climate change and palaeo-seismic reconstruction. In addition, the resulting turbidite deposits are of interest to the oil industry, as they are able to form hydrocarbon reserves, thus highlighting the need to predict the topographic characteristics of those deposits. Due to their nature, there is only a limited amount of quantitative turbidite deposit data from natural flows available for analysis. Therefore, laboratory experiments are required to increase the knowledge of the flow structures and concentrations under which these deposits are formed. A study is underway in the Fluid Mechanics Laboratory at The University of Auckland to evaluate the temporal and spatial topographical evolution of turbidity current deposits. The objective of this paper is to introduce the experimental setup for the unconfined basin study, and provide results for three-dimensional turbidite structure characteristics. A brief overview of the observed depositional evolution will be provided. The results of this study will help to provide a more detailed picture of flow and depositional evolution for subsequent currents.

Keywords: *turbidity currents, unconfined flow, depositional evolution*

Introduction

Turbidity currents are defined as a type of sediment gravity flow where sediment is held in suspension by fluid turbulence [4]. They are part of the larger family of gravity currents, also known as density currents, where the flow of one fluid through an ambient medium is caused by the density difference between the two fluids [8].

Turbidite Deposition

Due to the complicated nature of turbulent flows, the normal rules of sediment settled do not apply [2]. The effect of gravity on a sediment particle can be countered by an upward eddy velocity that retards downward movement [2]. Different particles can meet varying degrees of upward or downward eddy velocity interaction, and hence overall settling of a turbidity current is highly variable [2]. Due to the presence of three dimensional eddies in the flow, not only is the settling time retarded, but lateral spreading is increased if it is unconfined, and therefore deposition occurs across a greater area [2]. Though sediment is less sorted than that of conventional settling theory, there is an overall trend of greater grain size toward the bottom of the flow [2]. Deposition is also affected by the velocity distribution of the flow, which in turn is determined by the density distribution within the flow [2]. The increasing hydrostatic pressure distribution in the downward direction, and turbulence retarding flow at the top layer also affect sediment settling [2]. These factors vary the grading of a deposit very differently than that for static settling [2]. Deposition from a typical turbidity flow lies somewhere between static settling and settling for a fully turbulent sediment cloud [2] and the resulting deposit reflects this complicated mechanism by which it is formed [2].
[4], in experimenting on the head of a turbidity current, noted that after an initial constant velocity, the velocity diminished rapidly, due to material being deposited from just behind the head. This was reflected in a diminishing bed thickness as the flow distance progressed. [6] conducted experiments on the thickness of beds deposited by turbidity currents. Bed thickness was uniform near the source, except where sediment was poorly sorted, and was found to be directly proportional to grain size [6]. High concentrations produced more uniform deposits, and shorter, thicker beds [6]. A relationship for bed thickness was established, where the square of bed thickness over suspension volume, is proportional to settling velocity over head velocity [6]. From this relationship, the head velocity can be estimated from observable properties in the bed [6]. In experimental horizontal channels, the bed tends to have a uniform thickness, except at the distal end [6]. Uniformity is encouraged by uniform grain size, high concentration, low settling velocity and large lock height [6]. Suspension volume is equivalent to bed thickness [6].

Previous Unconfined Basin Experiments

[3] conducted experiments in a basin of dimensions 10-m long, 6-m wide and 1-m deep. Fifteen tests were run, with a constant sediment flow of 3.5-l/s, with the run stopping when the flow met the far end of the basin. A wide flow angle (about 40°) occurred as flow entered into the basin, with the current diluting rapidly with distance from the flow origin. The density of the flow was 2% of its original density, 6-m from the origin, and the thickness of the deposit decreased by 50% per metre along the main axis, with a much greater decrease in the lateral direction.
[7] conducted experiments in an unconfined basin, and presented 'lobe switching' in a turbidite fan. A series of flows were passed through the basin, and deposits accumulated with a lobe focusing after eight flows. At the centre of the lobe, a small channel formed, and after twenty runs the lobe switched direction. Switching events are primarily influenced by lobe size and sedimentation rate. The experiments showed precursors to channel forming, which are analogous to natural scale lobe formation, and submarine canyon formation.

Experimental Methodology

Basin Setup

The experimental basin used at The University of Auckland has dimensions 2000-mm width, by 2420-mm length, and sits on the concrete floor of the laboratory. The side walls of the basin have a height of 600-mm, and are made of clear Perspex, with a width of 12-mm. At the centre of the proximal end of the basin there is an appending lockbox, with dimensions 400-mm width, 570-mm length and 820-mm height, constructed out of Perspex. The lockbox has a hand lifted gate mechanism, which separates the lockbox from the main basin. It is in the lockbox that the initial sediment concentration is placed and stirred before being released into the basin. The basin has a false floor which sits 200-mm above the concrete floor. It was constructed out of plywood, with a black silicon surface glued to the top of it. It has dimensions 2000-mm wide by 1800-mm long, leaving a gap of 620-mm between the end of the false floor and the distal end of the basin. The false floor has a constant horizontal gradient in all directions. For all test runs, the water level was kept constant at a height of 465-mm from the concrete floor, and hence a height of 265-mm from the false floor. A Nikon D90 Digital Single Lens Reflex (DSLR) camera was suspended above the basin to provide a plan-view photo-series of the flows as they developed across the false floor of the basin. Two video cameras were used to take recordings of the flows, one on the right hand side on the basin, peering in through the Perspex wall, and one providing video footage of the floor at an angle downward, with the flow and lockbox in the field of view. An Acoustic Doppler Velocimeter (ADV) probe was employed in the basin to record velocities and related fluctuations in three dimensions for the flows. This paper only focuses on the resulting turbidite evolution across the ten flows during the experiment, and hence the video, photographic, and ADV data bears little relevance here, but are introduced to illustrate the complete experimental setup.

Flow Mixture

For the first series of flows through the basin, an initial 4% turbulent sediment mixture was formulated by evenly mixing 2% Ballotini and 2% Kaolinite by volume. Ballotini is a trademarked product manufactured by Potter Industries Inc. that comprises of very small glass beads. Kaolinite is a layered silicate clay mineral, part of the kaolinite-serpentine mineral group. The Kaolinite used in the test runs is in a crushed powder form, with a specific gravity between 2.3-2.6 g/cm^3. The 4% value was based on the ratio between the volume of sediment material in litres, and the total water volume (including water in lockbox, as well as the amount added to create the initial mixture). It was calculated that 1.35-l of both Ballotini and Kaolinite, mixed with 4.5-l water, in the initial mixture added to the volume in the lockbox gave an exact result of 4% by volume. To create the initial mixture, the Ballotini and Kaolinite volumes and 4.5-l of water were added to a bucket and stirred until the sediment was in complete turbulent suspension, with little to no sediment settling at the base of the bucket.

Experimental Procedure

Once the initial setup had been completed, the experimental run was ready to begin. A stopwatch was set to start timing the moment the ADV was set to ‘record’ on the computer ADV interface. The sediment mixture was then poured from the bucket into the closed lockbox and stirred to produce an even sediment distribution within the lockbox. The continuous high speed photography was then started, using the attached remote control. The stopwatch was stopped the moment the camera started taking photos. At this point the gate mechanism containing the mixture in the lockbox was lifted and a hyperpycnal sediment plume started to develop travelling across the basin floor. Once the flow had travelled the entire way across the false floor, the test was ended, with all ADV, photographic and video data saved and logged. The time taken between the ADV starting to record, and the photo-series starting was also recorded. Ten experimental runs, using a constant 4% mixture for each, were conducted over two weeks.

Bed Profiling

To gather the accurate data required to generate three dimensional surface plots for the sediment deposits, ultrasonic measurement techniques were used. Ultrasonic waves are generated by a probe, and directed toward the deposit, with the resulting reflected wave being received again by the probe. The time taken between the sent and received wave is recorded, and therefore the distance between the probe and deposit can be determined by the equation $z = ct/2$, where c is the speed of sound in water, t is the time, and z is the distance. Theoretically, ultrasonic measurements should be unaffected by suspended particles in the water that have a grain size smaller than the size of the generated ultrasonic wave. If the sediment size is larger, it can effectively block and reflect the wave causing an erroneous result [1].
The bed profiler consists of an ultrasonic sounding probe mounted on a mechanical carriage, which passes over the area of interest in the basin. The probe has a 20 mm diameter, and emits acoustic waves with a frequency, f, of 2 MHz. The temperature of the water was measured at 17 °C, which gives a sound wave resolution of (+/-) 0.74 mm, following the equation: $\Delta z = (+/-) c/2f$. The probe is connected by a 2-m cable to a signal conversion box, which is then connected to the basin computer through its printer port. The settings for the ultrasonic probe were controlled from the basin PC, using a software package called DSP 2002. The software allowed the basin water temperature to be inputted, and an in-built algorithm would use the data to determine the correct wave celerity, and hence output accurate distance values.
To ensure that the acoustic probe was positioned correctly, known location markings on the lips of both side walls were made at 5-cm increments up to 175-cm from the proximal end of the basin. The first run was taken at 175-cm, with the probe moving from left to right across the flume width. The bed profiler was then moved to 170-cm, and the second run had the probe move from right to left. This process continued as above with the last reading being taken at 5-cm. The final bed profile be taken was the datum, measured after the basin had been completely cleared of sediment with the false floor again level. Each profile run picked up 1560 points across 1.84-m, creating 2-D arrays with 35 columns and 1560 rows.

Analysis of Bed Profile Data

To create surface plots from the gathered profile data, the 2-D arrays were inputted into MATLAB, and 3-D surface plots were generated. First, all the 2-D arrays were subtracted by the datum plot to give the accumulative sediment difference over each test. Next, M-files were created to despike clear outliers in the original data, to smooth the surface plots. Points that were not filtered by the MATLAB algorithm were identified and averaged manually in the original file. The result of this filtering and generation process was a series of turbidite profiles showing clearly the turbidite evolution across the ten flows. The length of each deposit surface plot is 175-cm, and each width is 180.4-cm.

Results

Figures 1 and 2 show the spatial and temporal turbidite evolution across the ten experimental flows. Table 1 gives a qualitative summary of the observed lobe growth. Figure 3 highlights the spatial difference between the first and the last deposit. A typical propagation of an unconfined turbidity current for the first experimental flow is shown in Figure 4.

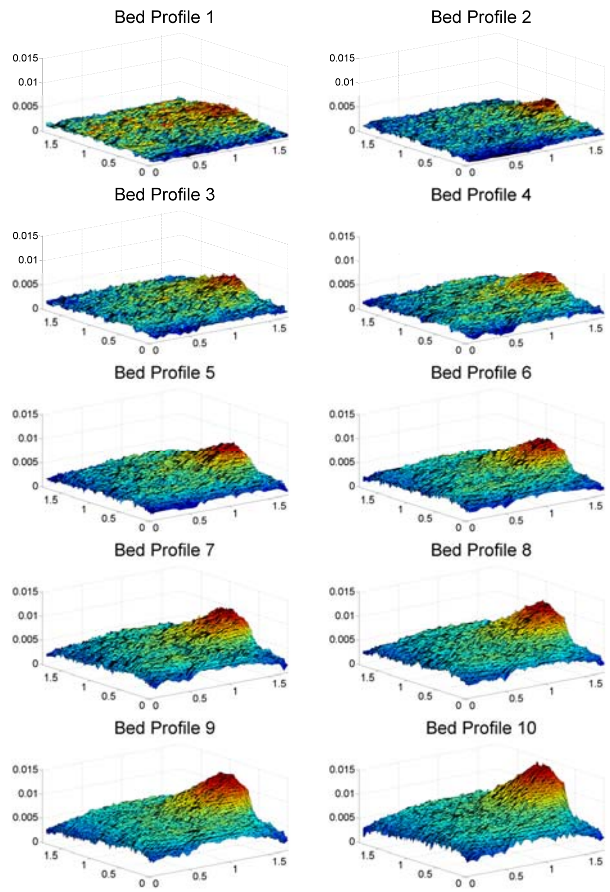
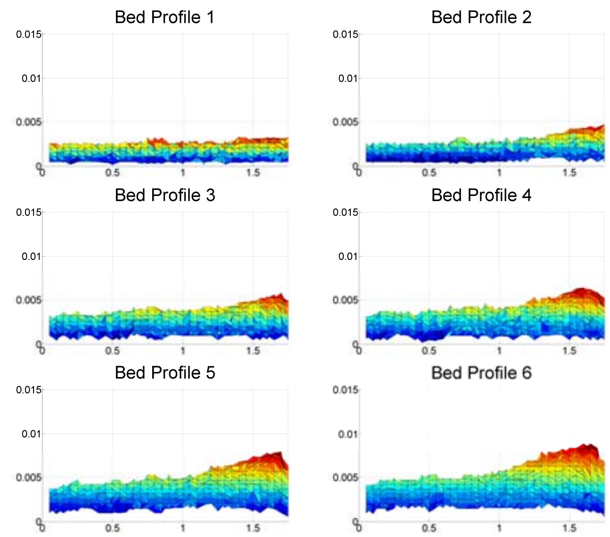


Figure 1. Turbidite evolution across the ten experimental flows (all dimensions in metres)



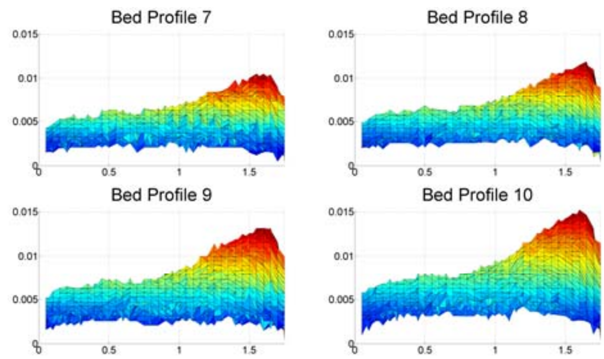


Figure 2. Turbidite evolution across the ten experimental flows (side views) (all dimensions in metres)

	Thickness at lobe tip	Distance from lockbox to lobe tip	Distance from lockbox to lobe toe	Thickness at distal end
1	0.0032	0	0.4	0.0026
2	0.0047	0	0.4	0.0026
3	0.0058	0.05	0.45	0.0032
4	0.0063	0.15	0.6	0.0036
5	0.0079	0.05	0.75	0.0042
6	0.0089	0.1	0.95	0.0046
7	0.0105	0.1	1.05	0.0052
8	0.0119	0.1	1.05	0.0059
9	0.0131	0.1	1.05	0.0063
10	0.0151	0.15	1.05	0.0066

Table 1. Summary data for the ten deposits. Note the second column gives evidence to the formation of a channel across the accumulating deposits. All measurements are in metres (m).

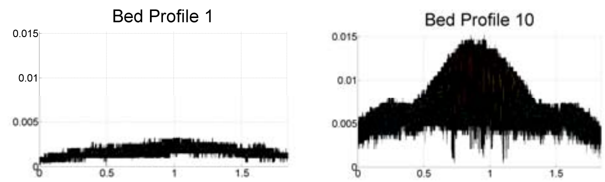


Figure 3. Initial and final deposit profile from the distal end of basin. Note the symmetrical nature of the latter deposit (dimensions in metres).

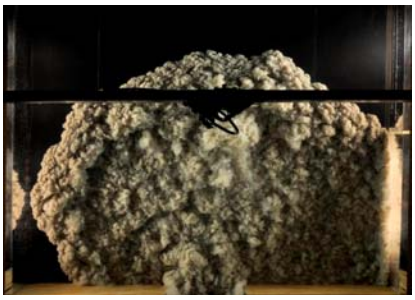


Figure 4. Typical 2-D propagation of an unconfined turbidity current. Note the upward transport and reflections at the left hand side wall.

Discussion

Lobe and Channel Formation

Figures 1 and 2 clearly show the development of a lobe across the ten turbidity flow deposits. The upstream apex of the lobe occurs just in front of the lockbox down the central axis of the basin, and its thickness increases from 3.2-mm, to 15.1-mm across the ten deposits (Table 1, column 1). The final lobe is symmetrical in the lateral direction (Figure 3), and has a constant gradient along the main axis until it reaches a constant gradient from the lobe toe, to just before the distal end of the false floor, where it tapers off to a smaller bed thickness (Figure 2). The length of the lobe, from its upstream apex to its toe, increases across the ten test runs from 0.4-m to 1.05-m (Table 1, column 3). As the flow leaves the lockbox and propagates across the false floor, it decelerates rapidly from the moment it is released. There are two reasons behind this. Firstly, water is entrained at the nose of the flow causing the sediment concentration in the head to decrease [4,8]. Secondly, sediment begins to settle out from the flow as soon as the flow is initiated [4],[8]. This loss of sediment also causes the 2-D velocity to decrease, allowing more time for the sediment in the flow to settle. This process is a self-reinforcing cycle, and is reflected in the 3-D symmetry of the developing lobe, with the smooth gradient of the deposit in all directions.

A clear depression behind the lobe tip starts to occur from the fourth flow (Figure 1, Bed Profile 4). The length of this feature increases from 0.5-m to 0.15-m across the course of the experiment, and becomes progressively deeper relative to the average bed thickness and height of the lobe tip. A reason for this depression could be the initial large flow velocity from the lockbox entraining previously settled sediment into the flow head. This feature gives evidence to the initial formation of a channel in a turbidite, with the process being erosion and entrainment.

Comparisons with Previous Studies of a Similar Nature

The results of this experiment compare well to other studies attempting to make similar observations of turbidity flow and resulting turbidites. [3] found that their flows underwent ‘rapid dilution’ with distance and time, and deposit thicknesses decreased ‘radially from the source’. A similar result occurred here, with the lobes being symmetrical, their thicknesses decreasing smoothly in two dimensions from the lockbox. [7] presented lobe formation over a series of flows with a ‘subtle channel-form’ occurring at the centre of the lobe. The same can be observed in the present experiments. Scouring, which becomes longer and deeper across subsequent flows, is observed between the lockbox and lobe tip after the fourth run.

Influence of Sidewall Reflections

During each test run, the turbidity current would travel in two dimensions as a plume. As a result, sediment transport in the lateral direction meant that the flow would eventually meet the side walls and travel upward parallel to the wall. This resulted in some sediment being reflected back toward the centre of the basin, and some sediment being deposited close to the wall (see Figure 4). This was observed to happen across all ten tests. This phenomenon had an effect on the shape of the formed turbidite, especially in the latter surface profiles. In Figure 1, Bed Profiles 7 through to 10 exhibit a symmetrical depositional arc, with the maximum deposition occurring midway down the length of the wall. This is a result of flow deceleration at the wall resulting in increased deposition, and is related to the way a typical turbidity flow would propagate (Figure 4). This could have implications in scaling to a natural event.

Conclusions

A symmetrical lobe is shown to develop across the ten turbidity flows just beyond the lockbox down the central axis of the basin. The lobe thickness increases from 3-mm to 15-mm, and stretches from a length of 0.4-m to 1.05-m across the ten tests. A scour hole develops behind the lobe as the deposits accumulate. This aspect could be construed as the formation of a channel in the newly formed deposit. The results compared well with previous studies of a similar nature, and present a picture of how turbidites may form in deep ocean basins. The potential initiation of channels in turbidites is also implied by the results, indicating the role turbidity flows have in channel formation.

Future Research Directions

Flow properties will be constructed using the results from the ADV recordings and Nikon D90 data to provide turbulence information and changing velocities/accelerations in two dimensions.

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