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Experimental Study of Longitudinal Sorting of Particles Differing in Size and Density

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Experimental Study of Longitudinal Sorting of Particles Differing in Size and Density

by

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DEDICATION

This thesis is dedicated to my parents Mohammad Yousuf Farooq and Mrs. Faizun Nahar, my dear husband, Riaz Ahmed, and our precious daughter, Rahma Nawar Ahmed.

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ABSTRACT

Transport, deposition and erosion of sediment particles differing in size, shape and density may result in particle segregation, which in geosciences applications is generally referred to as sediment sorting. A thorough understanding of sediment sorting processes is important to describe and model a wide variety of natural processes such as the decrease in particle size and/or density in a fluvial system (downstream fining and/or lightening), the formation of economic placers, concentration of heavy minerals, chemical and metal pollutants etc. Sorting of sediment grains associated with sediment transport in the streamwise direction results in the development of *longitudinal sorting* patterns. *Vertical sorting* patterns are the results of sediment sorting within the alluvial deposit. Laboratory experiments were conducted at the Hydraulics Laboratory, University of South Carolina to study the physical processes associated with the transport of a mixture of particles differing in size and density, and the resulting longitudinal sorting patterns. Experiments were performed in a sediment feed flume, which is an experimental set up that is traditionally used for these type of studies. Three experiments were performed with sediment mixture differing in both size and density, the sediment feed rate and the flow rate of water were held constant in each experiment. The sediment feed rate was the only parameter that changed from one experiment to the next. In each experiment data were collected to characterize equilibrium and non-equilibrium conditions, with equilibrium referring to a condition in which the characteristics of the

flow and the sediment transport can be reasonably considered steady and uniform. The analysis of the experimental data shows that 1) a downstream lightening pattern developed in the experiment with the highest feed rate, which means that the heavy particles were preferentially deposited in the upstream part of the deposit and the light particles travelled further downstream; 2) a downstream fining pattern was observed in the experiments with a comparatively low feed rate, with the coarse particles deposited in the upstream part of the deposit and the finer particles deposited further downstream.

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CHAPTER 1.   **INTRODUCTION**

1.1 Motivation

Transport, erosion and deposition of sediment particles differing in size, shape and density may result in particle segregation, which in the sedimentology and civil engineering community is known as *sediment sorting*. Although sediment sorting is commonly observed in natural systems, not all the governing physical mechanisms are clearly understood. In general, depending on the processes of interest, different types of sorting are considered.   Sorting associated with sediment transport in the streamwise direction results in the formation of *longitudinal patterns*, sorting in a cross section results in *transverse patterns*, and *vertical patterns* are the results of sediment sorting within the alluvial deposit. The variation of the physical characteristics of the particles, e.g. size, shape and density, influences the nature and of sediment sorting.

A thorough understanding of sediment sorting processes is important for the study of problems that are not only of interest to the civil engineering community, but also to the sedimentologists, petroleum geologists, the mining industry and the ecologists. These processes span from the downstream fining and armoring to the formation of economic placers Slingerland (1984); Force (1991); the deposition of heavy minerals, chemical and metal pollutants Best and Brayshaw (1985). In the past decades several studies were

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conducted to determine the nature and the characteristics of the processes controlling sorting of sediment particles differing in size and density. However, the large majority of the quantitative studies focused on the effects associated with differences in grain size Knighton (1980); Parker et al. (1982); Parker (1991) and the number of studies that also considered sorting of sediment grains differing in density is comparatively limited Slingerland (1984); Viparelli et al. (2014). The author of this thesis is not aware of quantitative studies of sediment sorting of particles differing in shape.

1.2   Information relevant to the present study

In this background section the following information will be provided that is needed for the interpretation of the experimental results.

Downstream Fining and Downstream Heavying

A classic example of longitudinal sorting pattern is the *downstream fining*, i.e. the gradual decrease in sediment size in the streamwise direction observed in numerous alluvial systems and generally associated with the reduction of channel bed slope Parker (1991); Wright and Parker (2005). The physical in-channel processes that are responsible for the formation of this longitudinal pattern are particle abrasion and selective transport. Abrasion is the reduction of (mostly gravel) particle sizes due to wear. Selective transport is the result of the different mobility of coarse and fine grains: the latter are easier to transport, and this results in the preferential deposition of coarse and less mobile particles in the upstream part of an alluvial system (Parker, 1991).

As shown in previous laboratory experiments, at mobile bed equilibrium, i.e. when the system is able to transport the input sediment load without streamwise changes in rate and size distribution of the sediment load, the granulometric characteristics of the deposit surface did not change in space (and time). In other words, at mobile bed equilibrium longitudinal sorting patterns on the bed surface were not observed. Selective transport contributed to the formation of downstream fining patterns in net depositional systems. Longitudinal sorting patterns can be stored in the stratigraphic record, but they weaken as the system approaches mobile bed equilibrium conditions. Particle abrasion always occurs and contributes to the formation of stable downstream fining patters on spatial scales that are too long to be reproduced in laboratory unidirectional flumes.

For the case of mixtures of particles differing in density, the longitudinal sorting pattern analogous to downstream fining is supposed to be characterized by the deposition of heavy particles in the upstream part of the deposit. The light particles, which are more mobile than the heavy grains, are preferentially deposited in the downstream part of the channel. Because of the similarity between the processes the streamwise decrease in particle density has been referred to as downstream lightening Viparelli et al. (2014). In our experiments the sediment mixture consists of sediments differing in both size and density. Hence the pattern of preferential deposition in a net-depositional system has to be carefully investigated to determine the relative role of particle size and density on the resulting longitudinal sorting pattern.

It is important to note here that basin scale processes, such the streamwise changes in flow regime, sediment load magnitude and size distribution-- for example –

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due to the presence of tributaries and overland flow, also contribute to the formation of a downstream fining pattern, but studying their role on longitudinal sorting goes well beyond the objective and scope of this thesis.

Sediment Sorting at Lee Face

The downstream face of the migrating steep front, e.g. small Gilbert delta fronts and the downstream part of migrating bars and dunes, is called lee face. The sorting pattern observed at lee face is characterized by a change in grain properties in the vertical direction, i.e. vertical sorting. Blom and Kleinhans (2006) mathematically described vertical sorting on lee faces for systems transporting sediment particles differing in size. As further discussed in the next chapter, due to the formation of small amplitude and long wavelength bedforms during the experiments, sediment sorting at the lee face plays a significant role in the present study. In particular, it helps to explain part of the scatter of the experimental data.

Vertical sorting on a lee face is the result of the combined effect of two different types of deposition processes.

i) **Grain fall**: Due to the flow expansion on the lee face, bed load sediments are deposited in the upper part of the lee face while the finer portion is preferably deposited further downstream (black particles in Figure 2.1). The sorting pattern associated with grain falls is characterized by a decrease in grain size in the streamwise direction. As grain fall deposition continues, a sediment

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wedge forms in the upper part of the lee face until the angle of repose is reached Blom and Kleinhans (2006); Viparelli et al. (2014).

ii) **Grain flow:** When the angle of repose exceeds, the sediment grain started to slide down the slope as a grain flow. During the grain flow the grain fall deposit is rearranged with the coarse grains transported in the lower part of the lee face and the fine grains trapped in the upstream part of the lee face Blom and Kleinhans (2006); Viparelli et al. (2014). So the resulting deposition pattern is characterized by an upward fining profile.
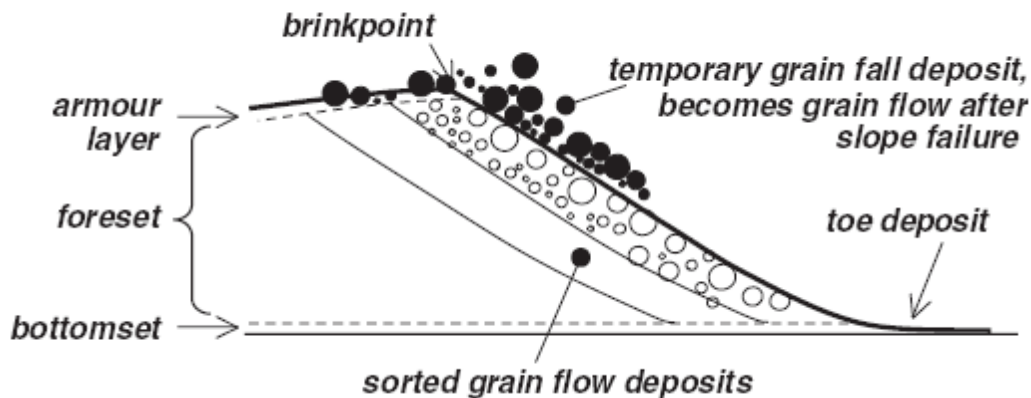
Figure 1.1: Sediment sorting at lee face Blom and Kleinhans (2006)

The lee face sediment sorting model described above, in the case of a mixture of sediment particles with uniform density and different grain sizes results in the upward fining pattern observed by Blom and Kleinhans (2006). However, Viparelli et al. (2015) noticed that in experiments with a mixture of sediment particles of uniform size and differing in density the lee face sorting results in a pattern of upward heavying with the heavy particles preferentially trapped in the upper part of the lee face deposit. In other words, in the Viparelli et al. experiments the heavy particles behaved as analogue of the fine particles, as commonly observed in rotating drum experiments on grain sorting

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processes. In the present study we will try to characterize by visual observations the vertical sorting patterns associated with a mixture of sediment grains differing in both size and density.

Relative Mobility and Equal Mobility

Natural streams and rivers carry mixture of sediment particles differing in size and density. In the case of bedload transport of a mixture of sediment particles with heterogeneous size and uniform density, coarse particles feel a higher drag force than in the case of uniform coarse material, with a consequent increase in mobility (exposure effect). In other words, coarse particles in a mixture of sediment grains differing in density are easier to move than in the case of uniform coarse material. At the same time, the coarse grains surround the fine particles, which become harder to move compared to the case of uniform fine material (hiding effect). Thus, in a system transporting a mixture of particles differing in size, fine particles are less mobile than in the case of uniform fine sediment. It is important to note here, however, that the net effect of the described increase in coarse particle mobility and the associated decrease in fine particle mobility is not a mobility reversal, i.e. in a system of particles with uniform density coarse particles are always less mobile than the fine material Einstein (1950); Powell (1998); Viparelli et al. (2014).

In summary, in the bedload transport of a mixture of sediments differing in sizes but not in density, coarse particles are heavier than fine particles; hence they require a larger boundary shear stress to be entrained in transport, i.e. the critical shear stress. This critical shear stress, however, is smaller than the stress needed to mobilize the coarse

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particles in the case of uniform coarse material Parker (2004). The limiting case in which all the particles are entrained at same boundary shear stress is called equal mobility Viparelli et al. (2014).

To regulate the different mobility between coarse and fine grains in gravel bed rives, i.e. in systems in which the preferential mode of bed material transport is bedload transport, a coarse surface (armor layer) develops. This coarse layer reduces the availability of fine particles to the flow and thus removes the remaining mobility difference between coarse and fine grains Parker et al. (1982); Powell (1998); Viparelli et al. (2014).

In their analysis of experimental results on bedload transport of mixtures of sediment particles with uniform size but differing in density, i.e. a case in which hiding/exposure effects are not present, Viparelli et al. (2015) documented a mobility reversal, i.e. heavy particles became more mobile than light grains. In other words, in a mixture of light and heavy grains having the same size, the light grains behaves as analogue of the coarse particles in a system transporting same-density sediments differing in size. The same behavior (light grains = coarse grains) was observed for the vertical sorting on the lee faces of small bedforms and Gilbert deltas. The physical processes that would explain the observed mobility reversal are presently unknown and are likely to be explained by means of granular physics studies and controlled traditional bedload transport experiments in unidirectional flumes.

In this study I collected preliminary data on bedload transport of a mixture of sediment particles differing in both grain size and density to explore the characteristics of

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the armor layer when the relative grain mobility depends on both particle density and geometry.

1.3   Related Previous Studies on Density Sorting

Understanding the mechanics that govern sediment transport and sorting processes is important for the interpretation of geophysical phenomena and for the design of river engineering projects. This motivated numerous studies to understand and describe sediment transport and deposition, and these studies were performed with different approaches, i.e. laboratory experiments, mathematical modeling and field observations. This study focuses on the poorly explored case of bedload transport and longitudinal sorting patterns of a mixture of sediment particles differing in both size and density. Some previous studies about sediment sorting due to size difference have already discussed to explain some related phenomena. Here I present a review of the past studies on sediment sorting associated with density differences and their main conclusions.

Steidtmann (1982) performed experiments to investigate the effects of size and density on sediment transport and deposition. He performed net depositional experiments under upper plane bed bedload transport conditions, i.e. relatively high bed shear stresses, and he found that heavy particles were preferentially deposited in the upstream part of the deposit with a resulting pattern of downstream lightening. The streamwise changes in grain size reported in Figure 4 of the paper show that in the case of plane bed the characteristics grain size of the heavy particles decreases in the streamwise direction, while a pattern of downstream coarsening was observed for the light material. In the case of a bed covered with ripples (defined as downstream migrating bedforms 1.0-1.5 cm

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height and with ~12 cm long wavelength), significant streamwise changes in grain size of the heavy and light fractions were not observed.

Kuhnle (1986) performed an experimental study to analyze the mechanism of transport and deposition of heavy with a mixture of poorly sorted gravel particles differing in density. In particular, poorly sorted gravel (mean size 3mm, density 2.65 g/cm^3) with magnetite (density 5.2 g/cm^3), lead (density 11.4g/cm^3) and tungsten (19.3 g/cm^3) were used. The grain size range of magnetite and tungsten was 0.125-0.500 mm, and the lead particles had a characteristic size of 0.500-0.707 mm. Khunle (1986) observed that the surface layer was coarser than the parent material in the vast majority of the runs. A coarse and light bed surface did not developed in the runs with the highest transport rate. In other words, a coarse armor layer formed during most of the runs. Dense sediments concentrated into a heavy sublayer just below the light coarse armor layer. Viparelli et al. (2014) performed experiments on bedload transport and deposition of a mixture of sediment particles with uniform size (~ 0.6 mm) but differing in density. In particular, they used plastic (density 1.5. g/cm3), sand (density 2.6 g/cm3), black diamond (a coal slag with density of 2.8 g/cm3) and crushed garnet (density 4 g/cm3). This study focused on two types of sorting i) longitudinal sorting with heavy particles preferentially deposited at the upstream end of the flume and light particles transported further downstream -downstream fining; andii) vertical sorting pattern characterized by the deposition of light particles to the lowermost part of the migrating front - upward heavying.

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Mobile Bed Equilibrium

The understanding of mobile bed equilibrium is crucial to study the basic mechanism of sediment transport processes because at mobile bed equilibrium the characteristics of the flow and of the bed deposit depend on the flow and sediment transport rates, and on the sediment properties, e.g. density and size. At mobile bed equilibrium in a fully alluvial system, i.e. systems in which sediment transport processes are not influenced by bedrock or other non-erodible surfaces, carrying uniform material:

1) The channel bed elevation does not change over time scales that are long compared to the time scales of bedform migration, thus the average bed slope is constant in time and the net sediment transport rate does not change in the streamwise direction and in time (conservation of sediment mass); and

2) If the sediment transport rate is constant in space and time, the flow characteristics (the bed shear stress in particular) have to be steady and uniform.

The condition for mobile bed equilibrium is slightly more complicated for alluvial systems carrying mixtures of sediment differing in size. Besides above mentioned characteristics, the grain size distribution of the sediment load also has to be steady and uniform (grain size specific sediment mass conservation). Recalling that the grain size distribution of the sediment load depends on the grain size characteristics of the bed surface, defined herein as the portion of the deposit that exchanges sediment with the bedload transport, at mobile bed equilibrium the grain size distribution of the bed surface has to be steady and uniform Parker and Wilcock (1993); Viparelli et al. (2014).

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To further illustrate the equilibrium condition in the case of non-uniform material, let's consider the ideal case of steady and uniform flow over a deposit with a downstream fining pattern on the bed surface. Due to the uniformity of the flow the bed shear stresses, and thus the sediment transport capacity of the coarse and the fine material, do not change in the streamwise direction. However, because of the limited availability of fine material on the bed surface in the upstream part of the domain the sediment transport rate will change in the streamwise direction. In particular, the increasing availability of fine (more mobile) sediment on the bed surface will result sediment transport rates in the downstream part of the deposit in higher and finer than in the upstream part. If the sediment transport rate increases in the streamwise direction, net channel bed erosion (and thus disequilibrium conditions) is expected. Similarly, if the grain size distribution of the sediment transport changes in the streamwise direction, sediment mass conservation is not satisfied in each grain size range and thus conditions of mobile bed equilibrium are not possible.

In this study I collected data on equilibrium conditions in a system transporting a mixture of sediment particles differing in both size and density. I am not aware of any other attempt of systematically characterize bedload transport in these conditions, thus I can only compare my results with previous studies performed with mixtures of particles differing in size or in density.

1.4 Study Objective

Most of the natural systems carry mixtures of sediment particles that, depending on the geology of the basin, may differ in shape, in size and/or in density. These particles

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can be transported as bedload or in suspension. This study focuses on bedload transport, a mode of sediment transport with moving particles that are constantly interacting with the surface of the deposit. The interaction between bedload particles and the deposit surface can be described as follows: the particles that are at rest on the deposit surface move for a distance that is on average few hundred times larger than their size, then they are re-deposited on the deposit surface for a period of time that is long compared to the time that they spent in motion (Einstein, 1937).

The objective of this study is to collect preliminary data on the role that particle size and density play in the bedload transport process and in the formation of longitudinal sorting patterns. In particular I

- Performed experiment to reproduce longitudinal sorting patterns with a mixture of sediment particles differing in size and density in net-depositional conditions;
- Waited for the flow and the sediment transport to reach mobile bed equilibrium conditions to characterize bedload transport processes;
- Photographically documented vertical sorting processes on the lee face, i.e. the steep fronts of migrating triangular-shaped low amplitude and long wavelength bedforms that formed on the bed deposit during the experiments.

1.5   Organization of the Thesis

The present thesis is organized in the following chapters:

Chapter 1 is the very first chapter of the thesis which introduces the basic idea, the main objectives and the significance of the study topic.

In Chapter 2, the experimental set up, protocols and requirements are described and presented in detail.

Chapter 3 summarizes the experimental results. A preliminary analysis of the data is also be presented there.

Chapter 4 is the last chapter with preliminary conclusions and recommendations for future work.

CHAPTER 2.   **THEORY AND EXPERIMENT**

In this preliminary study three experiments were performed. Each experiment consisted of two runs, a non-equilibrium net depositional run, and a mobile bed equilibrium run. In this chapter I describe the experimental set up, the basic properties of the used materials and the experimental procedure.

The objective of this study is to investigate the sorting processes associated with a mixture of sediment particles differing in both size and density. Three types of well sorted sediment were mixed - coarse sand, fine sand and plastic. Both the size and the density is highest for the coarse sand (density 2632.06 kgm-3, 1.11 mm geometric mean diameter), the plastic has the smallest density but not the smallest grain size (1418.65 kgm-3, 0.842 mm) and the fine sand has the finest grain size and a density slightly smaller than the coarse sand (density 2465.28 kgm-3, 0.543 mm geometric mean diameter, The grain size distribution of each sediment type used in the experiments is reported in Figure 2.1. It is important to note here that the grain size distribution of the parent material was designed to be as close as possible to the grain size distribution of the plastic, i.e. the lightest material in the mixture.

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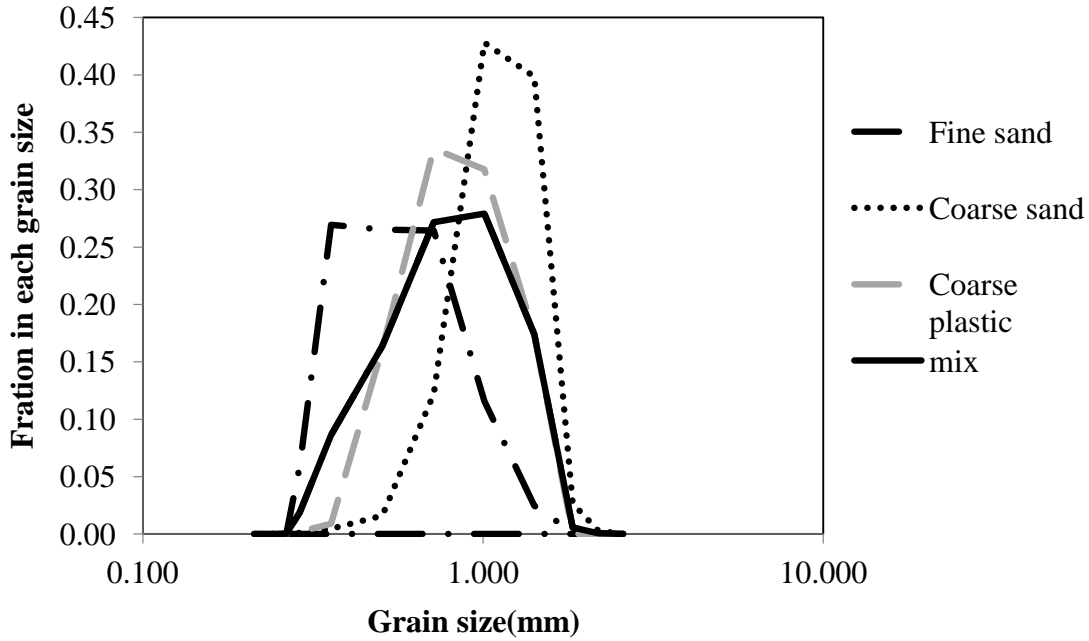
Figure 2.1: Grain size distribution for individual sediment and parent sediment mixture

The sediment properties are summarized in Table 2.1. In the first row I report the percent by volume of each sediment fraction in the parent material, i.e. the material used in the experiments. In the second and third column I report the geometric mean diameter and the geometric standard deviation. The particle settling velocity computed with the Dietrich relation is in the last row of Table 2.1.

The particle settling velocity was used to constrain the experimental conditions. If the ratio between the settling velocity and the shear velocity, which is related to the bed shear stress, is smaller than ~1 suspended load may be significant. Noting that our experiments are designed to study bedload transport, our experimental conditions were designed with a ratio between particle settling velocity and shear velocity greater than 1 for each sediment type.

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The geometric mean diameter of each sediment type and of the parent material was calculated for each of the individual sediment type and also for the sediment mix. Sieve analysis was performed to determine the grain size distribution of each sediment type, and the geometric diameter of the sediment grain was then calculated as Parker (2004)

$$D_g = 2^{\overline{\psi}} \tag{2.1}$$

Where, D_g = geometric mean size of sediment

$\overline{\psi}$ = mean grain size on psi scale defined as

$$\overline{\psi} = \sum_{i=1}^{N} \psi_i f_i$$

f_i =Fraction of sample in each characteristic grain size range measured with the sieve analysis, and $\psi_i = \log_2 D_i$

D_i =Characteristic diameter of each grain size range defined as $(D_{b,i}D_{b,i+1})^{0.5}$, with $D_{b,i}$ and $D_{b,i+1}$ denoting the maximum and minimum (bound) diameters of each grain size range.

Sediment Trap: We performed the experiments in an existing wooden water-feed flume of the laboratory. The flume needed to be equipped with a sediment trap to collect the sediment at the downstream end. We thus built a wooden sediment trap 1.83 m long and 0.61 m in wide and deep. A weir at the downstream part of the trap to fixes the water depth at 0.49 m. A 15.24 cm diameter vertical pipe connects the flume to the trap and a 10.16 cm diameter pipe drains the water from the trap into the laboratory basin.

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Table 2.1 Characteristics of individual sediment and parent sediment mixture

	Coarse Sand	Fine Sand	Plastic	Mix
% by volume	20	30	50	100
Geometric Mean diameter	1.11	0.543	0.842	0.780
Density (kgm-3)	2632.06	2465.29	1418.65	2160
Settling Velocity(cm/s)	17.07	8.14	5.727	12.09
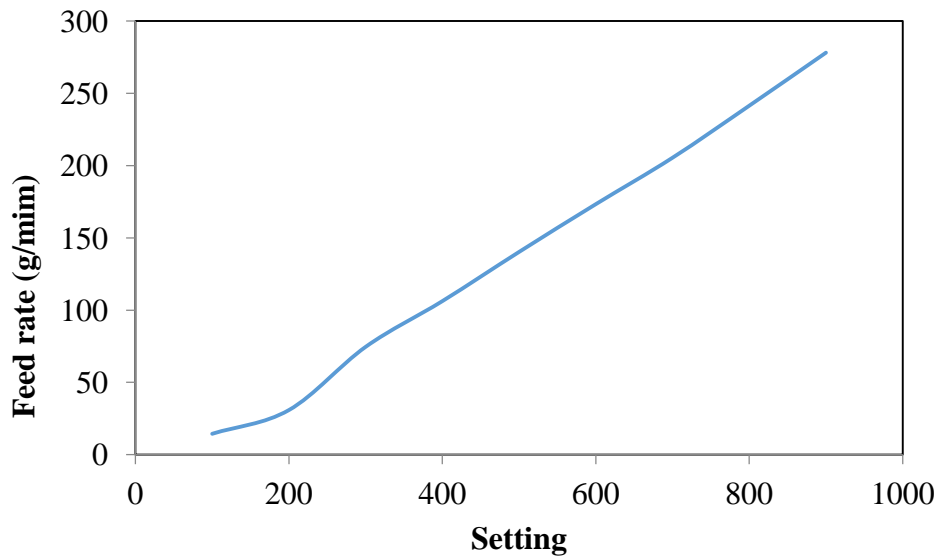
Figure 2.2: Calibration curve for parent sediment mixture

Calibration of sediment feeder: The sediment feeder is used to supply sediment at a constant rate at the upstream end of the flume. The feeder has controller that controls the rotation speed of a screw to deliver sediment into the flume. The controller can be set

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at variable speeds ranging from 100 to 900, with 100 denoting the minimum rotation speed that provides measurable sediment feed rates. The calibration curve indicating the mass of parent material discharged into the flume for different rotation speeds is presented in Figure 2.2.

2.1 Experimental Setup

The flume is 3.35 m long, 15.24 cm wide and 27.94 cm deep. The slope of the flume was measured with standing water and it is equal to 0.0029, which corresponds to a hydraulically mild slope. The sediment and water were fed at a constant rate from the upstream end for each experiment.
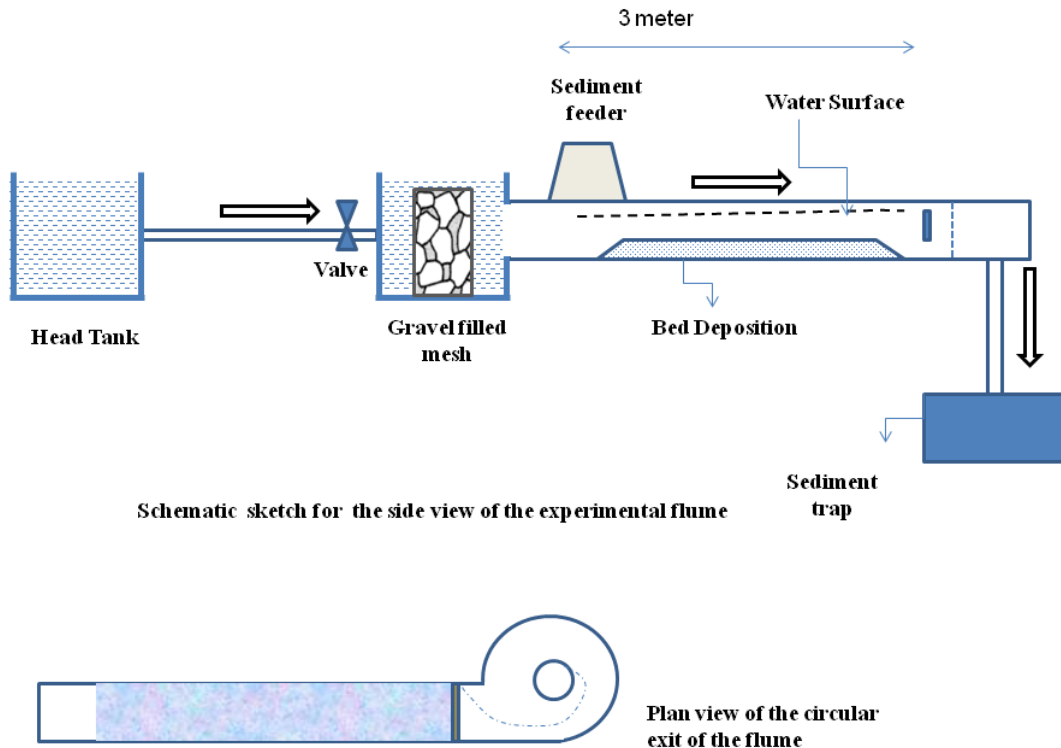
Figure 2.3: Schematic sketch for experimental setup

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The flow rate of water was controlled by a valve and was measured with a calibrated flow meter. The flow rate was constant for all the experiments and equal to 4 l/s. Water was discharged from the laboratory pipes in a basin equipped with a gravel filter to guarantee a relatively constant head on the flume. The flow depth at the downstream end of the flume was kept constant at a height of 12.7 cm. A long vertical pipe connected the downstream end of the flume to the sediment trap. Water surface elevations and bed elevations were carefully measured by a point gauge. A schematic sketch and an image of the experimental set up are presented in Figure 2.3 and Figure 2.4, respectively.

Figure 2.4: Image of experimental flume

2.2   Experimental Procedure

The main objective of this study is to investigate the effects of grain size and density on the transport and deposition of sediment in the longitudinal direction. To fulfill these objectives, some basic experimental procedures were defined:

1) Each experiment started with an empty flume, water and sediment were fed at the upstream end. A deposit with a sharp downstream front (laboratory scale Gilbert delta), formed and prograded downstream until it reached the downstream end of the flume;

2) Non-equilibrium measurements of water surface and bed elevation were performed when the front reached the downstream end of the flume. Intermediate measurements were not collected due to the limited length of the experimental facility;

3) Non-equilibrium bed surface samples to study longitudinal sorting patterns were then collected to characterize downstream fining and lightening patterns;

4) The experiment continued until the flow and the sediment transport reached conditions of mobile bed equilibrium;

5) At mobile bed equilibrium measurements of water surface elevation and bed elevation, and of the grain size and density characteristics of the bed surface were repeated to preliminary characterize the bedload transport processes.

During the surface sampling, the surface deposit was then divided into sections at every 15.24 cm in streamwise direction with width was equal to the flume width. Then the surface samples were collected with a spoon. The samples were stored in labeled

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containers for the measurements of density and grain size. The collected sample was not reintroduced in the system. This did not affect the final equilibrium because in sediment feed flume equilibrium conditions are independent from the initial conditions Parker and Wilcock (1993). The sample size varied due to the presence of small amplitude (~1 cm or less) and long wavelength (~15 - 20 cm) migrating bedforms, which defined the thickness of bed surface.

The collected samples were oven dried at ~170 degree Fahrenheit. Care was taken to control that the plastic in the samples did not melt. Sieve analysis was performed to measure the grain size distribution at different sections of the surface deposit. The geometric mean size of sediment for each section was also calculated as described above. These results were used to study preferential sediment deposition according to size.

The density analysis was then performed with the volumetric method. The weight and volume of a known amount of water was noted. The sediment sample was then submerged in that water, and the changes in water volume and weight were recorded. The bulk density of each sediment sample was computed as the ratio between the sediment mass and the volume of water displaced. These measurements gave insight on the preferential deposition of heavy particles.

Equilibrium condition defined based on the measurements of water surface and bed elevation. In particular, I declared that the flow and the sediment transport reached conditions of mobile bed equilibrium when

i) Two or more following profiles of water surface and bed elevation were reasonably equal (see Figure 2.5), or when the water surface slope did not significantly change in time, as shown for experiment 1 in Figure 2.6.
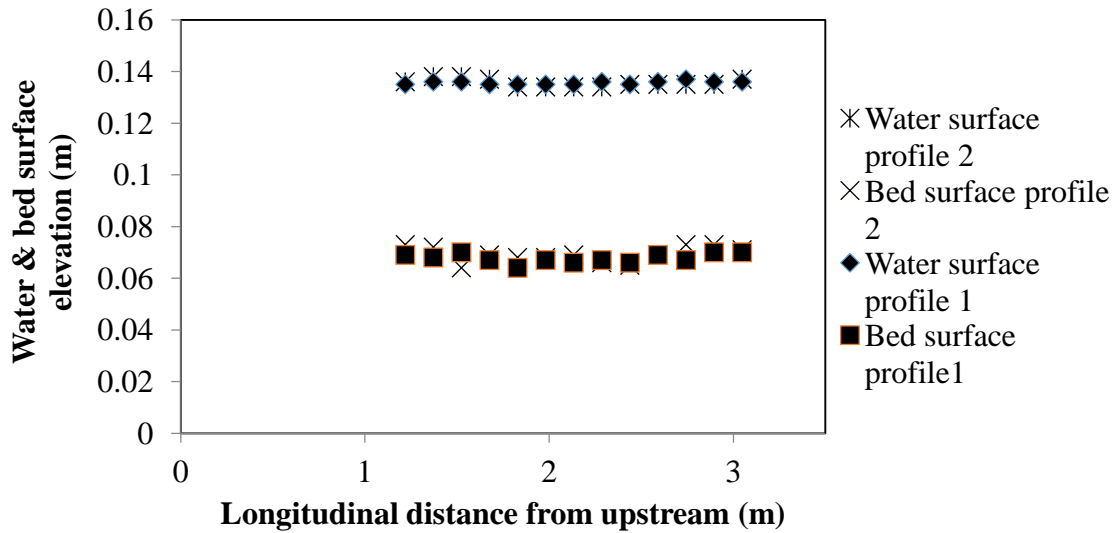

Figure 2.5: Two consecutive water and bed surface profile for experiment 2 equilibrium condition
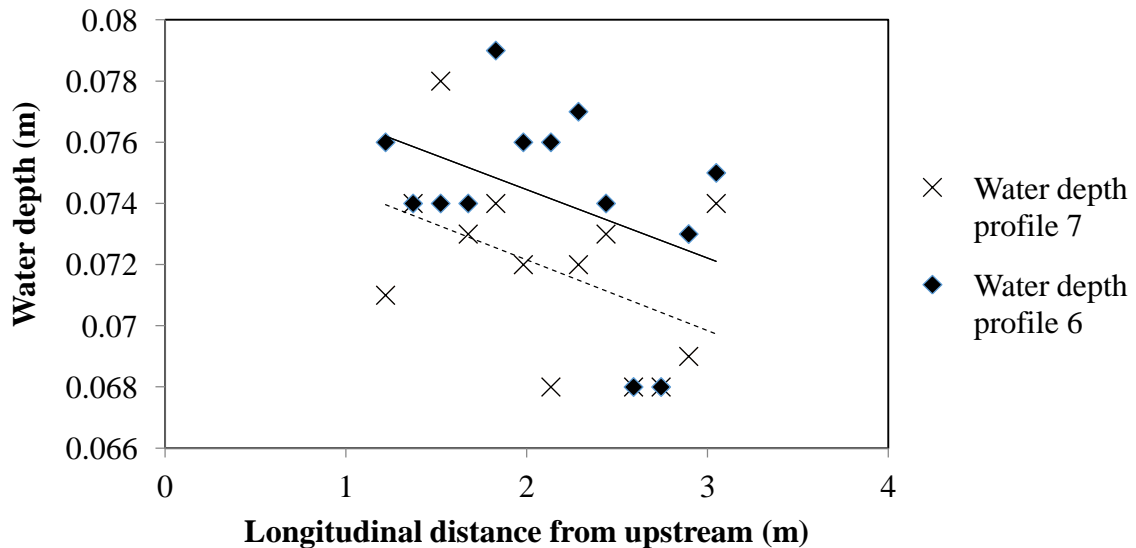
Figure 2.6: Two consecutive water depth profile for experiment 1 equilibrium condition

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Both the figures are plotted for the flume length from 1.22 meter to 3.05 meter (from upstream). The real pattern of deposit starts from 1.22 meter (4 feet) and continues until 3.05 meter (10 feet).

ii) Sediment distribution of the bed surface becomes almost constant in space (no downstream fining no downstream coarsening) from visual observations

iii) Average Density distribution of the bed surface becomes constant in space (no downstream lightening no downstream heavying) from visual observations

The last two conditions cannot be quantitatively determined until surface samples are collected.

As briefly mentioned above, three experiments were performed with different sediment feed rates, as summarized in Table 2.2. The feed rate in experiment 1 was 150 g/min, it increased to 250 g/min in experiment 2 and it was reduced to 50 g/min in experiment 3. Due to the different feed rate, i.e. volume of sediment released in the flume per unit time, the duration of the experiments varied considerably as reported in the last column of Table 2.2. In other words, the migrating front propagates fastest for the highest feed rate. The time to reach equilibrium conditions is also shortest for the experiment with the highest feed rate (see Table 2.2).

Table 2.2 shows the basic information about the experiments. The flow rate was kept constant in all of the experiments and equal to 4 l/sec, the grain and density distributions of the parent material did not change from one experiment to the other, the sediment feed rate was highest in the second experiment (250 g/min), hence it was the fastest experiment. The slowest experiment was experiment 3 with a feed rate of 50

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g/min. The results of each of the experiment are presented and discussed in the next chapter.

Table 2.2: Basic data for experiment

Experiment	Flow Rate (l/sec)	Feed Rate (g/min)	Time
Exp1-Non Equilibrium	4	150	2 h 35 min
Exp1-Equilibrium	4	150	2 h 35 min+3h 45 min (6 h 20 min)
Exp2-Non Equilibrium	4	250	1 h 45 min
Exp2-Equilibrium	4	250	1 h 45 min+1h 30 min (3h 15 min)
Exp3-Non Equilibrium	4	50	7h50 min
Exp3-Equilibrium	4	50	7 h 50 min+6h (13 h 50 min)

2.3 Side Wall Correction for Bed Shear Stress

Bed shear stress plays a very important role for the transportation of sediment. Coarser particles or heavy particles need high shear stress to be entrained for the effect of inertia but coarser particles can easily move due to the effect of hiding effect. These two

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types of effect together still makes the fine particles more mobile than the coarse particles but their combined effect decreases the difference of required bed shear stress for coarse and fine particles to be mobilized. Hence the relative mobility and equal mobility of sediment particles are closely related to bed shear stress. Equal mobility is the state when the limiting value of bed shear stress allows all the sediment particle to be mobilized .Usually the higher the feed rate, the higher the bed shear stress becomes Viparelli et al. (2014). Considering the vital role played by bed shear stress in the transport and deposition of sediment, it is very urgent to calculate the accurate value of bed shear stress. Different types of factors can affect the value of bed shear stress; wall roughness is one of those factors. Roughness of wall is removed following some successive steps. The process of removal of wall roughness and calculate side wall corrected bed shear stress have been described below.

Steps for Removal of Side Wall Roughness:

1. Some initial assumptions are necessary to start the calculation. The assumptions are

   - The required cross section needs to be divided into two independent regions where the gravitational force in stream direction is balanced by bed shear stress and wall shear stress

   - U (mean flow velocity and S (slope) is assumed to be constant for bed and wall region

   - Darcy-Weisbach relation is applicable for both of the regions

2. Basic Parameters

- Flow velocity (U) is calculated by dividing the flow rate (Q) by the total cross sectional area (A)

- This U is then used for the calculation of Froude number, $Fr = \frac{U}{\sqrt{gH}}$

- Wetted perimeter is calculated for bed (P_b)and wall region(P_w)

- Hydraulic radius is calculated for wall and bed region

3. Formula required for the calculation

- Finding ratio of Darcy weisbach friction coefficient (f) and non dimensional friction coefficient(C_f)

$$C_f = \frac{f}{8}$$

- Bed shear stress and wall shear stress is calculated using the formula$\tau_b = \rho C_{fb} U^2$ and $\tau_w = \rho C_{fw} U^2$

- Then the shield parameters are calculated for wall region and bed region using the following formulas

$$\tau_b{}^* = \frac{\tau_b}{(\rho_s - \rho)gD} \quad \text{and } \tau_w{}^* = \frac{\tau_w}{(\rho_s - \rho)gD} \text{ respectively}$$

- Then the Reynolds number for both the region is calculated using the basic formula, $Re = \frac{r.U}{\vartheta}$ the parameter will be changed according to the concerned area.

- The slope S is then calculated using Darcy-Weisbach relation $S = \frac{C_f U^2}{g.r}$

- The wetted perimeter for the whole cross section is the summation of the wetted parameters for bed and wall region

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- Mass conservation shows that the total cross sectional area is the summation of bed and wall cross sectional area

$$A = A_b + A_w \qquad (2.2)$$

- $C_f P = C_{fb} P_b + C_{fw} P_w \qquad (2.3)$

  this relation is derived from momentum conservation

  C_{fb} = friction coefficient for bed region

  C_{fw} = friction coefficient for wall region

- $\dfrac{C_f U^2}{gr} = \dfrac{C_{fb} U^2}{gr_b} = \dfrac{C_{fw} U^2}{gr_w} \qquad (2.4)$

  as slope S is same everywhere

- The equation can be written as

$$\frac{C_f}{Re} = \frac{C_{fb}}{Re_b} = \frac{C_{fw}}{Re_w} \qquad (2.5)$$

  (using Reynold's number formula)

- The unknowns are $C_{fb}, C_f , C_{fw} , A_b$ and A_w

- C_{fw} is calculated by the relation of smooth pipe developed by Nikuradse

$$\frac{1}{\sqrt{f_w}} = 0.86 \ln\left(4 Re_w \sqrt{f_w}\right) - 0.8 \qquad (2.6)$$

4. Procedure for solving the equations

- The friction co efficient for entire section (C_f) is calculated using darcy-Weisbach relation

$$C_f = \frac{S.g.r}{U^2} \qquad (2.7)$$

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- The ratio of friction coefficient and Reynold's number is calculated using the following formula $\quad \frac{C_f}{Re} = \frac{C_f}{r}\frac{\vartheta}{U}$ $\qquad\qquad$ (2.8).

- Equation (2.5) is used to calculate the ratio between friction coefficient and Reynold's number for wall region

- The value of friction coefficient and Reynold's number is calculated by using equation (2.6) which needs to be solved iteratively as both of the side of the equation has unknown friction coefficient

- The first estimation for $f_w, f_{w,o}$ is done with modified version of Blasius equation Chiew and Parker (1994)

$$f_{w,0} = 0.301(\frac{f}{Re})^{1/5} \text{ and } Re_{w,o} = f_{w,o}(\frac{f}{Re})^{-1} \qquad\qquad (2.9)$$

- The other estimations for friction co efficient and Reynold's number is done as a function of the values of them from previous iteration

$$\frac{1}{\sqrt{f_w}} = 0.86\ln(4Re_{w,i-1}\sqrt{f_{w,i-1}})^{-0.8} \quad \text{and} \quad Re_{w,i} = f_{w,i}(\frac{f}{Re})^{-1} \qquad (2.10)$$

- The area of wall region is computed using the equation for reynold's number

$$Re_w = \frac{r_w}{v}.U = \frac{A_w}{P_w}.\frac{U}{v} \qquad\qquad (2.11)$$

- Now the area of bed region calculated by subtracting the wall area from the total area

- Friction coefficient for bed region then is calculated by using equation (2.3)

- Bed shear is calculated

- Shield number for both bed and wall region has been computed

- Side wall corrected shear velocity is computed using the following formula

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$$U^* = \sqrt{\frac{\tau_b}{\rho}} \tag{2.12}$$

- Chezy coefficient for bed region is computed by using the following formula

$$C_{zb,b} = \sqrt{\frac{g}{C_{fb}}} \tag{2.13}$$

This process has been used for the calculation of side wall corrected bed shear stress. The corrected values of shear stress will be presented and compared in next chapter.

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CHAPTER 3.   **RESULTS AND DISCUSSIONS**

Three experiments were performed to study bedload transport and deposition of a mixture of sediment particles differing in size and density. Each experiment consisted of two runs – a non equilibrium run that terminated when the migrating front reached the downstream end of the measuring section, and an equilibrium run that terminated when the flow and the sediment transport reached conditions of mobile bed equilibrium.

Water surface and bed elevation profiles were periodically measured during the runs, bed surface samples were collected at the end of each run, grain size analysis and density analysis were performed to determine the density and grain size characteristics of the bed surface, as well as longitudinal sorting patterns. Photographs of the small (compared to the migrating front) lee faces of the bedforms that formed on the deposits were taken to qualitatively characterize the vertical sorting patterns. The density and size characteristics of the parent material, the flow rate and the downstream water surface elevation, which controls the accommodation space and thus the deposit thickness, were kept constant in all the experiments. In other words, the sediment feed rate only changed from one experiment to the other.

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3.1 Experimental Results and Discussions: Non -Equilibrium Runs

At the beginning of each experiment there was no sediment in the flume. When the sediment feeder was turned on, the deposit formed and grew. This deposit was characterized by a prograding front. Front progradation was associated with sediment deposition on the upstream part of the deposit. All the measurements are done for the range of 1.22 meter (4 feet) to 3.05 meter (10 feet) distance from the upstream end because the initial and end length of the flume doesn't show any real pattern of deposition. Deposit starts to get a clear pattern from 1.22 meter and continues until 3.05 meter (10 feet). So the initial and end length of the flumeis not shown in any plotting. The non equilibrium runs ended when the front reached the downstream end of the measuring flume section. The results of the non equilibrium runs are presented in terms of longitudinal profiles of 1) bed and water surface elevation, 2) geometric mean diameter of the bed surface and 3) average density of the bed surface.

Longitudinal Profile for bed Surface and Water Surface Elevation

Longitudinal profiles of bed surface elevation and water surface elevations are presented in Figure 3.1, Figure 3.2 and Figure 3.3 for experiment 1 (feed rate 150 g/min), 2 (250 g/min) and 3 (50 g/min) respectively.   In the figures, the diamonds represent the water surface elevation and the triangles are the bed elevation. The bed profiles of Figure 3.1 to Figure 3.3 are characterized by small fluctuations in bed elevation.   These fluctuations are partially representative of the long wavelength (~15 cm) and small amplitude (~1 cm) bedforms that formed on the bed deposit.

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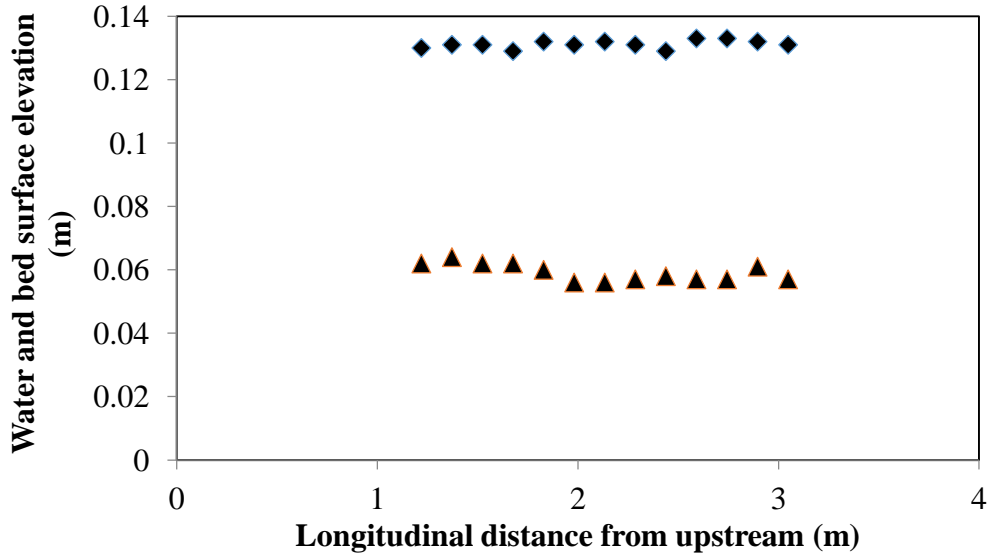Figure 3.1: Water surface and Bed surface profile for experiment 1 non- equilibrium run (Sediment feed rate =150 g/min). The diamonds represent the water surface and the triangles indicate the bed elevation.
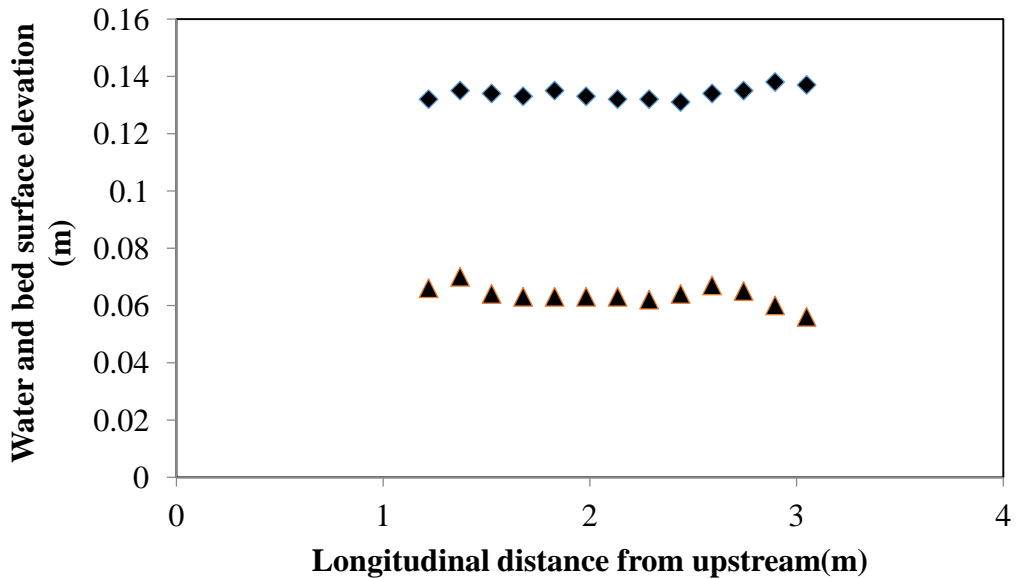

Figure 3.2: Water surface and bed surface profile for experiment 2 non-equilibrium run (250 g/min). The diamonds represent the water surface and the triangles represent the bed elevation.
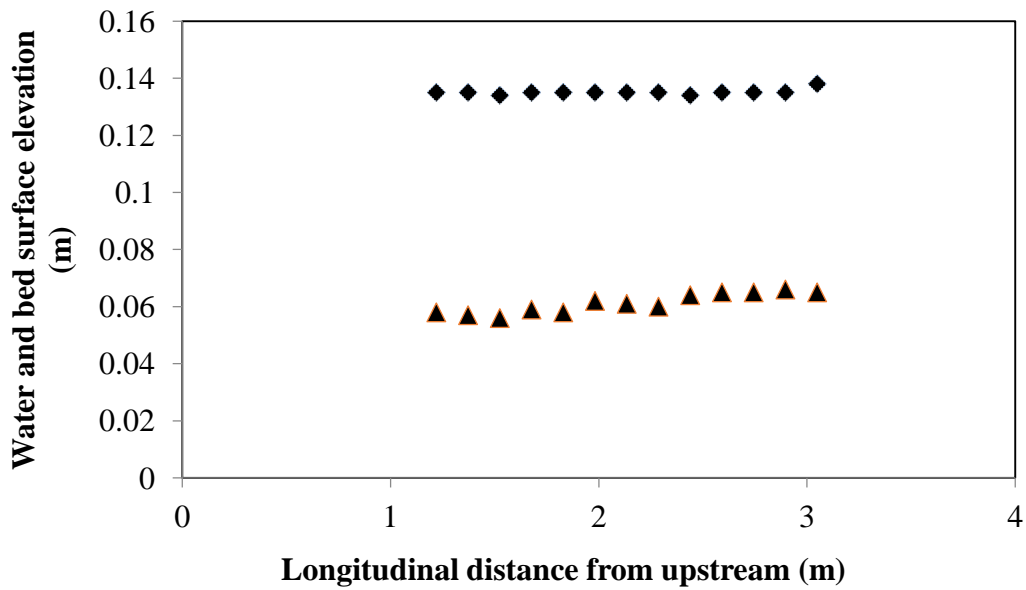
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Figure 3.3: Water surface and bed surface profile for experiment 3 non- equilibrium run (feed rate 50 g/min). The diamonds represent the water surface and the triangles represent the bed elevation.

Further, the bed surface elevation in experiment 1 and 2 is decreasing in the flow direction, as expected, but in experiment 3 we observe an inverse bed slope. Noting that an inverse slope characterizes the upstream part of the deposit in a sediment feed flume, the inverse slope observed in experiment 3 is probably a consequence of the low feed rate and the relatively shallow water depth. If the flume was longer and/or the flow depth deeper a proper deposit characterized by a downstream migrating front would have formed. This interpretation is substantiated by the equilibrium profile of experiment 3, which has a deposit mildly sloping in the downstream direction. This profile is presented in the continuing of this chapter.

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Grain Size Distribution for Non -Equilibrium Condition

The streamwise change of the geometric mean size of the bed surface is presented in Figure 3.4 to Figure 3.6, with the diamonds representing the data, the horizontal dashed black lines represent the geometric mean diameter of the parent material and the continuous black lines are trend lines to indicate the general sorting patterns. The data in Figure 3.4 pertain to our base case, i.e. experiment 1 (150 g/min), data for the experiment with the highest feed rate (250 g/min) are presented in Figure 3.5 and the results of the experiment with the lowest feed rate (50 g/min) are reported in Figure 3.6.
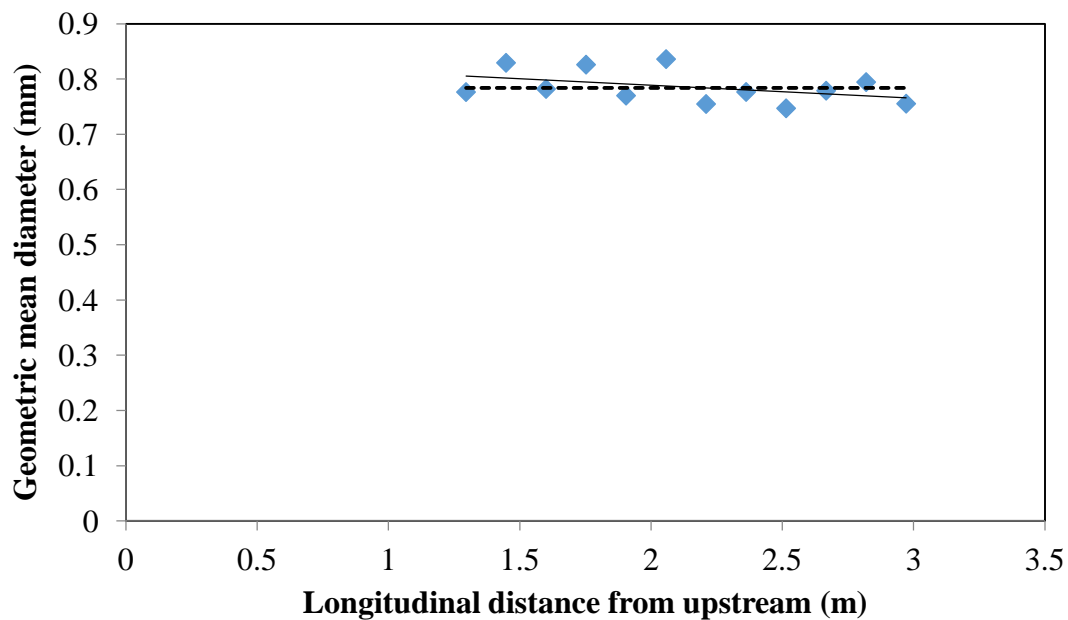
Figure 3.4 : Longitudinal variation of geometric mean size of the sediment mixture for experiment 1(150 g/min) non- equilibrium run

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Figure 3.5: Longitudinal Variation of geometric mean size of sediment mixture in experiment 2(feed rate 250 g/min) non -equilibrium condition

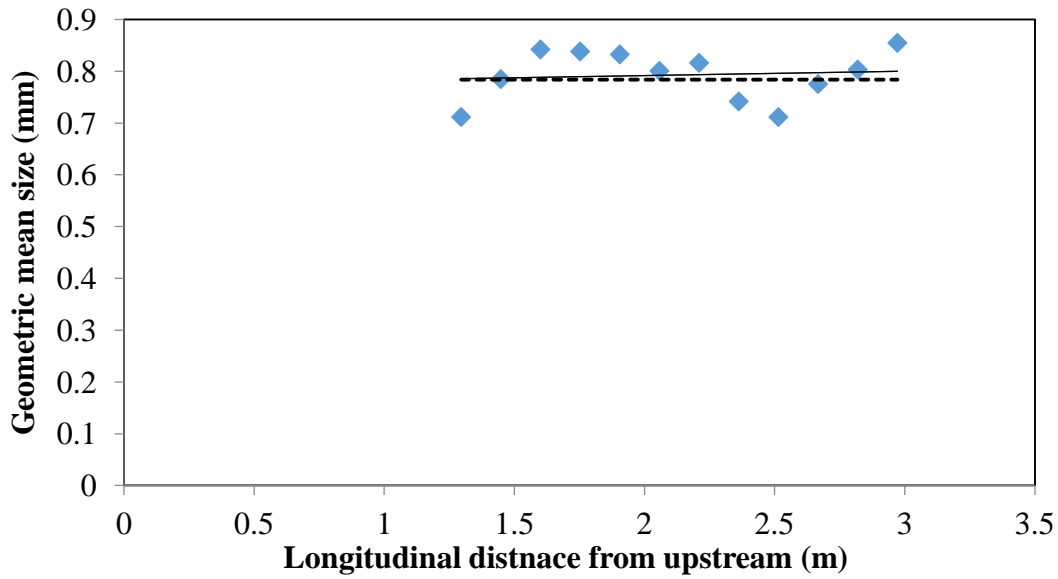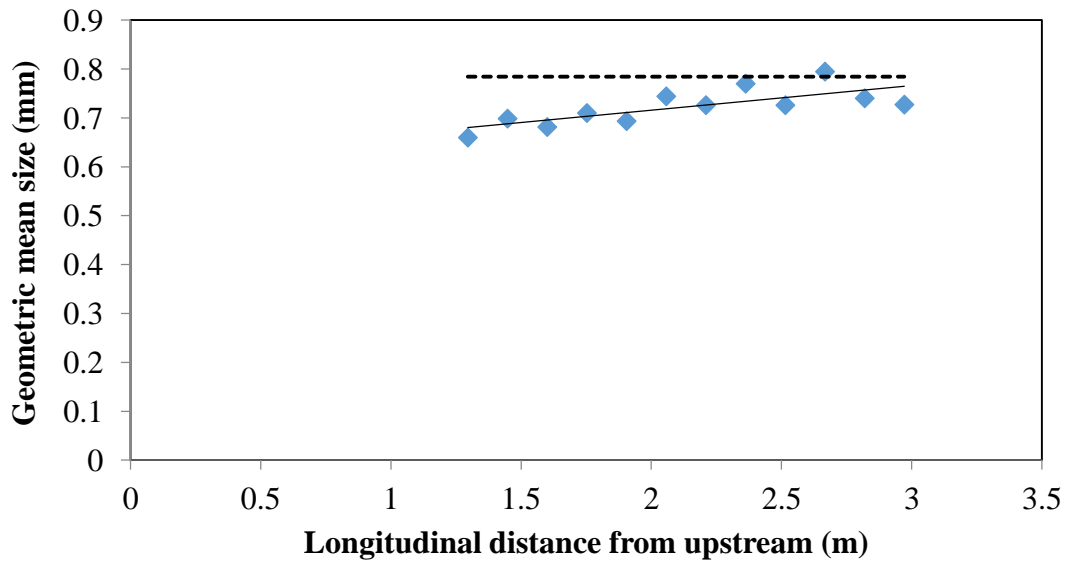Figure 3.6: Longitudinal variation of geometric mean size of sediment mixture for experiment 3(feed rate 50 g/minute) non -equilibrium run

The grain size analysis of the bed surface samples was performed for each non equilibrium run to investigate the effects of sediment grain size on the selective sediment deposition (keep in mind that the system is net-depositional). The trend lines in Figure

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3.4 to Figure 3.6 clearly show 1) a pattern of downstream fining in experiment 1 (feed rate 150 g/min), 2) a relatively constant surface geometric mean diameter in experiment 2 (250 g/min), i.e. in the experiment with the highest feed rate, and 3) a clear pattern of downstream coarsening in experiment 3 (50 g/min). In the interpretation of the results of above figures it must be kept clear in mind that the parent material consists of sediment particles differing in both size and density. The finest particles in the mixture are not the lightest, the lightest particles have in intermediate size of ~0.84 mm, and this complicates the problem. In other words, are the fine and heavy particles more mobile than the medium-coarse light particles?

The preliminary data presented herein do not allow me to answer this question. However, they clearly show that particle relative mobility (i.e. the mobility with respect to the uniform sediment case) in a mixture of sediment grains differing in both size and density may result in unexpected sorting patterns.

Density Analysis for Non- Equilibrium Condition

The streamwise variation of bed surface density for the non equilibrium runs is presented in Figure 3.7 to Figure 3.9. The longitudinal distance of the section from the upstream end has been plotted along horizontal axis and the density of the sediment has been plotted along vertical direction. The diamonds represent the experimental data and trend lines were added to show the general pattern of density distribution in streamwise direction. The density for the parent mixture has been shown by the dashed line.
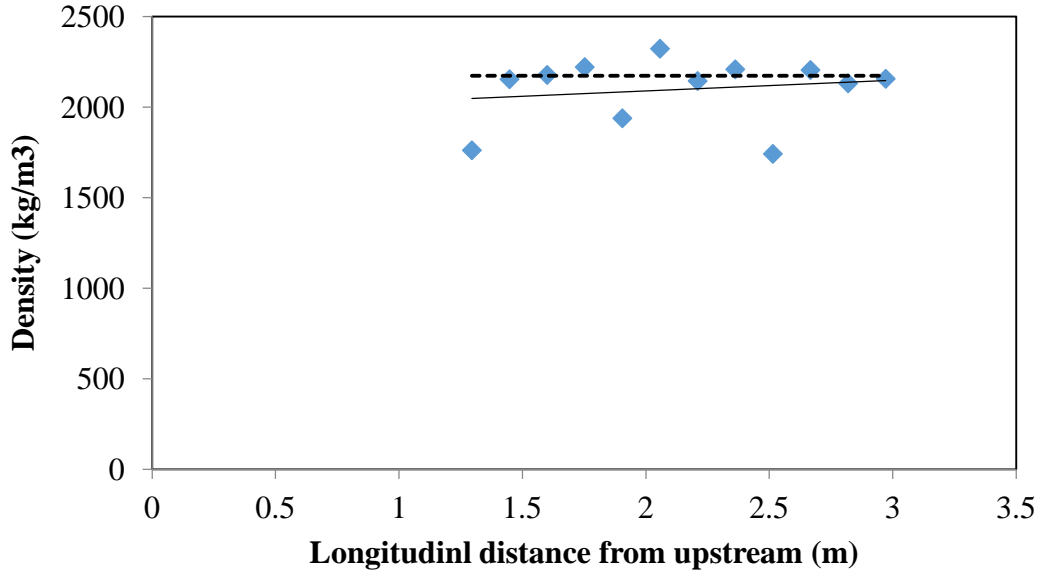
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Figure 3.7: Density variation of bed surface deposit in longitudinal direction for experiment 1 (150 g/min) non -equilibrium run
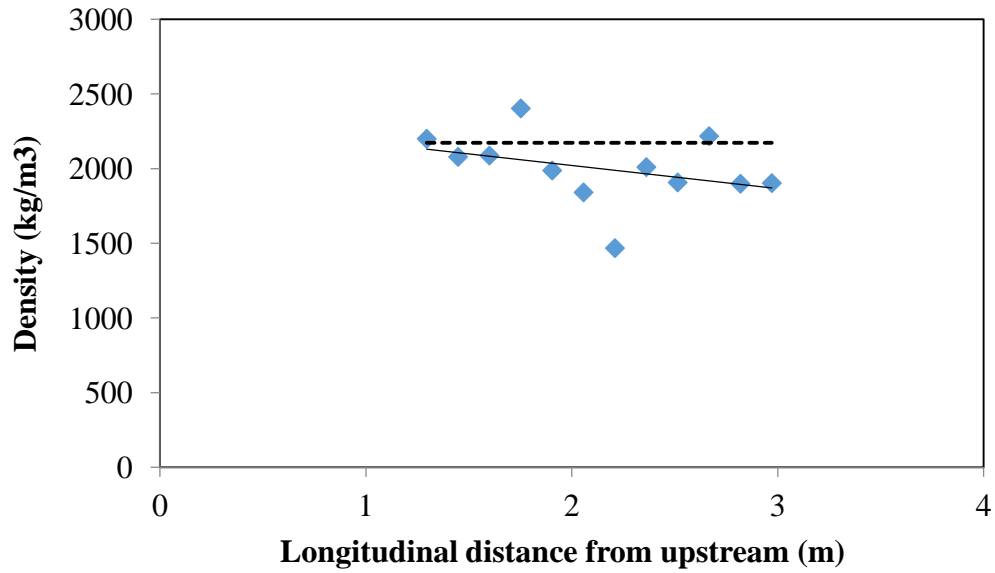

Figure 3.8: Density variation of bed surface deposit in longitudinal direction for experiment 2 (feed rate 250 g/min) non- equilibrium run

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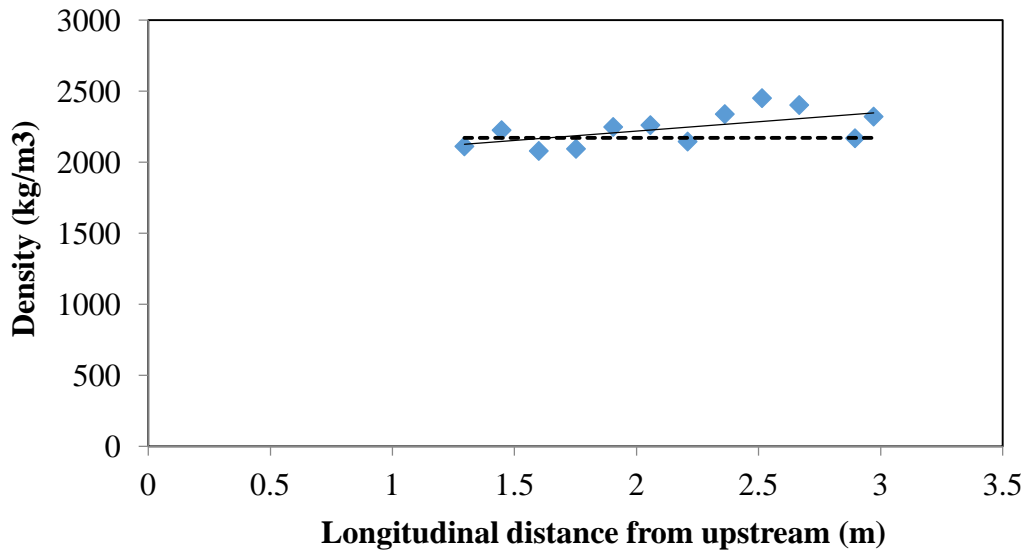
Figure 3.9: Density variation of bed surface deposit in longitudinal direction for experiment 3 (feed rate 50 gm/minute) non- equilibrium run

For the non equilibrium runs of experiment 1 (150 g/min) the density of the bed surface does not significantly change in the streamwise direction. In experiment 3 (50 g/min) the density of the bed surface increases in the streamwise direction (downstream heavying), while a clear pattern of downstream lightening is observed in experiment 2, i.e. the experiment with the highest feed rate.

It is interesting to note here that as the feed rate decreases from 250 g/min to 50 g/min the longitudinal sorting pattern changes: constant geometric surface grain size associated with a pattern of downstream lightening in experiment 2, downstream fining associated with a nearly constant bed surface density in experiment 1, and downstream coarsening and heavying in experiment 3. The sorting pattern of experiment 3 is most likely associated with the adverse slope of the deposit.

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The sorting patterns observed in experiments 1 and 2, respectively downstream fining associated with constant density of the bed surface and downstream lightening associated with nearly constant geometric mean diameter of the bed surface, resemble the sorting patters observed by Steidtmann (1982) in his experiments on upper plane and rippled bed. In particular, Steidtmann noticed that the presence of ripples (1-1.5 cm height and ~12 cm long wavelength) in his experiments inhibited the formation of a clear pattern of downstream fining or lightening. In the case of upper plane bed runs, Steidtmann observed a clear pattern of downstream lightening, associated with a pattern of downstream coarsening of the light material and fining of the coarse material, with an nearly constant surface mean grain size.

3.2 Experimental Results for Equilibrium Run

Equilibrium conditions were determined based on water and bed surface profiles and visual observation of sediment and density distribution. Hence, the runs might have been halted a little earlier, i.e. the system was neither net-depositional nor net-erosional but the grain and density distribution of the bed surface was still adjusting to the upstream conditions.

Longitudinal Profiles for Water Surface and Bed Surface Elevation for Equilibrium Condition

The longitudinal profiles of bed and water surface elevation are presented herein from Figure 3.10 to Figure 3.12. The streamwise distance from the sediment feeder is plotted in the horizontal direction and the water surface and bed elevations are reported

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on the vertical axis. All the plotting are for the length of 1.22 meter to 3.05 meter distance from the upstream end or the sediment feeder.
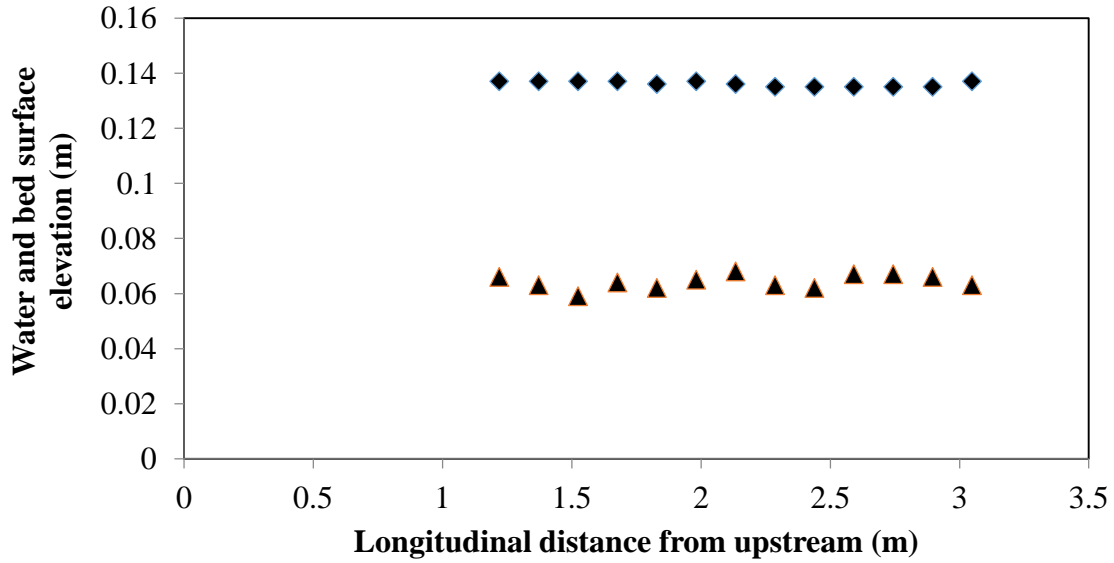

Figure 3.10: Longitudinal profile for water surface and bed surface elevation in experiment 1(feed rate 150 g/minute) equilibrium run
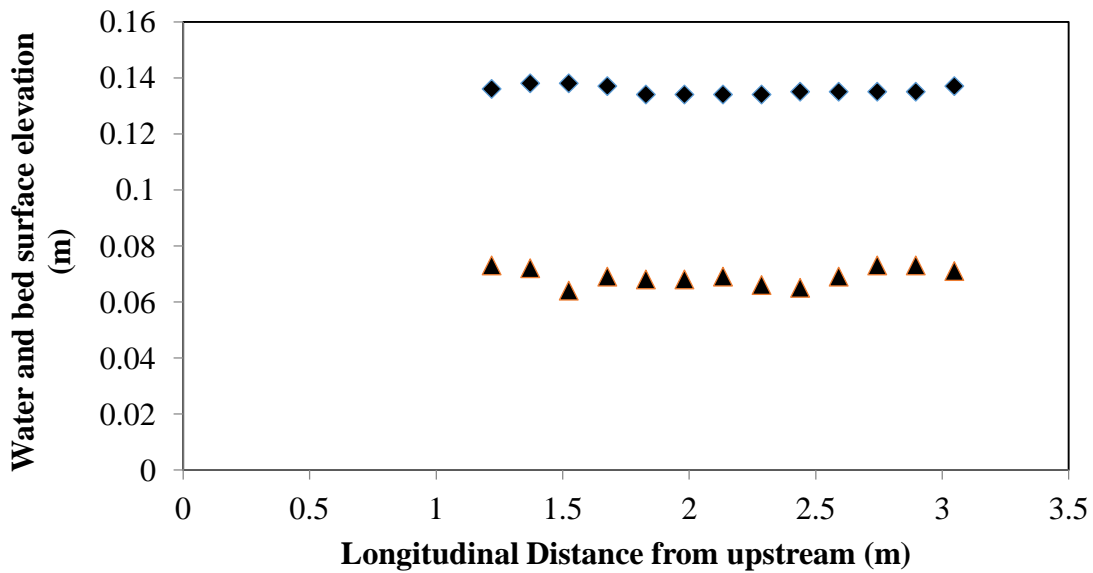

Figure 3.11: Longitudinal profile for water surface and bed surface elevation in experiment 2 (feed rate250 g/minute) equilibrium condition

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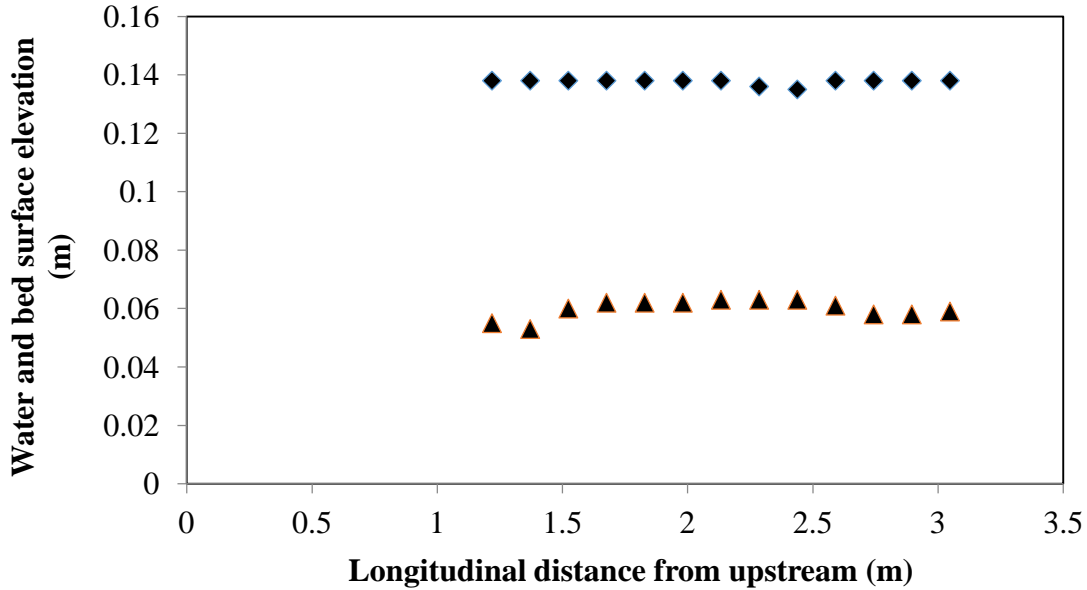
Figure 3.12: Longitudinal profile for water surface and bed surface elevation for experiment 3 (equilibrium run)

The initial and final length of the flume doesn't show the real pattern of deposit. The deposit start to develop from very beginning but it is well developed for the length 1.22 meter to 3.05 meter (4 to 6 feet). The diamond symbols represent the water surface measurements and the triangles represent the bed surface elevation. This profiles are necessary to determine when the system is approaching equilibrium, i.e, when it becomes not net erosional nor net depositional, and to characterize the flow properties, i.e., water depth and bed slope and bed shear stress.

<u>Longitudinal Variation of Grain Size of Sediment in Equilibrium Condition</u>

The information about grain size distribution and density distribution is also crucial for understanding mobile bed equilibrium. Besides the water and bed surface profiles, grain size and density also needs to be constant in place and time at mobile bed equilibrium. The longitudinal variation of geometric mean size for the three experiments

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is plotted in Figure 3.13. The longitudinal distance from the sediment feeder has been plotted along the horizontal axis and the geometric mean size is reported on the vertical axis (the upstream and downstream length of the flume has been ignored as previously explained). The geometric mean size of parent mixture has been shown by straight line.
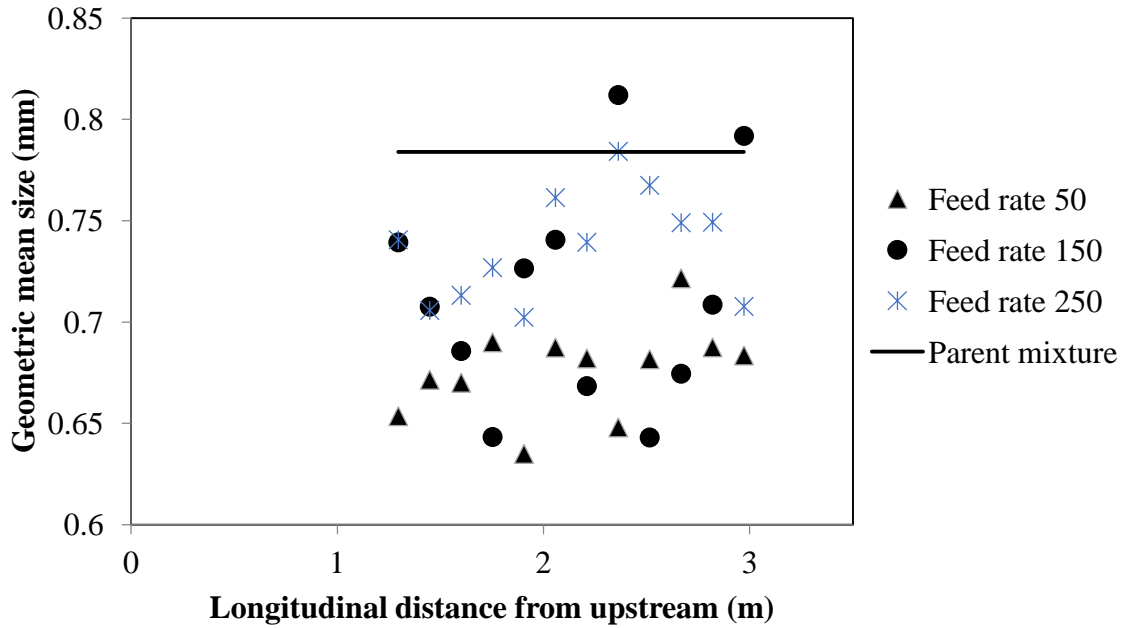
Figure 3.13: Longitudinal variation of geometric mean size for three equilibrium conditions

Figure 3.13 shows the longitudinal variation of grain size of bed surface for the equilibrium runs. The triangle, circle and cross symbols indicate the grain size variation for experiment 3 (50gm/min), experiment 1 (150 g/min) and experiment 2 (250 g/min) respectively. As expected, the geometric mean diameter of the bed surface is almost constant in space at mobile bed. It can be seen from the above figure that 1) the bed surface is always finer than the parent material, i.e. a coarse armor layer did not form during the experiments, and 2) the geometric mean diameter of the surface, D_{sg}, becomes finer for decreasing feed rates, i.e. the surface geometric mean diameter in experiment 3

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(50 g/min) is finer than in experiment 1 (150 g/min), and D_{sg} in experiment 1 is finer than in experiment 2 (250 g/min).

Figure 3.14: Comparison of grain distribution of sediment for experiment 1 (feed rate 150 g/min) equilibrium condition and grain size distribution of parent sediment mixture

The grain size distributions of the surface samples at mobile bed equilibrium are compared to the grain size distribution of the parent material in Figure 3.14, Figure 3.15 and Figure 3.16. The average diameter (D_i) for each grain size is plotted in the horizontal axis and the fraction in each grain size (f_i) has been plotted in vertical direction. The grey lines represent the surface grain size distribution for equilibrium condition and the black line represents the grain size distribution for parent mixture. In Figures 3.14-3.16 the grey lines are the grain size distributions of the bed surface. In experiment 1 (150 g/min) the fraction of sediment particles in the bed surface with size smaller than ~ 0.5 mm (fine sand) is higher than for the parent material. Similarly, the fraction of particles coarser than ~1.3 mm (coarse sand) on the bed surface is smaller than for the parent material.

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Figure 3.15: Comparison of grain size distribution of sediment mixture for experiment 2(feed rate 250 g/min) equilibrium run and grain size distribution of original sediment mixture
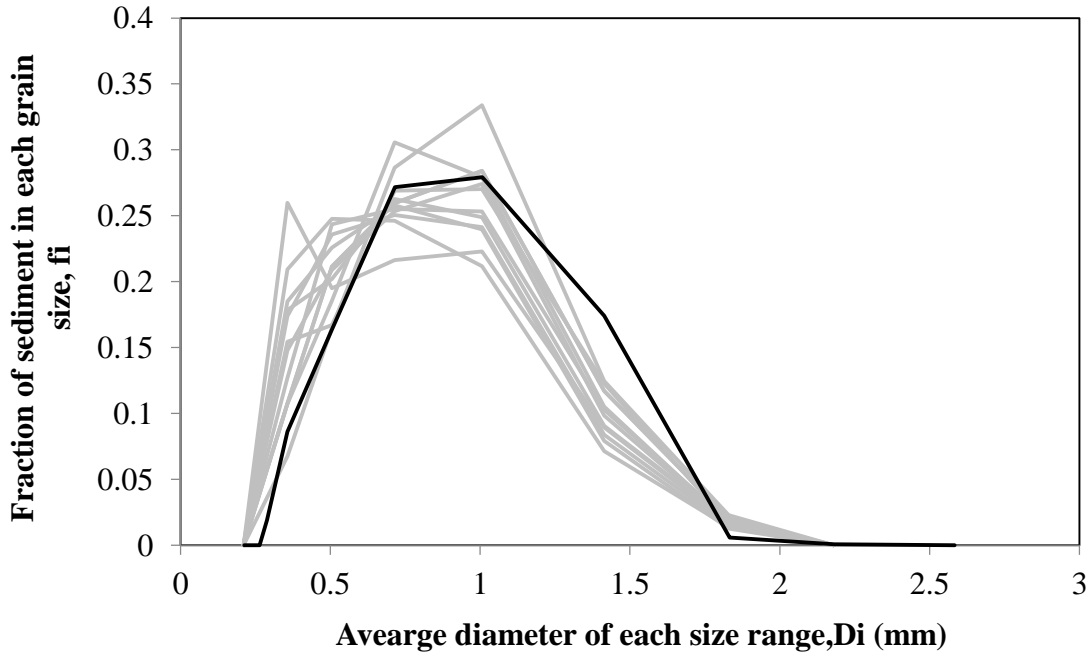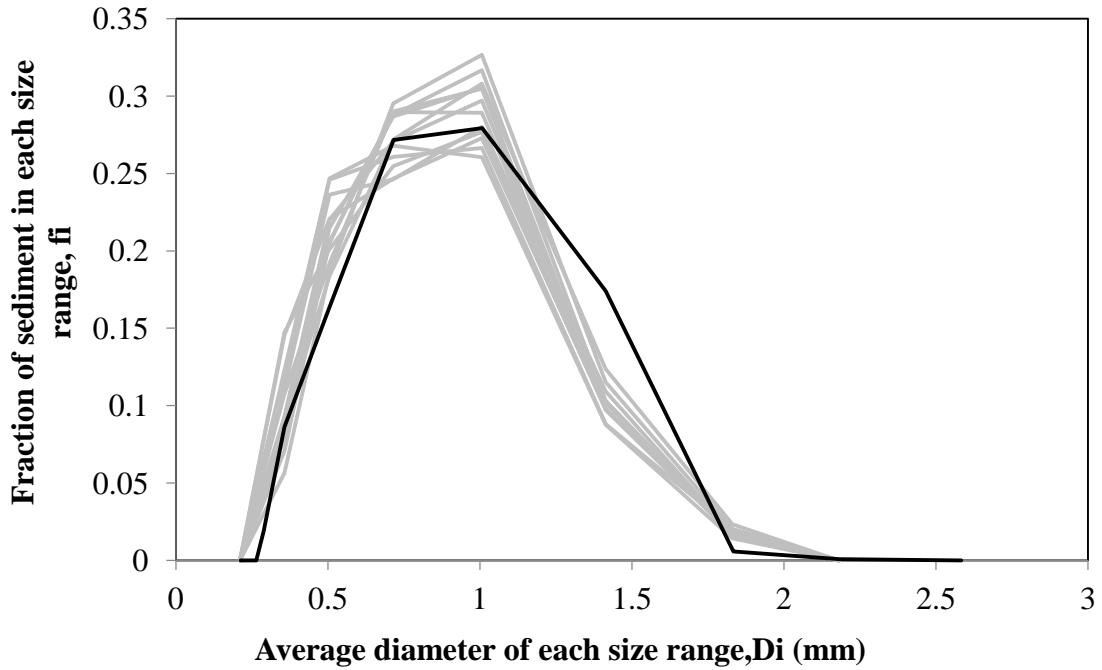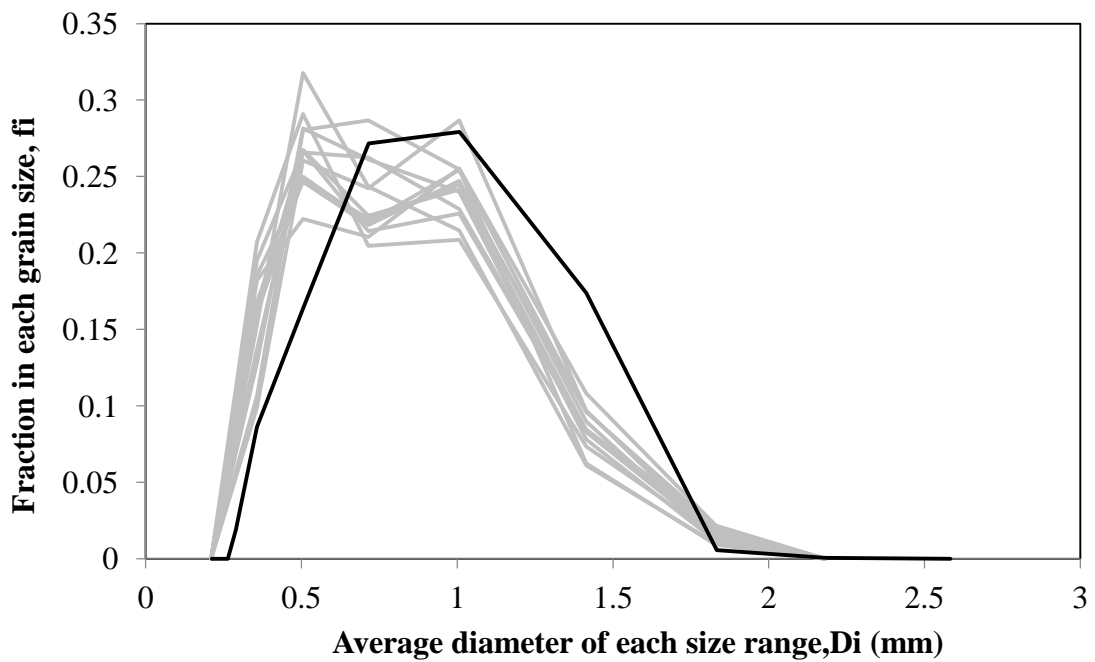

Figure 3.16: Comparison of grain size distribution for sediment mixture of experiment 3 (feed rate 50 g/min) equilibrium run and grain size distribution of original mixture

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In the experiment with the highest feed rate (experiment 2), the difference between the fractions of sediment finer than ~ 0.5 mm on the bed surface and in the parent material is smaller than in our base case (experiment 1) suggesting an change in mobility of the fine material. The fraction of particles in the ~0.8mm – 1 mm range on the bed surface highest than for the parent material, and the fraction of particles coarser than ~1.3 mm on the bed surface is still smaller than for the parent material. In the experiment with the lowest feed rate (experiment 3), the grain size distribution of the bed surface is characterized by a bimodal distribution, with modes at diameters of ~ 0.5 mm and ~1 mm suggesting a change in particle mobility compared to experiment 1.

<u>Longitudinal Variation of Density of Sediment in Equilibrium Condition</u>

Longitudinal variations of density for equilibrium condition of three experiments are presented in the Figure 3.17. Longitudinal distance of the section from upstream end is reported on the horizontal axis and the density of the surface samples are on the vertical axis. Triangle, circle and cross mark legends indicate the general pattern of density change for experiment 3 (50 g/minute), experiment 1 (150 g/minute) and experiment 2 (250 g/minute) respectively. The continuous black line denotes the density of the parent material.

Virtually no spatial changes in the density distribution of the bed surface can be observed in Figure 3.17and Tables 3.1 and 3.2 except for experiment 3(feed rate 250) when it mildly decreases in the downstream direction suggesting that mobile bed equilibrium might not have been reached. As shown in Figure 3.17, the density of the bed surface is higher than the density of the parent material suggesting the formation of a

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heavy armor layer to regulate the difference mobility between heavy and light particles, In addition as the feed rate increases, the transport capacity of the flow increases and the bed surface becomes finer. This suggests a decrease in relative content of heavy – hard to move – particles on the bed surface, as observed in experiments with mixtures of particles of uniform density but differing in size, i.e. the bed surface becomes finer (smaller concentration of coarse –heavy to move – particles) for increasing feed rates Deigaard (1982); Lisle et al. (2000).
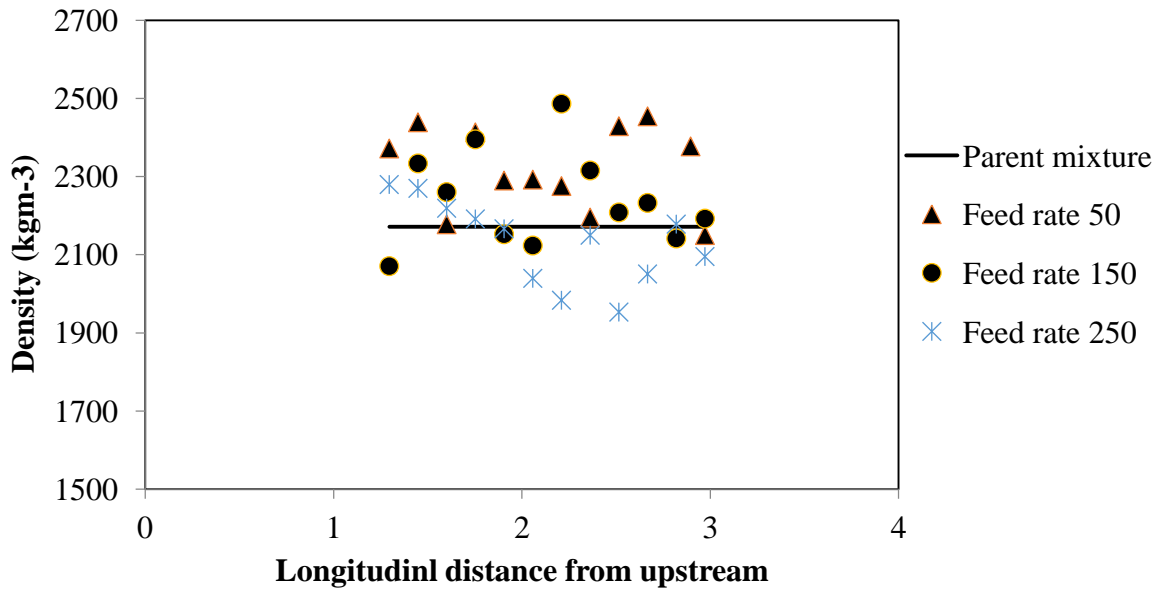
Figure 3.17: Longitudinal variation of density of sediment mixture for equilibrium runs

The average densities of the bed surface at equilibrium are reported in Table 3.1 for each experiment. Recalling that theparent material consisted of 50 % light material (plastic) and 50 % heavy material (30% fine sand, 20% coarse sand),the fractions of plastic and sand in the equilibrium surface, are computed as flows (and reported in Table 3.2). The average density of the bed surface, ρ_{avg}, is defined as

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$$\rho_{avg}F = \rho_s F_s + \rho_p F_p \tag{3.1}$$

$$\rho_{avg}F = \rho_s F_s + \rho_p (1 - F_s) \tag{3.2}$$

Where

ρ_{avg}= Average density of sediment mixture for equilibrium condition

ρ_s =Average density of coarse sand and fine sand

ρ_p = Density of plastic

F =Total fraction of plastic and sand

$$F = F_s + F_p = 1 \tag{3.3}$$

F_s = Fraction of sand in final mixture

F_p = Fraction of plastic in final mixture

The fractions of sand and plastic in sediment mixture for equilibrium condition have been presented in Table 3.2.

The data presented in Table 3.3 show that in my experiments 1) the bed surface is always heavier than the parent material, and 2) as the feed rate increases, the fraction of heavy particles on the bed surface decreases.

Table 3.1 Table for average density

	Mixture	Equilibrium 1 (150 g/min)	Equilibrium 2 (250 g/min)	Equilibrium 3 (50 g/min)
Density (kgm-3)	2172	2242.494	2131.117	2321.903

Table 3.2: Table for fraction of sand and plastic in sediment mixture for equilibrium condition

	Original Mixture	Experiment 1	Experiment 2	Experiment 3
Feed Rate (g/min)		150	250	50
Fraction of sand	0.5	0.729	0.630	0.799
Fraction of plastic	0.5	0.271	0.370	0.201

Summary of experimental data for equilibrium condition and comparison

The summary of the significant results obtained from the equilibrium condition of the experiments has been presented in Table 3.3. The comparison of mobile bed equilibrium data from Table 3.3 shows that the average flow depth increases with decreasing feed rate and the slope of water surface increases with increasing feed rate. The shear stress is highest for experiment 2 (feed rate 250 g/min) and lowest for the

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lowest feed rate experiment (50 g/min) which was expected. The higher the feed rate, the higher is the transport rate of sediment and shear stress also increases consequently.

Table 3.3: Summary of Experimental Data

Experiment (equilibrium)	Feed rate (g/min)	Average flow depth (cm)	Average slope of water surface	Side wall corrected bed shear stress (N/m2)	Average geometric mean size (mm)	Average density of bed surface (kgm^{-3})
Experiment 1	150	7.184	.001	0.37	0.711	2242.49
Experiment 2	250	6.631	.0016	0.66	0.737	2131
Experiment 3	50	7.769	.0003	0.16	0.675	2321.90

3.3 Observed Pattern of Sediment Sorting at Lee face

The sorting of sediment at lee face is governed by gravitational effectss. The pattern and mechanism of sediment sorting at lee face for sediment mixture with different size and uniform density has been described by Blom and Kleinhans (2006), as in Chapter 1. Photographs of the lee face sorting patterns observed during the experiments are presented in Figure 3.18. Though the actual pattern of sediment deposition can't be accurately quantified, these photographs provide visual information about vertical sorting patterns at the lee face.

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Figure 3.18: Sample photographs for deposition of sediment at lee face.

In the photographs, it is evident that the white light particles (plastic) are preferentially deposited in the lower part of the lee face, and the heavy sand grains are trapped in the upper part of the lee face. . Thus, an upward heavying density profile, analogous to the upward heavying measured by Viparelli et al. (2015), is observed. The pictures, however, do not provide any information of the spatial variation in grain size over the lee face, thus my sorting patterns cannot be compared with the Blom and Kleinhans (2006) model.

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CHAPTER 4.   SUMMARY AND CONCLUSION

4.1 Summary

Principal objective of this study was to investigate the effect of grain size and density variation on the transport and deposition of sediment in streamwise direction. For the purpose of this study three set of experiments were performed in a wooden flume. Sediment feed rate was constant for each experiment but varied for different experiments and other experimental conditions were same. Each experiment consisted of two runs- one is for non-equilibrium condition and another for equilibrium condition. After each run, the sample from the bed surface was collected and dried. Then, density and grain size analyses were performed to understand the sediment sorting pattern. Sediment feed rates for the first two sets of experiment were relatively high and the results obtained from those experiments were much satisfactory. But the third experiment was run with very slow feed rate and the equilibrium condition was not perfectly reached. The sorting pattern at lee face was visually observed and photographically documented; no density or grain size analysis was performed for that part as that was not the main concern of present study.

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4.2 Major Findings

- For the mixture of sediment differing in both size and density, any definite pattern of sediment transport and deposition cannot be forecasted in a straightforward way.

- For the case of experiment with relatively lower feed rate (150 g/min) downstream fining pattern of grain size sorting is observed.

- The experiment with higher feed rate (250 g/min) showed downstream lightening pattern which means the heavy particles preferably deposit at the upstream end and the light particles travel further downstream.

- Sediment mixture on the surface bed was finer than the original mixture, so no coarser or armor layer was formed.

- The density of surface deposit was higher than the density of the original mixture and the layer was the heaviest with the lowest feed rate. So it can be argued that a 'heavy' armor layer analogous to a coarse armor layer might have developed.

- The shear stress increases with increasing feed rate which is expected.

- longitudinal sorting profiles observed from this study are in agreement with previous work by Steidtmann (1982) on size and density sorting in the presence of ripples and in upper plane bed regime.

- Photographic evidence shows that an upward heavying sorting pattern has occurred at lee face or at the steep downstream front of the migrating deposit.

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4.3 Future Scopes

- The selective transport and deposition of sediment is highly influenced by both size variation and density variation. But very few studies have been performed to analyze their combined effect on sediment sorting. Therefore, extensive future studies are required to investigate the pattern and characteristics of sediment sorting for sediment mixture differing in both size and density.

- Lee face sediment sorting has not been covered elaborately in this study, future studies on this field is recommended

- Vertical sorting pattern with sediment mixture differing in size and density can be a promising field for future study.

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